EXPERIMENTAL VALIDATION OF MODELS FOR PREDICTING WAX REMOVAL FORCES IN PIGGING OPERATIONS

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Abstract. *Pigging is one of the most used solutions for removing wax deposits from the interior of production and transportation pipelines. However, the mechanics of the interaction between the pig, the pipe wall and wax deposits is not yet fully understood. The present paper reports results of an ongoing research program aimed at studying the interactions between different types of pigs and wax deposits. A special test section was constructed to measure the forces developed while the pig was being pulled through a pipe having wax deposited under controlled conditions. The experimental results were used for validating models for predicting contact forces between disc and foam pigs with the pipe wall. The agreement between measured and predicted forces was very good. The experiments with wax deposits have shown that the force for breaking the wax deposits can be much smaller than the force necessary to push the wax already removed. The present paper concentrated on studying the initial stages of the wax removal process, where the wax is removed but no accumulation is present. The results revealed that the assumptions made in the only model available in the literature seem to be correct: depending of the stiffness of the pig it can either push the deposit axially, or it can ride on the deposit imposing a shear deformation on the wax surface.*

Keywords: *wax removal, pigging, flow assurance*

1. Introduction

Wax deposition in the interior walls of production and transportation pipelines is a relevant problem for the industry, particularly in deep water offshore operations. Crude oil leaves the well head at about 60^{o}C entering the long lines that take the production to platforms or to shore. The water temperature at large water depths is around 5^{o}C, what promotes the cooling of the oil flowing in the lines. When the temperature of the oil reaches a level called wax appearance temperature (WAT), wax crystals come out of solution and may deposit on the pipe inner wall. The accumulation of the deposited layer can lead to decreased flow rate or even to the total loss of production. The costs associated with reestablishing the normal production flow rates are significant especially if sections of the line have to be substituted due to total blockage.

Pigging has been established as one of the most used solutions for removing wax deposits in pipelines. Pigs are devices driven by the flowing fluid and introduced into the pipelines with geometric interference so as to produce a contact force against the wall that it is responsible for removing the deposited wax layer. Figure 1 is an illustration showing a disk pig performing a wax removal operation.

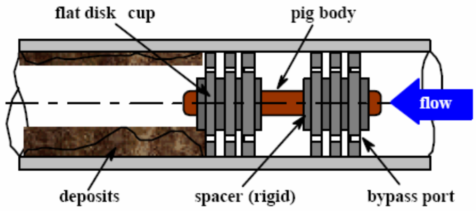


Figure 1. Pictorial view of a disc pig in a wax removal operation.

Although the procedures and the technology on pipeline pigging have evolved significantly in the last years, pigging is still a risky operation due to the possibility of the device becoming stuck in the line, causing the total or partial loss of production. Since the last decade a research program has been conducted with the objective of studying the dynamics of pig motion in pipelines (Azevedo *et al.*, 2003). As part of this research program, the equations governing the transient fluid flow where combined with equations modeling the pig dynamics to yield, for the first time, accurate predictions of pig velocity and acceleration, together with all the relevant transient flow variables distributions such as pressure, velocity and temperature. One of the key inputs to this model is the contact force on the pipe wall exerted by the different type of pigs while they are driven through the pipeline. These forces are crucial to the determination of the pig dynamics, once they act against the driving pressure developed by the flowing fluid. The prediction of these forces is a difficult task due to the complex and varied geometries of the different types of pigs used by the industry. In the research program mentioned before, special attention was dedicated to the development of models for predicting the contact forces of the most commonly used pigs. As will be reviewed shortly in the present paper, finite element models and experimentation were combined to devise simple models that could be coupled to a transient flow simulator, in order to provide the desired dynamic behavior of the pig.

In the case of pigs used for wax removal, the force necessary to break the wax deposit and to carry the removed material can be a relevant portion of the total force necessary to drive the pig. Indeed, as will be shown shortly in the results section, the force necessary to move the removed wax deposits can be the most important and, sometimes, the only responsible for pig stall.

The present paper presents results of an ongoing experimental program aimed at validating the models for contact forces between pigs and pipe walls developed previously by Azevedo *et al.* (2003), and also those developed by Souza Mendes *et al.* (1999), focused on the prediction of the forces necessary for removing wax deposits.

For completeness, a brief review of the models developed will be presented prior to description of the experiments conducted and the results obtained.

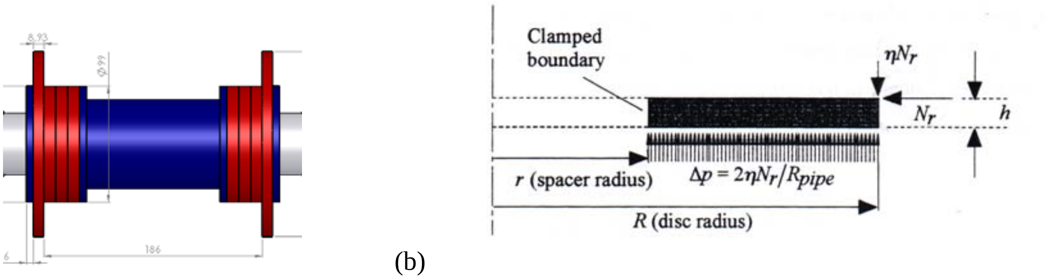
It is important to observe that, although pigging and wax removal are relevant operations conducted daily by the industry, there is practically no studies in the open literature devoted to the investigation of the fundamental phenomena that govern these problems. This type of study could help decrease the level of uncertainty normally associated with these operations. The paper by Wang *et al.* (2001), together with those already mentioned, are the only contributions available the field.

2. Theoretical models for predicting contact forces and wax removal forces.

In this section we will review the models available in the literature for predicting the contact forces between pigs and the pipe wall and that for predicting the force necessary for removing a wax deposit. These models will later be verified by the experiments conducted.

2.1 Contact force model for disk pigs.

The model for predicting the contact force between disk pigs and the pipe wall was proposed by Azevedo *et al.* (2003). This model develops an analysis of the post buckling behavior of disks inside the pipe by means of the finite element technique. Figure 2(a) presents a photograph of a commercial disk pig formed by 2 disks, while Fig. 2(b) presents the loading on the models developed for studying the behavior of a single disk.



(a) (b)

Figure 2. (a) Typical disc pig. (b) Model for forces acting on a disc (Azevedo *et al.*, 2003).

In the analysis conducted the spacers that separate the disks were considered as rigid, and submitted to radial loads due to the geometric interference between the disc and the pipe, and axial loads due to friction against the pipe wall. The effects of the pressure gradient across the disk were also considered in the model. In Fig. 2(b), R is the radius of the disk, h is the thickness of the disk, r is the spacer radius, E and υ are respectively, the Young's modulus and Poisson's coefficient for the disk material, η is the friction coefficient between the disk and the pipe wall, and N_r is the radial load per unit length. Also, u_r is the displacement in the inward radial direction, $R_{pipe} = R - u_r$ is the internal radius of the pipe, and Δp is the pressure differential across the disk. Based on the equations for non linear buckling of thin circular plates (Timoshenko, 1961), the authors chose the following dimensionless variables for the problem:

$$\widehat{p} = \frac{(1-\nu^2)\Delta p}{E(h/R_{pipe})} = \eta \frac{(1-\nu^2)N_r}{Eh(R-u_r)} \text{ and } \widehat{u} = u_r/(R-u_r) \quad (1)$$

The authors also defined the following dimensionless parameters, H/R, h/r, υ, and η. Tests conducted revealed that the chosen dimensionless parameters represent well the problem. Further, it was also shown that there exits an approximate linear dependence between pig oversize and the pressure differential required to drive the pig. Thus, for oversizes larger than 2% this relationship can be written in the form $\widehat{p} = a(h/R, h/r, \nu, \eta)\, \widehat{u} + b(h/R, h/r, \nu, \eta)$, where values of the coefficients $a(h/R, h/r, \nu, \eta)$ and $b(h/R, h/r, \nu, \eta)$ were determined by means of finite element solutions for the problem. A table containing values for a and b was prepared based on 500 finite element runs encompassing values for the dimensionless parameters normally encountered for commercially available polyurethane disks. The parameters were within the following ranges: $0{,}05 < h/R < 0{,}11$, $0{,}14 < h/r < 0{,}22$, $0{,}2 < \eta < 0{,}6$ and $\nu = 0{,}42$.

The tables containing the values obtained from the finite element solutions were incorporated with an interpolating routine in the software *PIGSIM* developed by the Mechanical Engineering Department of PUC-Rio. The data obtained with the experiments of the present study were compared with the results of the model briefly described.

2.2 Contact force model for foam pigs.

Foam pigs are widely used in pigging operation for wax removal. These pigs normally do no exert contact forces on the pipe wall as high as those observed in disk pigs. However, they are employed due to safety reasons since they are much easier to be removed if they happen to get trapped in the line.

The model developed by Azevedo *et al.* (2003) for predicting the contact forces exerted by foam pigs is quite simple, and will now be described. In the model the contact force is estimated by,

$$F = \eta\, \pi\, D_T L\, E \left(1 - D_T / D_P\right) \tag{2}$$

where, F is the contact force, η is the friction coefficient between the foam pig and the pipe wall, L is the length of the foal pig, E is Young's module of the foam , D_T and D_P are, respectively, the pipe and pig diameters.

2.3 Model for the force required to remove a wax deposit.

In a paper published in 1999, Souza Mendes *et al.* proposed what is, to date, the only model available for estimating the force necessary for a pig to remove a wax deposit. The model proposed is based on the assumption that a specific wax deposit on the pipe wall will be removed if the shear stress imposed by the pig surpasses the mechanical shear resistance of the wax. The model proposes two types of possible interactions between the pig and the deposit. In the first mode of interaction, named Load Model 1, the pig acts axially on the face of the deposit of thickness t, as illustrated in Fig. 3(a). In the second mode of interaction devised, Load Model 2, the pig is supposed to be positioned on the deposit, acting radially on it, as shown in Fig. 3(b). For Load Model 1, a force balance yields,

$$\sigma = \Delta P / \left[(4t/D)(1 - t/D) \right] \tag{3}$$

where σ is the axial stress imposed by the pig on the deposit, ΔP is the pressure differential across the pig, t is the deposit thickness and D is the pipe internal diameter. For Load model 2, the shear stress imposed on the deposit is related to the pressure differential across the pig by,

$$\tau = \Delta P \left[(1/2 - t/D) / (2L/D) \right] \tag{4}$$

where L is axial dimension of the pig in contact with the wax deposit. Finite element models were solved for different thicknesses of the deposit for load models 1 and 2. These solutions yielded the maximum shear stress imposed by the pig on the deposit, τ_{max}. For Load Model 1 the results obtained were adjusted by the following relation,

$$\tau_{\max} / \Delta P = 3.11 (t/D)^{-0.50} \tag{5}$$

For Load Model 2 the results from the finite element analysis also depend on the dimensionless parameters, *L/D,* besides *t/D.* The results were presented in tabular form and were obtained for friction coefficients of 0.3 and 0.4. These results are not presented here due to space limitations. The comparison of the maximum shear stresses predicted by the calculations just described with the mechanical shear resistance of the wax deposit gives, according to the model, an estimate of the capability of the pig of removing the wax deposit. In the same paper, the authors also propose a method for estimating the shear strength of the wax. This method is based on the measurement of the compression yield stress of a cylindrical sample of the wax prepared by a casting procedure, and obtaining the shear stress by applying the Tresca yield criteria (e.g. Juvinall, 1967).

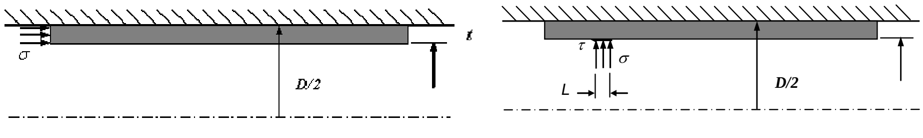


Figure 3. Two possible interactions between pig and wax deposit. (a) Load Model 1. (b) Load Model (2). (Souza Mendes *et al.*, 1999)

As already mentioned, the models just described are the only models available in the literature for predicting the contact forces developed by disk and foam pigs and for predicting the forces for removing wax deposits. They do need, however, to be tested against laboratory experimental data. This is the main objective of the present paper, and the details of the test procedures adopted will now be described.

3. Experiments

The test section designed to conduct the experiments is illustrated in Fig. 4. The basic concept behind the test section designed was to pull the pigs through a pipe using a winch, while measuring the force exerted by the pig on the pipe. To this end, a set of three, 1-m long pipe pieces were joined together forming a longer test pipe. Tests were conducted with pipes having 75 and 150 mm of internal diameter. The pipes were internally machined to a tolerance of 0.1 mm. Each pipe end section was machined so as to allow a perfect mating with the neighboring pipe. The set of three pipes was mounted on a V-shaped support, equipped with rollers that allowed free axial motion of the setup over the steel frame that supported the test section. Two pre-calibrated load cells were mounted at the edge of the steel frame limiting the axial motion of the test pipes. The detailed view of the test section shown in Fig. 4(b) helps to better visualize the location of the load cells. When a pig was introduced at the inlet section of the test pipe and pulled by a steel cable connected to the winch, friction between the pig and the pipe wall transmitted the force from the pig to the test pipe mounted on the rollers that pressed the load cells that impeded its motion, thereby registering the axial force while the pig was being pulled. A data acquisition system recorded the force variation sensed by the load cells. A calibration procedure revealed that the constant rotational speed of the winch produced a constant linear pulling speed of 48 mm/s.

The description of the experiments just presented was related to the test where the contact forces between the pig and the pipe were measured. For the experiments where the force required to remove a wax deposit was being measured, the pipes received a wax deposit of controlled dimensions on its interior surface. The procedure for producing the wax deposits was to mount each one of the three pipes that formed the test pipe vertically on a specially designed casting rig. Each pipe was mounted vertically on a supporting base. An aluminum cylinder with external diameter smaller than the internal diameter of the pipe was introduced in the interior of the pipe living a concentric annular gap of 3 mm. This gap was filled with a mixture of molten commercial wax and spindle oil and allowed to solidify. The inner cylinder and the external surface of the pipe where the deposit was being cast were both cooled by circulating cold water. After the removal of the internal cylinder, a wax deposit of excellent finishing was left on the test pipe. For tests using more than one pipe piece with deposited wax, the casting procedure was repeated and the pipes were assembled together and positioned on the V-shaped support.

Prior to each data run for wax removal studies, the pipe with the deposited wax was weighed on a balance. After the passage of the pig, the pipe was once again weighed. The difference in weight was a measure of the amount of wax removed in that particular pig run.

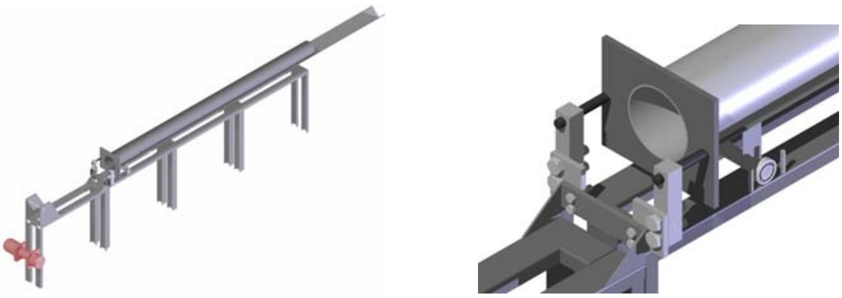


Figure 4. Schematic view of the test section for force measurements. a) General view. b) Detail of the load cells setup.

4. Results

The results section will be presented in two parts. In the first part, a presentation will be made of the results for the contact forces between the pigs and the pipe wall measured in the experiments, followed by a comparison with the prediction of the models described before. In the second part, attention will be focused on the results for the forces required for removing the wax deposits. Also in this case, a comparison will be made with the available model.

4.1 Contact force results

During the experimental program several types of pigs were tested, namely, 75 and 150-mm foam pigs, foam pigs with plastic scrapers on the outer surface, foam pigs with different foam densities, 75 and 150-mm disc pigs with different levels of flexibility, and 75 and 150-mm conical cup pigs. Due to space limitation, only representative results will be presented that are sufficient to demonstrate the typical behavior of the contact force and the predicting capability of the models. A complete set of results can be found in Barroso, 2004 and Silva, 2005.

Figure 5 presents typical results obtained for the force required to pull the polyurethane disc pig shown in Fig. 2(a). This pig was manufactured by Hidropig, having two 9-mm-thick, 158-mm-diamter disks, mounted on a steel frame with spacers with diameter of 99 mm. This pig, when fitted in the test section produced an oversize of 3.8%. In Fig. 5 the abscissa is the axial coordinate along the test pipe given in meter, while the ordinate shows the force measured by the load cells in Newton. Five replications of the tests are presented in the figure. In all tests the internal pipe wall was lubricated with spindle oil prior to the runs. The horizontal lines in the figure show the length of each pipe section. The sets of thee vertical lines drawn around the boundary of the central pipe are reference marks that indicate the length of the pig. A general observation of the force results displayed in Fig. 5 shows that, within the level of uncertainty expected for this type of experiment, the results for the five runs present the same behavior. At the beginning, the force level rises sharply until the static friction force between the pig and the pipe is reached. At this point the pig begins to move and the force level decreases to the dynamic value of the contact force. Two small peaks on the force distribution are observed at the border between the first and second pipes. These are due to the passage of the two pig disks over the junction between two adjacent pipes. The two peaks are again present with stronger intensity at the next pipe junction. Other than these peaks, the force is approximately constant throughout the run. The same qualitative behavior was observed for all the other types of pigs tested.

Figure 6 presents the results for the contact forces measured for the different pigs tested. Each curve is an average of the results of several runs. The average of the results presented in Fig. 5 for the disk pig is also presented in Fig. 6. Besides the disk pig already mentioned, the pigs tested and presented in Fig. 6 were the RS-7 foam pig made by TDW, the RRR-7 foam pig equipped with plastic scraper bands on the outer surface made by TDW, and a polyurethane conical cup pig also made by TDW that receives the commercial name *Vantage*. Photographs of these pigs are presented in Fig. 7. The average contact forces measured for these pigs were: 520 N for the RS-7, 608 N for the RRR-7, 1472 N for the conical cup *Vantage,* and 363 N for the disc of Fig. 2(a).

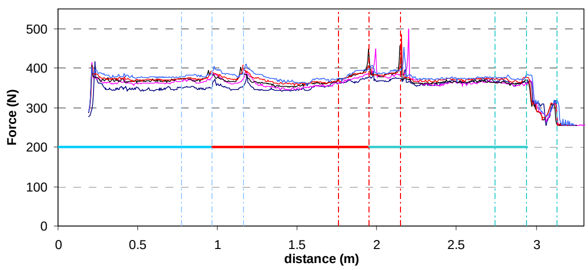


Figure 5. Contact forces between disk pig and pipe wall

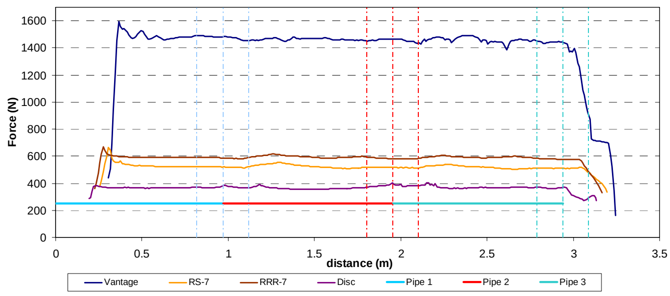
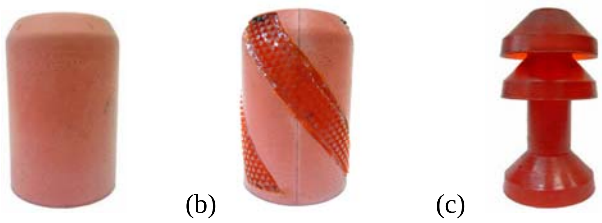


Figure 6. Measured contact forces for different pigs with 150mm nominal diameter



(a) (b) (c)

Figure 7. Pigs tested: (a) RS-7 foam pig, RRR-7 foam pig with scrapers, (c) Vantage conical cup pig.

The experimental results just presented in Fig. 6 can be used to validate the contact forces models available in the literature and briefly described in sections 2.1 and 2.2. Table 1 was prepared to facilitate the comparison of experimental and predicted results. An observation of the results presented in Tab. 1 shows that an excellent level of agreement was obtained between experiments and the model predictions. At this time, no simple model for predicting the contact force for conical cup pigs is available. The values of the measured forces for these pigs were included in the table to allow a comparison of the level of force attainable with this type of pig.

Table 1. Comparison between measured and predicted contact forces

Pig Type	Disc	Foam RS-7	Foam w/scraper, RRR-7	Conical *Vantage*	Disc, 75 mm	Foam, 75 mm	Conical cup, 75mm
Measured force (N)	363	520	608	1472	785	540	981
Predicted force (N)	383 eq.(1)	550 eq.(2)	569 eq.(2)	-	844 eq(1)	530 eq.(2)	-

4.2 Wax removal force results

We now turn our attention to the tests were the forces required to remove a wax deposit were measured. A general picture of the wax removal process by a pig can be seen in Fig. 8. These tests were conducted with a 75 mm test pipe formed by the assembly of 8, 450-mm-long pipes. Six out of those eight pipes were covered with a 4-mm-thick wax deposit. A stiff, two-disc polyurethane pig was employed.

Although the force is seen to that vary appreciably due to the nature of the interaction between the pig, the pipe wall and the wax deposit, some interesting general trends can be observed in Fig. 8. At start, the pig is positioned in the interior of the first pipe section that did not have a wax deposit. The pig nose is positioned approximately at the axial coordinate 150 mm. The force reading is zero. When the winch is activated, the force sensed by the load cells increases sharply, until the pig starts moving. From that point on the force is leveled until, at the axial coordinate of 300 mm, the downstream pig disc encounters the wax deposit. The force increases sharply again, until it reaches a level sufficient to break the wax deposit. It would be expected that this level of force would be maintained approximately constant along the remainder of the pipe length as the deposit was removed. The force however, is seen to increase steadily until it reaches a level that is approximately three times the value originally required to break the deposit. This constant rate of increase in the force is attributed to the additional force required to drive the removed wax that is now accumulating downstream of the pig. This finding is corroborated by information from the field where several episodes of pig stall have been attributed to the formation of a plug of removed wax that is progressively compressed by the pig until the available pressure level upstream of the pig is no longer sufficient to drive the pig and the wax plug. The force is finally seen to decrease as the wax removed is driven out of the pipe set.

The solid straight lines fitted to the data can be used to separate the different phase of the wax removal process. The lines are keyed to numbers that represent the following phases: 1) wax breakage phase, 2) pre-obstruction phase, 3) obstruction phase, 4) wax plug displacement phase, and 5) wax production phase. These phases were identified in the work of Wang *et al.* (2001).

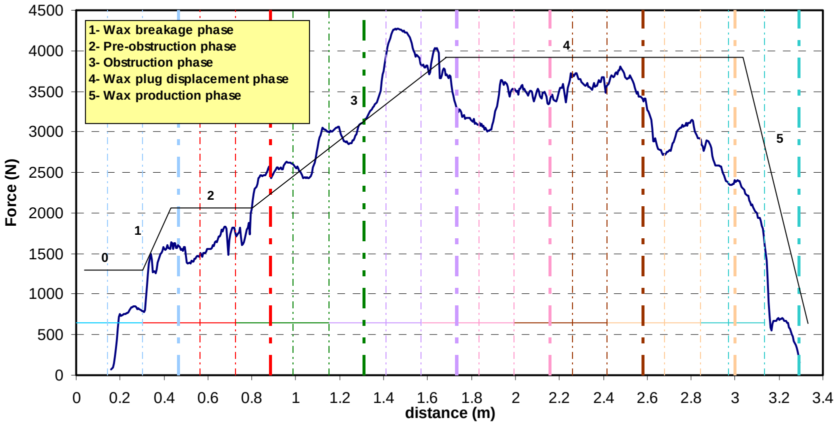


Figure 8. Typical force distribution for pig removing wax in a pipe

Results such as those presented in Fig. 8 were used to define the focus of the present study. It became clear that the study of the forces required to remove wax had to be divided into two parts: wax breakage studies and wax plug formation and displacement. The present paper only deals with the study of the forces required to break the deposit, the second part of the problem is the objective of current research.

In order to separate the two phases of the problem for study, the tests were conducted with only one pipe section having wax deposit. This way, there was never enough wax removed to form a plug, and the force measured was only that necessary to break the deposit. Figure 9 shows a summary of the force results obtained for the 150-mm-diameter pigs tested. In the tests that generated the data shown in the figure only three pipes were used, the middle one having the wax deposit. As can be seen in the figure, for all pigs tested, despite the different levels of contact force exerted by the pigs on the first pipe piece, the same general behavior is observed. The force measured initially rises sharply to get the pig in motion, keeps a constant value while the pig moves in the first pipe without wax, until it reaches the deposit in the second pipe. The increase in the force is the amount of force necessary to break the wax deposit. It should be mentioned that in the curves shown, the wax deposit was not always removed completely. Depending of the pig type, only a portion of the wax was removed. In these cases, the pig climbed on to the deposit and the contact was no longer made between the pig and the pipe wall, but between the pig and the wax surface.

Table 2 was prepared to present a comparison of the measured and predicted values for the force required to break a wax deposit. The predicted results were obtained by applying the model described in section 2.3. The table shows for each pig tested the oversize in relation to the pipe internal diameter, the removing efficiency obtained by weighing the pipe with the deposit before and after the pig passage, the experimentally determined contact force between the pig and the pipe wall, the force measured while the pig was running in the pipe sector having the wax deposit, the net force that one expects to be acting on the deposited to break it, and the predictions from the Souza Mendes *et al.* model for load models 1 and 2. In order the compare measured and predicted results, the possible types of interactions between the pig and the wax deposit need to be commented. If the pig touches the front of the deposit without going over it, a type of interaction as assumed in Load Model 1 is in effect. In this case, it is expected that the front of the pig interacts with the wax deposit while the rest of the pig rides over the pipe wall.

The net force applied by the pig on the deposit is, therefore, the difference between the total force measured by the load cells minus the contact force between pig and pipe wall measured previously in the experiments without wax deposit. This net value is presented in Tab. 2 and should be compared with the minimum value required for wax removal predicted by Load Model 1. If the measured net force value is larger than the minimum value required, then total wax removal should be expected. Conversely, if the net force is smaller than the minimum value predicted, only partial wax removal should be expected. The numbers in brackets in the column presenting the net force value in the table indicate the type of interaction assumed for the pig and the deposit, either (1), meaning Load Model 1, or (2) meaning Load Model (2).

When the pig is expected to ride on the wax deposit, the type of interaction assumed by Load Model 2, all parts of the pig are in contact with the wax deposit and none are in contact with the pipe wall. The total force measured by the load cell is, in fact, the force being transmitted to the deposit by the pig. In this situation, the total force measured should be compared with the predictions assuming Load Model 2. Again, if the measured force is larger than the minimum value predicted by the model, total wax removal should be expected, if not, partial or no removal should be expected. Based on the arguments just presented, we can now proceed and evaluate the predicting capability of the model proposed by Souza Mendes *et al.* (1999).

The 150-mm disc pig tested and presented in the first column of Tab. 2 was equipped with rather flexible discs. It was assumed, therefore, that they would bend easily and that the pig would ride on the deposit, i.e, interaction of the Load Model 2 type. Calculating the force required for this type of pig to break the 3-mm-thick wax deposit formed by 20% spindle oil and 80% commercial wax, Load Model 2 predicted a minimum value of 720 N. The load cell measured only 667 N, what indicates that this pig was not able to develop the necessary force on the wax deposit to break it. So, poor removal should be expected. Indeed, the data of table indicates only a 1% removal efficiency. The same type of interaction was assumed for the foam pigs tested and presented in Tab. 2. Foam pig have large lengths in contact with the wax deposit what, according to the model, require large force values (large oversizes) to impose the minimum values required to break the deposit. An inspection of Tab. 2 shows that for all these foam pigs the force values measured where below the minimum value set by Load Model 2. In all cases the removal was not complete.

For the three stiffer pigs testes namely, the 150-mm diameter conical cup *Vantage*, the 75-mm conical cup, and the 75-mm hard disc pig, the interaction of type Load Model 1 was assumed to prevail. In these cases, the net force acting on the deposit was obtained by subtracting from the total force measured on the load cells the pig/wall contact forces. The comparison of these net results with the minimum values predicted by Load Model 1 show that in all cases the values measured are above the minimum requirement to break the wax deposit. As a consequence, total removal should be expected. The results of Tab. 2 validate the model predictions since they indicate 100% removal efficiency for all these pigs.

Although the interaction between a pig and a wax deposit is a complex problem, it is believed that the model proposed by Souza Mendes *et al.* provides an useful first order estimate of the capability of a particular pig to break a deposit formed by a wax of known properties.

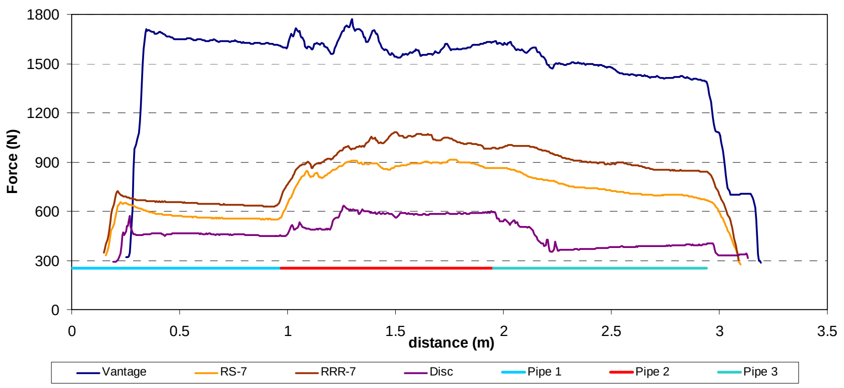


Figure 9. Force exerted by different pigs for breaking a wax deposits.

5. Concluding remarks

The present paper presented results of an ongoing research project aimed at studying the process of wax deposit removal by pigs. In the phase of the work reported here, experiments were conducted with a two-fold objective. Firstly, data were obtained for the contact forces developed by different types of pigs as they move through a pipe without a wax deposit. Following this study, attention was focused in generating data on the forces required to break a wax deposit.

In both cases, the experimental data were used to validate models for predicting contact forces and minimum values for wax breakage. The tests were conducted in a specially designed test section where the pigs were pulled by a winch while the forces exerted on the wall were measured. Foam, disc and conical cup pigs were tested for two different diameters.

The experimental results obtained compared favorable with the predictions from the contact force models developed by Azevedo *et al.* (2003), for disc and foam pigs. No models were available for conical cup pigs. The wax removal experiments confirmed the general behavior of the interaction between a pig and a wax deposit. After an initial period where the additional force necessary to move the pig is dominated by the breaking of the wax, the accumulated wax in front of the pig forms a plug that requires approximately three times the initial force to maintain the pig in motion. The present study concentrated on the forces necessary to break the wax deposit.

The experimental results obtained when looked from the perspective suggested by the work of Souza Mendes *et al.*, indicate that there are two possible modes of interaction between the pig and the wax deposit. In one mode the pig would act upon the face of the deposit pushing it until the maximum resistive shear stress of the wax would be reached and the deposit would break. In the other mode of interaction the pig would ride on the deposit imposing a shear stress on it. The comparison of experiments with the model predictions indicate that harder pigs tend to operate in the first interaction mode, while softer pigs, like foam pigs, tend to operate in the second mode.

Table 2. Measured and predicted values for force required to remove a wax deposit

	***Oversize* (%)**	**Removal efficiency (%)**	**Experimental Pig/wall force (N)**	**Experimental force in deposited section (N)**	**Experimental net force on the deposit (N)**	**Minimum Force, Load Model 1 (N)**	**Minimum Force, Load Model 2 (N)**
Disc	3,8	1	363	569	569 (2)	235	706
Foam RS-7	5,6	30	520	844	844 (2)	235	16677
Foam w/scraper RRR-7	6,0	67	608	903	903 (2)	235	16677
Conical *Vantage*	7,3	100	1472	1717	245 (1)	235	2109
Disc, 75 mm	6,0	100	785	1315	530 (1)	86	226
Foam,75mm	6,0	30	540	1864	1864 (2)	86	4415
Conical cup, 75mm	6,0	100	981	1324	343 (1)	86	304

In view of the complex phenomena that are involved in the interaction between pigs and wax deposits, the level of agreement obtained between experiments and models can be considered satisfactory. The present paper is, to the best knowledge of the author, the first validation available in the literature of models developed for predicting forces for removing wax deposits employing pigs.

Further studies on the forces required to displace wax plug are necessary since this is the most likely situation to be present in field operations.

6. Acknowledgement

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7. References

Azevedo, L.F.A., Braga, A.M., Nieckele, A.O., and Souza Mendes, P.R., 2003,“Simulating Pipeline Pigging Operations”, in Pipeline Pigging and Integrity Technology, Ed. John Tiratsoo, Clarion Technology Publisher, London, ISBN: 0.971.7945.29.

Barroso, A. L., 2003,“Experimental Study of the Forces for Wax Removal Using Pigs”, Master’s Dissertation, Departamento de Engenharia Mecânica PUC-Rio (in Portuguese).

Juvinall, R. C.,1967,“Engineering Considerations of Stress, Strain and Strength”, McGraw-Hill, New York, NY.

Souza, R.O., 2005,“Analysis of the Performance of Models for Predicting Wax Removal in Pipes Using Pigs”, Master’s Dissertation, Departamento de Engenharia Mecânica, PUC-Rio, (in Portuguese).

Souza Mendes, P. R., Braga, A. M. B., Azevedo, L. F. A., Correa, K. S., 1999,”Resistive Force of Wax Deposits During Pigging Operations”, ASME Journal of Energy Resources Technology, September, Vol.121, pp. 167-171.

Wang, Q., Sarica, C., Xen, T. X., 2001,“An Experimental Study on Mechanics of Wax Removal in Pipeline”, Society of Petroleum Engineering, paper no. 71544.

8. Responsibility notice