Proceedings of the 2018 12th International Pipeline Conference
IPC2018
September 24 – September 28, 2018, Calgary, Alberta, Canada

IPC2018-78743

COLUMN SEPARATION IN A SHUT-IN LIQUID HYDROCARBON TRANSMISSION PIPELINE

Hamed Ghasvari Jahromi, Michael Roxas, Satya Mokamati

Vanmok Innovative Engineering Solutions
Edmonton, AB, Canada

ABSTRACT

Crude oil transportation pipelines depend on Computational Pipeline Monitoring (CPM) systems for leak detection. Accurate prediction of the volume of vapor phase in the pipeline is very challenging when crude oil goes though phase change (column separation) in the pipeline. It is also challenging to accurately predict the vapor phase volume when the pipeline is started from extended shut-in period during which thermal cooling or heating can occur depending on the season of the year. Pipeline operators rely on the accuracy of CPMs to make decisions on column separation and to avoid the masking of a leak during column separation. The column separation can happen due to heating and/or cooling during extended pipeline shut-in, or due to elevation changes or due to flow transients.

New methods of approach to address the hydraulics are necessary when dealing with a pipeline during shut-in period. Particularly a shut-in pipeline has no longitudinal motion of fluid, however phase change occurrence attempts to set the stationary fluid inside a pipe into motion and overcoming this difficulty was not available in the literature perhaps due to lack of encumberment with similar problems. This paper explains mechanism of column separation and its transients in pipelines during extended shut-in period. The results for a 90 Km long-pipeline shut-in over a 78-hour period will be presented to show the evolution of flow field and column separation (vapor phase change) prediction and hydrodynamic pressure in the whole pipeline over the shut-in period. This paper will also critically review the current approaches available in the literature to predict the column separation.

NOMENCLATURE

DVCM	Discrete Vapor Cavity Model
DGCM	Discrete Gas Cavity Model
GIVCM	Generalized Interface Vapor Cavity Model
CPM	Computational Pipeline Monitoring
θ	Angle of inclination
g	Acceleration due to gravity

INTRODUCTION

In hydraulics, when the thermodynamic pressure of the fluid reaches to the value of saturated vapor pressure at the given temperature or below that, phase change occurs. Phase change or cavitation occurrence therefore can be simply thought of the moment(s) that the local pressure of the fluid substance reaches to vapor pressure at that temperature, however circumstances that can provide the condition for cavity formation are not unique.

A transient-state in the system (such as sudden pump failure or valve closure, or drastic set point changes to control the flow in the pipeline) or rapid elevation gain of the pipeline are two of the reasons that could provide the favorable condition for cavity formation. Another important category under which the cavitation may occur is when the pipeline which contains the fluid, undergoes a substantial enough amount of heat transfer with its surrounding such that the pressure inside the pipeline falls below the value of vapor pressure (dictated by the thermodynamic equilibrium state that system and the surrounding wish to reach).

Due to any of the above-mentioned reasons, when favorable condition for cavity formation begins, the small vapor-filled cavities, can grow to bigger cavities and potentially (depending on pipeline configuration or transient-state in the system), lead to one or both the following:

1. Create a thin cavity confined to the top of the pipe extending over a long distance; referred to a condition known as cavitating flow.

2. To fill the entire cross section of the pipe and thus divide the liquid into two columns; referred to a condition known as column separation.

It should be kept in mind that column separation is used in this paper in a broader definition range, all the way from local cavitation to intermediate cavities as well as propagation of the near wall formed vaporous cavitation zones. Therefore "column separation" in this paper refers to both above-mentioned possible outcomes.

REVIEW OF THE CURRENT APPROACHES

Aside from theoretical approaches on the bubble growth and collapse in a liquid [1] and the bubble dynamics of two phase flow [2], there have been many experimental and computational efforts to study column separation and still limited number of data available to develop design criteria [3].

Safwat [4] employed high speed photography to visualize liquid column separation downstream of a valve in a short horizontal pipeline (approximately 40 meter in length and 100 mm in diameter) and then used a discrete bubble model to investigate the water column separation numerically. In a simple reservoir-pipe-valve system, Martin [5] examined the cavitation formation along the pipe and tried to classify the intensity of column separation. His experimental results showed that maximum pressure in a pipe could exceed the Joukowsky pressure rise.

There are a variety of one-dimensional numerical models developed to model the column separation, along which the discrete multi-cavity model, discrete gas cavity model and the two-phase flow model and shallow water model can be mentioned.

The discrete vapor cavity model, the most commonly used model for column separation studies, incorporates the vaporous cavitation within the method of characteristics [6-7] used in fluid transient analysis in pipelines. Cavities were confined to form at the computational grid points if the computed pressure fell below the vapor pressure of the liquid. For the liquid between computational grid points, the pressure wave was assumed to travel with a constant acoustic wave. Upon formation of a cavity, the computational grid point was treated as a fixed internal boundary condition and the pressure was set equal to the vapor pressure of the liquid until the cavity collapsed [8]. This method was employed for water hammer analysis in a 110 km pipeline [9]. Further development of the model to incorporate cavitation inception with negative absolute pressure waves was presented in [10].

One of the major deficiencies of the discrete vapor cavity was the existence of numerical oscillations generated during the existence of multi-cavities in the pipeline [11,12]. A remedy to this deficiency was to consider small amounts of initial gas at the computational grid points to suppress the numerical oscillations [12,13]. This lead to the construction of the discrete gas cavity model [7,12,14] a generalize formulation to distributed vaporous cavitation modelling. The model was able to provide maximum pressures predictions in good agreement with experimental data [15,16] and could exhibit nonlinear variable wave speed features of the physics [17]; however, the model would still suffer from adequate predictions of the frequency of repeated cavity formation and collapse.

Kalkwijk and Kranenburg [18,19] employed two-phase flow approach to develop a bubble model for description of the distributed vaporous cavitation in a horizontal pipeline. The dynamic behavior of gas bubbles was used in their first attempt, however, the model failed to provide reasonable predictions when the bubble radii exceeded a critical value. Consequently, they developed a second approach to the phenomenon to distinguish between regions with and without cavitation. This approach successfully merged the water hammer region to the vaporous region with a shock formation when the cavity stopped growing. Kranenburg [19] further developed a simplified one-dimensional model, known as simplified bubble flow model. He pointed that one of the difficulties in using the method of characteristics was the pressure dependence of the wave celerity because of the presence of free gas.

Shallow water flow was employed by several researches [20-21-22] to develop a shallow water model (also known as separated flow model) of liquid column separation. Vapor bubbles after formation were assumed to quickly rise and agglomerate to form a single long thin cavity compared to the diameter of the pipe when the pressure reached the vapor pressure. These early attempts were not successful in their predictions as Baltzer's model [21] could not predict high pressure rises found in experiments and Siemon's results [20] suffered from a mass imbalance at the boundary of the cavity and existence of gravity waves [18-19] which could limit the validity of the results on generation of high pressures. However, Vreudgenhil's [23] experimental results for a horizontal pipe of 1450 meters showed that there was an adequate agreement between the experimental results and those predicted by the separated flow model of Seimon [20] and bubble flow model of Kalkwijk and Kranenburg [19]. The simplified bubble mode was also not able to describe the entire pipeline flow in a pipeline with high points where local liquid column separation occurs [24]. The modeling of column separation during extended shut-in periods demand a non-isothermal approach to capture the evolution (not only inception) of column separation during slow and gradual changes in the temperature. This paper uses a novel mathematical model to tackle this problem.

NEED FOR A NOVEL MODEL

In the previous section, the models currently available in the literature for prediction of column separation were reviewed, and discussed some of the shortcomings of the available models. The major approaches among these reviewed models are those we refer to as “conventional models or methods” in this paper.

These conventional methods used to tackle the problems involving column separation are summarized and explained in detail at one place in the work of Bergant et al [25]. Bergant et al [25] familiarized the models and described their differences in detail.

Bergant et al [25] examined three major conventional methodologies known (DVCM, DGCM and GIVCM) by applying them to a 37 meter long inclined pipe model and they compared the results with a laboratory test pipe of the same length.

It is clear from their compared experimental results with these models that, all of them (DVCM, DGCM and GIVCM) are successful in predicting the onset of cavitation and its inception location. However, according to Bergant et al [25], the deviations between the laboratory experimental results obtained and the results from those models appears soon after the cavitation begins. In other words, the values of all of them compared to the experiment becomes worsen as time passes by.

Column separation evolution is characterized by how accurately the behavior of cavities are captured in time. The prediction of column separation evolution is as important as the prediction of the column separation inception.

For industrial scale pipelines, the prediction of column separation evolution becomes more important, otherwise the error would be more severe due to bigger reflection time for longer pipelines (Recall, reflection time is directly proportional to the length of the pipeline). Hence any evolution track of transient phenomenon demands accuracies which are not observed by any of the conventional models.

Inability to predict the column separation evolution is a major drawback, based on the results presented in [25], we conclude that accuracy of conventional models’ predictions is not reliable past the first few seconds and hence is not good enough to be used for the prediction of the column separation evolution over extended periods (such as hours and days).

In this paper we presented a novel mathematical model which would address short comings of conventional models. The novel model should also work with any topography provided as the elevation profile of the pipeline. This demands the smooth implementation of elevation profile to the conservation laws of mass, momentum and energy. We know that the extreme points in the pipeline profile are critical when it comes to column separation analysis. The novel model should not be isothermal in nature. This makes the problem very complex but it is inevitable if addressing the phase change due to thermal heating and cooling is the concern.

DESCRIPTION OF THE PHYSICS

Thermo-fluid solution of the hydrocarbon transportation pipeline means the knowledge of all quantitative values which are useful in the description of the physical state of the fluid flow (i.e. its hydraulics) and its thermal state of the equilibrium which requires value of a second independent property such as temperature.

Obtaining the thermo-fluid solution for this system requires predictive algorithms for the values of all operating parameters such as pressure, velocity, temperature, quality of the vapor phase (if present) along the pipe at any arbitrary space and during an arbitrary time interval.

These values should be available in real time and such a task requires simultaneous solution of conservation laws (mass, momentum and energy), as well as few constitutive laws for the quantification of friction along the pipe wall and correlation among thermodynamic properties such as temperature and pressure and the quality (i.e. volumetric or mass fraction of each phase when multi-phase fluid state presents in the system).

To triumph, one needs to solve for the conservation of mass and momentum and energy for all the phases present in the system in time and over the spatial coordinates. This can be achieved by simultaneous solution of the governing coupled partial differential equations given that an appropriate set of conditions are provided to uniquely distinguish the system (either in the form of initial and boundary conditions or equivalently qualitative technical descriptions related to operational events).

Governing Equations

Basic equations without cavitation and for an isothermal system are conservation of mass (equations 1) and momentum (equation 2) in one dimensional form:

$$\frac{\partial V}{\partial x}+\frac{1}{\rho c_0^2}\frac{\partial P}{\partial t}=0 \qquad (1)$$

$$\frac{\partial V}{\partial t}+\frac{1}{\rho}\frac{\partial P}{\partial x}-g\sin(\alpha)+\frac{f}{4r}V\left|V\right|=0 \qquad (2)$$

The equations (1) and (2) cannot address phase change but are used for water hammer modeling and transient flow for single phase fluid flow.

Governing equations for the case with two phases but without interphase mass transfer are provided below—equations (3) to (6):

$$\frac{\partial}{\partial t}\alpha_g\rho_g+\frac{\partial}{\partial x}\alpha_g\rho_g u_g=0 \qquad (3)$$

$$\frac{\partial}{\partial t}\alpha_l\rho_l u_l+\frac{\partial}{\partial x}\alpha_l\rho_l u_l=0 \qquad (4)$$

$$\frac{\partial}{\partial t}\alpha_l\rho_l u_l + \frac{\partial}{\partial x}\alpha_l\rho_l u_l^2 = -\frac{\partial \alpha_l P_l}{\partial x} + p - \alpha_l\rho_l u_l \sin\theta - F_l \pm F_i \quad (5)$$

$$\frac{\partial}{\partial t}\alpha_g\rho_g u_g + \frac{\partial}{\partial x}\alpha_g\rho_g u_g^2 = -\frac{\partial \alpha_g P_g}{\partial x} + p - \alpha_g\rho_g u_g \sin\theta - F_g \mp F_i \quad (6)$$

Where subscripts "l" and "g" are used to distinguish liquid phase from gaseous phase respectively. These pair of continuity and momentum equations again for the isothermal case can be used for an appropriate system of liquid flow with dissolved gases. For example, the gaseous phase can be thought of as dissolved gases in liquid. Here again the interphase mass transfer cannot happen as the phases are different materials.

Novel Mathematical Model

In this paper we are presenting a novel mathematical model for column separation, in which a set of additional modifications were applied to build the equations.

Conservation of Mass and Momentum

We examine the behavior of the first mentioned system of partial differential equations (see equations. 1 and 2) near the neighborhood of vapor pressure where the model is not meant for. By this practice we find out residues for mass and momentum transfer. We continue our method until we have a set of mathematical functionals for representation of deviation of each of these two governing equations. Then we add these found functionals to our governing equations to compensate for the deviations that the original equations face near the vicinity of phase change. This yield the modified version of mass and momentum transfer equations given by (7), (8) and (9).

$$a_1\frac{\partial P}{\partial t} + f_1(\varphi, x, t)\frac{\partial Q^*}{\partial x} + f_2(x, t, \Delta\rho) = 0 \qquad (7)$$

$$\frac{\partial Q^*}{\partial t} + (\frac{1}{f_1(\varphi, x, t)})\frac{\partial P}{\partial x} + f_3(z, \varphi, t)) + f_4(Q^*, \varphi) = 0 \quad (8)$$

$$a_1 = f_5(k_l, r, \delta, E, \rho) \qquad (9)$$

We present these correctional functionals as f_1, f_2 and f_3. The additional functional f_4 which is mainly for frictional losses and wall contributions is generalized to be a function of not only space and time but also the modified flow rate and existence of more than one phase. This enables the model to use frequency dependent friction factor. The effect of elevation is implemented within the functional f_3.

Conservation of Energy

We begin the implementation of the energy equation to the model by first considering the composite structure of a typical hydrocarbon transmission pipeline. As shown in Figure 1, from the core where the temperature is shown by T_c to the ambient temperature which in this case is the ground temperature T_G there are some other layers which are the wall thickness, insulation thickness and skin of the pipe (without lack of generality, the ambient temperature can be set to ground or atmosphere depending on the pipeline being buried in the ground or exposed to the atmosphere).

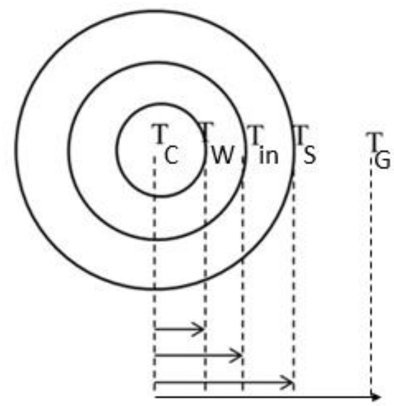

Figure 1. The composite structure of a typical hydrocarbon transmission pipeline showing the layers of pipe wall, insulation and ground.

These layers together provide a net effect for the lateral heat transfer as overall heat transfer coefficient and is usually denoted by U_∞.

$$\frac{\partial T}{\partial t} + \frac{1}{A_0}\frac{\partial (QT)}{\partial t} = \frac{k}{\rho c_p}[\frac{\partial^2 T}{\partial x^2} + \frac{dA_c}{A_c dx}\frac{\partial T}{\partial x}] + \frac{U_\infty}{\rho c_p}(\frac{P_i}{A_c})(T_\infty - T)$$
(10)

RESULTS AND DISCUSSION:

Part-1 VALIDATION OF THE NOVEL MODEL

The results from the novel model are compared against two experimental set of data in the literature. The first one is to compare the predictions of novel model with the experimental results of Bergant et al [25]. A pipeline of 37 meter length with a 3.2 degree slope upward between two reservoirs with known pressure head used in the laboratory experiments of Bergant et al [25]. The head versus distance was provided in the experimental results of Bergant et al [25] and compared with the conventional models of DVCM, DGCM and GIVCM in Figures 2,3 and 4.

All these models begin to deviate with the experimental results after the first peak of the head curve. The difference continues to increase for the consequent peaks over the range provided.

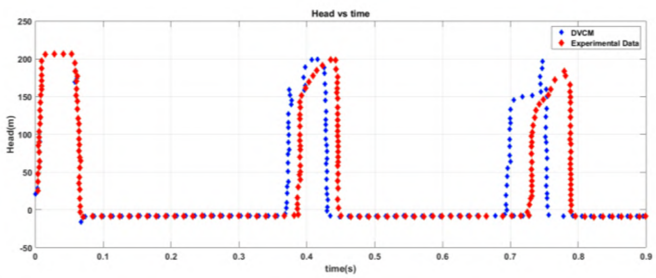

Figure 2. Comparison of Heads at Valve in Upward Sloping Pipe for DVCM and Measured Results (Figure 6 from reference [25]).

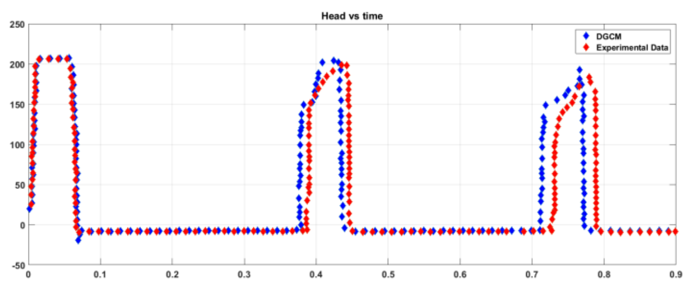

Figure 3. Comparison of Heads at Valve in Upward Sloping Pipe for DGCM and Measured Results (Figure 6 from reference [25]).

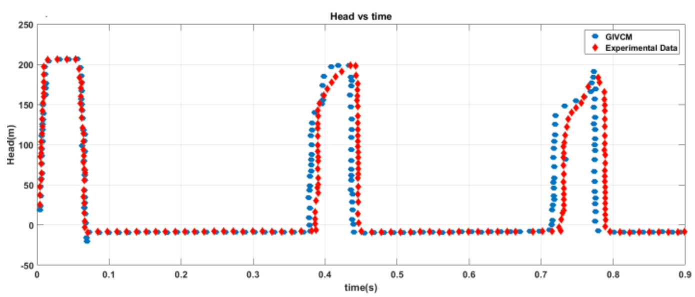

Figure 4. Comparison of Heads at Valve in Upward Sloping Pipe for GIVCM and Measured Results (Figure 6 from reference [25]).

Figure 5 shows the comparison between the presented novel model in this paper against the same experimental data from Bergant et al [25]. The discrepancies observed in time decreases unlike conventional models. This is due to the consideration of lower amplitude secondary waves with variable friction factor and more precise phase change predictions. In the novel model, the vapor phase can also exist between computational nodes, a feature that is not present in the conventional models. These features make the predictions of the novel model presented in this paper match up with the experimental results better as the time passes which makes the novel model more reliable for problems with longer time scales, such as the extended shut-in case.

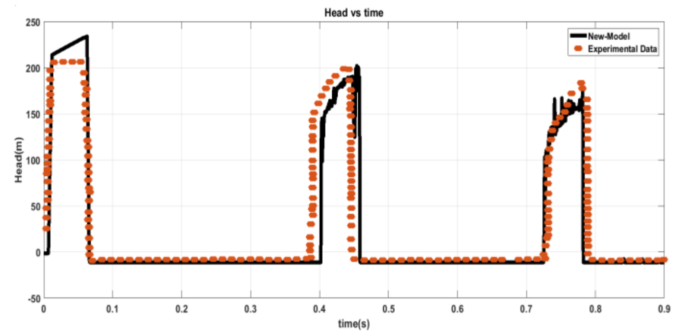

Figure 5. Comparison of Heads at Valve in Upward Sloping Pipe for novel model and Measured Results (Figure 6 from reference [25]).

Another comparison is done with the experimental results from Sanada et al [26] who captured a mid-stream cavitation in a 200 meter long laboratory pipe. The mid-stream cavitation is an interesting type of column separation which occur not due to closure of valves or elevation of the pipe but due to sudden change in pressure (a transient event). The drop of the pressure in the upstream of the 200 meter pipe caused bubbles to form 120 meter downstream of the pipe where they recorded the time of the appearance of the bubbles as well as time of disappearance.

Figure 6, shows the comparison of the space-time contour plot of cavitating flow region between the novel model presented in this paper and the results from Sanada et al [26]. The color legend in the figure shows the intensity of cavitation. The black arrow in Figure 6 is showing the exact location of the midstream cavitation at 120 meter location of the pipe, where they reported the appearance of the bubble at 0.146 second and its disappearance at 0.466 second. The appearance time is exactly predicted by the model presented in this paper which is 0.146 second and the disappearance time predicted by novel model is 0.4618 (an error of 1.3% compared to experimental results).

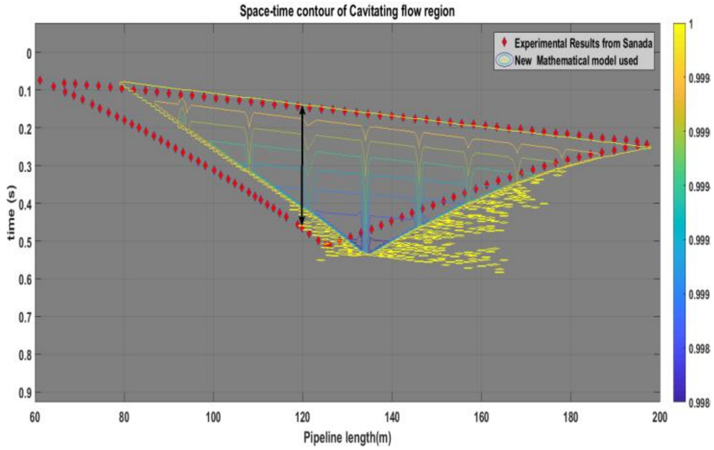

Figure 6. The comparison of the space-time contour of cavitating flow region between the novel model presented in this paper and the results from Sanada et al [26] (color legend shows the intensity of cavitation predicted from new model, red diamond symbols represent experimental results from Sanada et al [26]).

This global comparison over the entire space and time domain proves the ability of the novel mathematical model in all aspects we needed before proceeding to simulations with scale up in space and time.

From the comparisons explained in this section, the novel mathematical model presented is capable of accurate prediction of the location of the cavitation, precise prediction of the onset of cavitation, and reliable prediction of the evolution of column separation in time.

Part-2 APPLICATION OF THE NOVEL MODEL ON AN INDUSTRIAL SCALE HYDROCARBON TRANSMISSION PIPELNE

The pipeline simulated in this paper was a crude oil transfer pipeline that covers 90 km. The outside diameter of the pipeline is 36 inches. There are 12 intermediate pump stations in addition to an injection pump station and a delivery terminal. Only one segment of the pipeline was considered to study the column separation in detail for this paper. This pipeline transports Western Canadian Select (WCS) crude oil. The pipeline simulator has a topography from Alberta, Canada. The pipeline was modeled using, a commercial software used by the oil pipeline industry. A summary of all the parameters considered in the study is given in Table 1.

Table 1. Characteristics of the system under consideration

Property:	Value:	Unit:
Initial main pipeline Temperature	19	◦c
Pipe internal diameter	914.4	mm
Pipe wall thickness	12.4	mm
Hydrocarbon liquid density	928	kg/m^3
Hydrocarbon vapor density	2.5	kg/m^3
Hydrocarbon liquid viscosity	219	cP
Hydrocarbon vapor viscosity	0.0261	cP
Speed of sound in the fluid	1060.3	m/s
Pipeline length	84.39	km
Hydrocarbon Convection coefficient	100	W/(m^2 ◦K)
Insulation material thickness	0.7	mm
Ground’s conduction coefficient	5.8	W/(m◦K)
Hydrocarbon conduction coefficient	0.13	W/(m◦K)
Vapor Pressure	8.4	Psi
Thermal expansion coefficient	8e-4	1/◦c
Fluid compressibility	4.6e-6	1/Psi
Pipe’s Poisson’s ratio	0.285	
Pipe roughness	850	µm
Fluid bulk modulus of elasticity	1.67	GPa
Pipe Young Modulus of elasticity	200	GPa
Ground Temperature	9	◦c
Pipeline’s wall-conduction coefficient	205	W/(m◦K)
Insulation material’s conduction coefficient	0.02	W/(m◦K)
Ground effective thickness	5.0	m
Ambient Pressure	1.0	atm

DESCRIPTION OF THE PIPELINE

Figure 7 shows the elevation profile versus distance for the segment of the pipe considered. The two peaks visible in the figure are referred to as the left and right peaks.

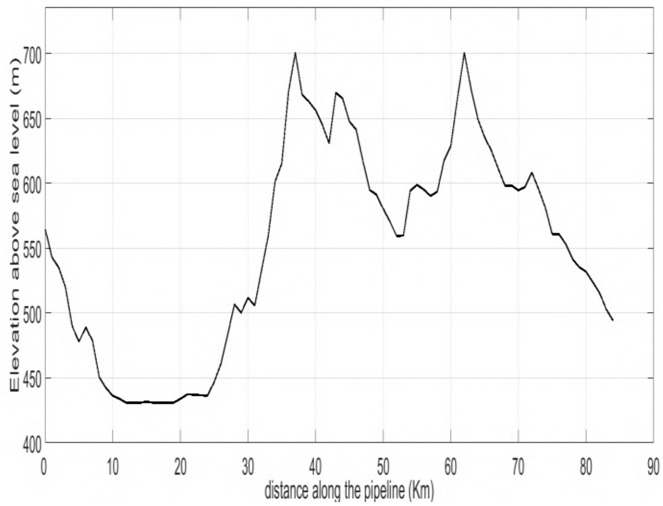

Figure 7. The elevation profile versus distance for the segment of the pipe considered.

IMPLEMENTATION OF EXTENDED SHUT-IN PERIOD

The data from pipeline simulator was used to prepare the boundary conditions on each end of the pipeline segments that undergoes a shutting in period by closing sectionalizing valves and continues to remain in shut-in status for more than 3 days (78 hours). Flow rate in the pipeline after the beginning of shutting down becomes zero on both ends and remain as such for the reminder of the simulation period.

The spatial pressure and temperature distributions along the pipeline are extracted from the virtual pipeline simulator and used as the initial conditions. These set of initial and boundary conditions are then used in the code built based on the novel mathematical model for column separation simulation.

The code built based on the novel mathematical model keeps track of the variables such as Pressure (P), Flow rate (Q) and Temperature (T) as well as any possible phase changes due to transients, extended heating and cooling, natural topographic variation of the pipeline as it passes over peaks and valleys.

The code built based on the novel mathematical model also predicts P, Q, T as a function of space and time along with percentage and the intensity distribution of the liquid column at any cross-sectional area along the pipeline should two-phase fluid exist in the pipeline.

Pipeline condition when shut-in initiated

Figure 8 shows the hydraulic grade line versus distance for the segment of the pipe considered at two instances—before shut-n and after shut-in. The solid black line shows the combinatorial effect of pressure and elevation summarized in the form of energy grade line before shut-in begins. The dotted line on the top is the hydraulic grade line right after shut-in.

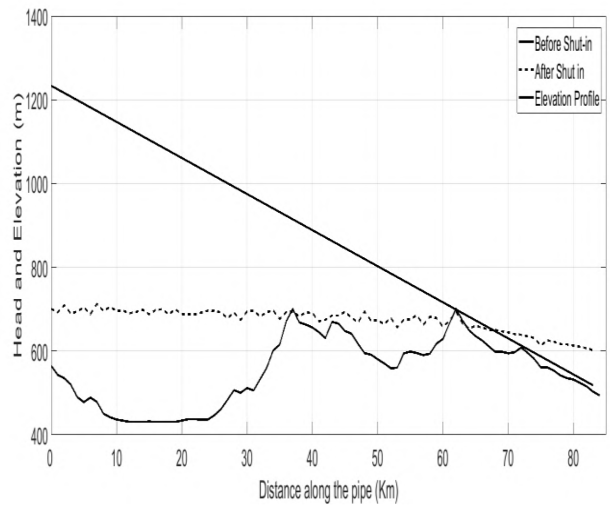

Figure 8. The hydraulic grade line versus distance

When dealing with a pipeline during shut-in period, the pipeline becomes a system, which is closed thermodynamically rather than needing to be considered as a control volume with mass fluxes permitted from through its control surfaces and therefore in absence of the leakage from the pipe (i.e. if pipeline has no leak hole in the simulations studied).

Therefore, it is not uncommon to assume fluid velocity being equal to zero everywhere in the pipeline, which stems from the assumption that a shut-in pipeline has no longitudinal motion of fluid. However, according to the code built based on the novel mathematical model this is not the case except for the end-point boundaries where due to definition of shut-in no flow in or out is allowed.

When phase change is dictated by the thermo-dynamical state of the system at any location in the pipeline, the local specific volume and the mixture density changes attempt to set the stationary fluid inside that pipe into motion. This is because the continuum hypothesis should not be violated at any point of the domain.

It means that when the fluid must change its phase to become consistent with both the surrounding conditions and thermodynamics laws of the equilibrium for that state of the matter (for example due to local pressure dropping and reaching to the vapor pressure at the given temperature), then it has a dynamical effect. The cavity in vaporous form that wants to be born as the first sign of cavitation claims its volume and that volume was previously occupied by the liquid state, hence the battle results in a longitudinal pressure wave that seeks elsewhere to carry its energy to, or dissipate it on its way.

As we discussed in an extended shut-in case, the dictation of temperature change is an ongoing process and so is the battle between the vaporous phase and the liquid trying to get its volume back from now being occupied by the vapor phase. This will set the fluid in a pipe back into a motion longitudinally even from an initial stagnant condition.

Figure 9 shows the standing wave velocity within the pipe at two different instances and is the clear sign of the continuous longitudinal back and forth motion of the fluid in the pipeline during the shut-in period. The blue line is showing the velocity of the standing wave (in the order of magnitude of 0.1 m/s to 50 mm/s) inside the pipe after shut-in. Variable fluid flow regimes can occur at the same spot as time passes by all the way from laminar to fully turbulent regime. This means that the friction factor can change dramatically over the course of simulation at the same location due to different velocity magnitudes of the fluid flow. One interesting period of this is when the stagnant fluid is set into the motion due to heat transfer. At such time moment no friction factor calculation guideline is available due to the lack of knowledge of the Reynolds number.

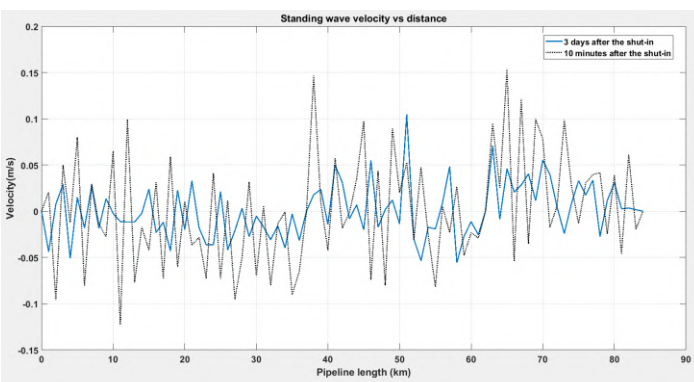

Figure 9. Comparison between the standing wave velocity within the pipe at two different instances—dotted black line 10 minutes after the shut-in, the solid blue line 3 days after shut-in.

Figure 10 shows the evolution of temperature profile along the length of the pipeline at different times during shut-in period. The solid line above the rest of lines is the initial spatial temperature of the whole pipeline and the subsequent lines show the temperature along the pipe as the point located farthest upstream undergoes some known transient temperate variation.

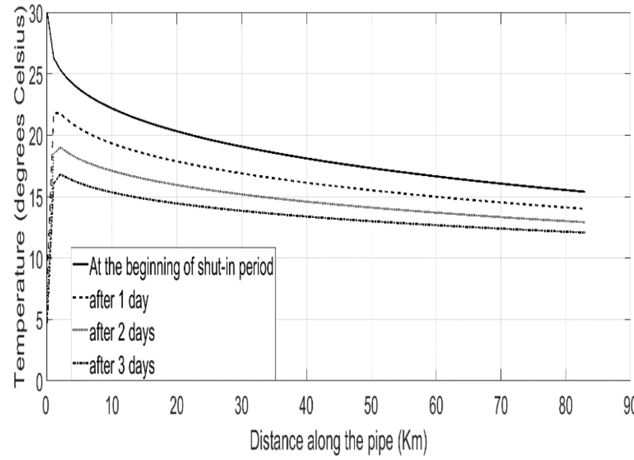

Figure 10. The evolution of mainline Temperature profile at different times.

Figure 11 shows the evolution of column separation (vapor phase changes) prediction for the whole pipeline and over the entire course of shut-in period. In other words, it is the space and time presentation of the whole shut-in period from column separation perspective, from which one has an eye-bird-view of the liquid column percentage of the whole pipeline. The colored legend is provided on the right-hand side of the figure to show the liquid-column% in space and time.

Left and right peaks are the two summits visible in the pipeline elevation profile (see Fig.2). They are located slightly before 40 km and after 60 km respectively.

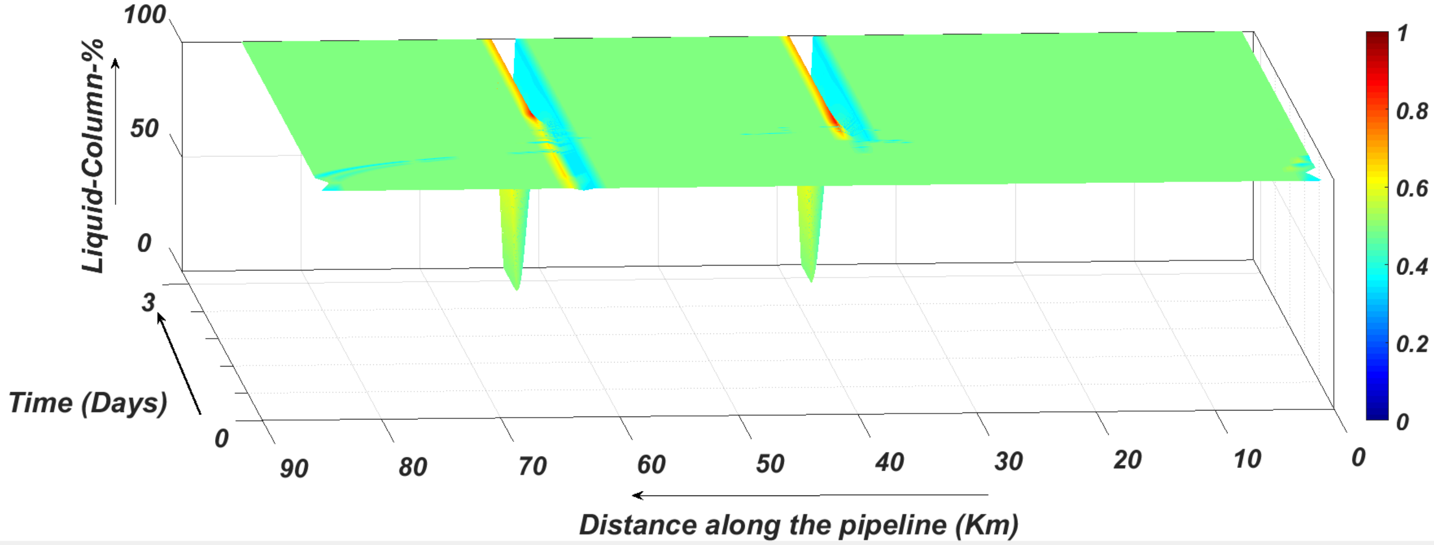

Figure 11. The transient-spatial contour of column separation in the pipeline segment during 3-day shut-in period The colored legend shows the liquid-column% in space and time.

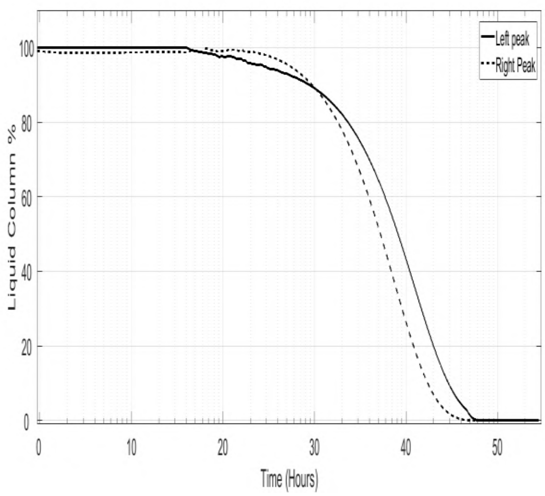

Figure 12. Evolution of column separation at the highest peaks in the initial 40 hours of shut-in period.

Figure 12 shows the evolution of the liquid column percentage at these peak locations with time during the shut-in period. In this example, both locations have reached to fully vapor phase. But the growth rate and the amount of vapor deposition are different at these locations as time passes by. Given enough number of hours in this simulation for shut-in period shows a similar final status at these locations, however if the shut-in period was less, significant differences would exist. For example, when the pipeline was shut-in for 40 hours only, there is about 20% difference between the amount of vapor existing at each of these locations.

Effective parameters in the local growth of the column separation

The rate of column separation growth is affected by the combination of two factors. One is the distance to the point undergoing maximum temperature changes (Closeness to the cavitation generation region) and the other is the local gradients of the elevation profile on the right and left sides of each summit (local steepness).

If a shut-in case continues long enough, then the fate of the liquid column percentage at different locations will be eventually determined by the second factor (i.e. local steepness). This means that in the longer run, the distance from the main region undergoing the most severe temperature drop (upstream of the pipe in this case) stands second to the gravitational potential of them. However, if one of these points had a little bit more elevation above the sea-level, the complete deposition of all vapors to that point and its neighborhood may occur. This is due to the tendency of the vapor phase to climb the pipeline as much as possible due to buoyancy force acting on a formed vapor pocket.
Therefore, for the same pipelines of similar length, properties and boundary conditions, the topography of the elevation profile is a crucial matter in determining where the final volume of vapor phase will move to by the means of advection process.

Effect of the transient temperature profile at the boundary

Figure 13 shows the two cases considered as the boundary conditions for the upstream end of the pipe. Case one, which exhibits an exponential decay, and case two a periodic behavior.

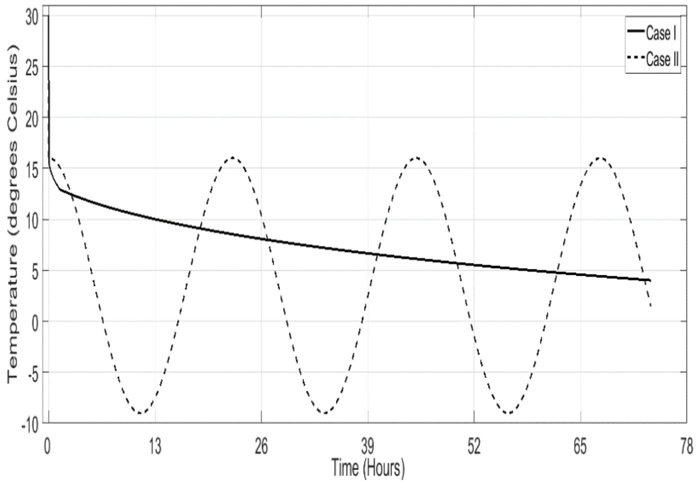

Figure 13. Comparison of the two cases considered for transient temperature at the upstream boundary --Case-I Exponential drop of Temperature with time, Case-II Diurnal temperature change.

The same mechanisms dictated the priority and speed by which the right or left peak become occupied with vapor are valid for the periodic case as explained in the previous part for the monotonically decaying case. (i.e. Effective parameters in the local growth of the liquid column percentage).

Figure 14 shows the transient-spatial contour of column separation for case with diurnal temperature change. In the end both peaks are filled with vapor like the Case-I. The colored legend is provided on top of the figure to show the liquid-column% in space and time.

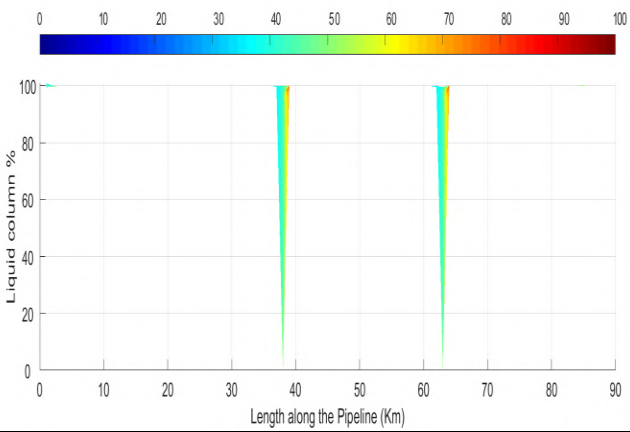

Figure 14. The Transient-spatial contour of column separation for Case-II. The colored legend shows the liquid-column% in space and time.

However, as shown in Figure 15, When the evolution of liquid column percentage is compared for each of these two scenarios, the difference between them appear to be in the rate at which the growth of vapor develops.

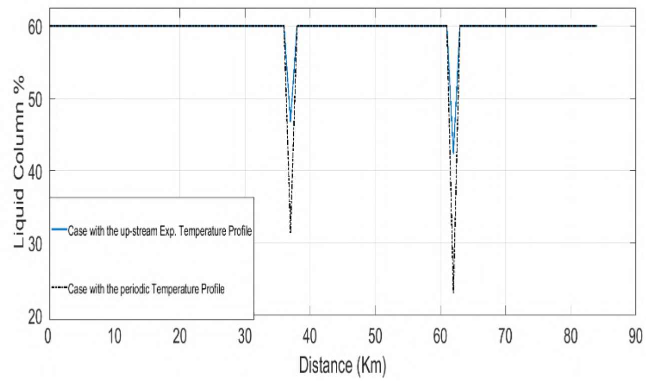

Figure 15. Different growth rates of the column at the same locations with different transient temperature scenarios shown in figure 13.

One of the advantages of the methodology used in this paper is that the code built based on the novel mathematical model can calculate the total amount of vapor phase at any section of the whole pipeline segment or the entire network of interconnected segments in real time.

Knowing this information is very important and can be critical in the determination of the way the pipeline should be started up after extended shut-in periods, because an operator usually needs to bring the columns back together (rejoin the separated parts of the column in the entire pipeline) and that needs a good estimation of the total volume of the vapor in the system as well as its location. By predicating the column separation, we estimate the final size of the growing bubbles and their locations.

Our analysis shows that there are approximately 1 km on each side of both summits which have undergone *a total column separation* during extended shut-in period, making 4 km of the pipeline in column separation condition. This is due to similarity of the elevation profile on each side of these two peaks and almost identical elevation head and should not be generalized to similar problems with different elevation profiles. In other words, small differences can cause one of the regions to be wider than the other or one region can lose all its vapor phase if they move along the pipeline to a new location. Also, as mentioned in the introduction, column separation can happen in a different way. A thin cavity confined to the top of the pipe extending over a long distance; referred to a condition known as cavitating flow. In this case the affected region in the pipe can be order of magnitudes longer. However, in the current conditions of extended shut-in, vapor phase has the tendency to rise to the highest peaks in the system due to buoyancy and with the aid of advection (i.e. longitudinal back and forth velocity of the standing wave helps the migration of these bubbles from everywhere to the peaks to balance with the buoyant forces exerted on the formed bubbles. This mechanism fills the entire cross section of the pipe and thus divide the liquid into two columns; referred to a condition known as column separation.

Each pipeline elevation profile therefore is unique and demands to be studied separately when exposed to extended shut-in periods (even if they are subjected to identical sets of initial and boundary conditions).

We calculate this affected local locations under column separation to occupy between 1.5 to 2 cubic meters of the vapor phase from which the extra amount of power needed for rejoining of the separated column back together could be estimated. Access to this information can make a smooth start-up procedure for a safe pipeline startup procedure when the pipeline is starting up from extended shut-in periods.

Figure 16 shows the liquid column percentages final values at the left and right-hand side peaks. From this graph the total amount of vapor phase and the length over which the column separation exists is calculated.

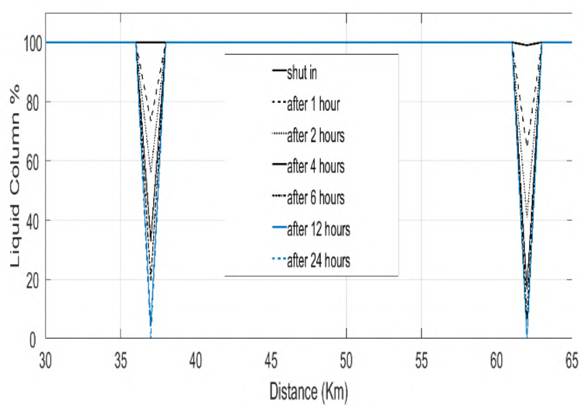

Figure 16. The liquid column percentage of the entire pipeline evolving from shut-in initiation time to the end of 78 hours.

CONCLUSIONS

The column separation intensity rate of change and longitudinal pressure waves must be predicted correctly to evaluate the column separation. Conventional methods in use for predicting the column separation, diverge only after a few seconds from the experimental trends. In the literature, these discrepancies were verified on a 37 meter pipe segment. Therefor conventional models such as DVCM, DGCM and GIVCM cannot keep up to the task of correctly simulating scenarios such as extended shut-in periods or naturally occurring column separation due to elevation gradient or pipeline transients in real time.

The code built based on the novel mathematical model was used in this paper to predict the evolution of column separation in liquid hydrocarbon transmission pipeline of an approximately 90 Km long during an extended shut-in period. Natural convection and advection in the pipeline transferred the vaporous pockets to their final locations. The solver makes the monitoring of the evolution of liquid column percent as well as temperature, pressure and flowrate possible in real-time.

Effective parameters in the local growth of the column separation found to be the closeness to a cavitation generation zone (such as a point with phase change due to fast temperature drop) and the local steepness or gradient of the elevation profile on upstream and downstream sides of the local extrema of the elevation profile.

Comparison of the two cases considered for transient temperature at the upstream boundary, showed that the same mechanisms dictate the priority by which the right or left peak becomes occupied with vapor, the difference between them appear to be in the rate at which the growth of vapor pockets evolves.

By predicating the column separation, we estimated the final size of the growing bubbles and their final locations. This information can be helpful in planning the pipeline operations.

ACKNOWLEDGEMENTS

The authors would like to thank the National Research Council of Canada Industrial Research and Assistance Program (NRC IRAP) for their financial contribution and advisory services.

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