International Journal of Sustainable and Green Energy
2014; 3(6-1): 1-6

doi: 10.11648/j.ijrse.s.2014030601.11

Modeling of hydrate deposition in loading and offloading flowlines of marine CNG systems

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To cite this article:
Esam I. Jassim. Modeling of Hydrate Deposition in Loading and Offloading Flowlines of Marine CNG Systems. *International Journal of Sustainable and Green Energy*. Special Issue: Renewable Energy and Its Environmental Impaction. Vol. 3, No. 6-1, 2014, pp. 1-6.
doi: 10.11648/j.ijrse.s.2014030601.11

Abstract: The main aim of this paper is to demonstrate the prediction of the model capability of predicting the nucleation process, the growth rate, and the deposition potential of hydrate particles in gas flowlines. The primary objective of the research is to predict the risk hazards involved in the marine transportation of compressed natural gas. However the proposed model can be equally used for other applications including production and transportation of natural gas in any high pressure flowline. The proposed model employs the following three main components to approach the problem: computational fluid dynamics (CFD) technique is used to configure the flow field; the nucleation model is developed and incorporated in the simulation to predict the incipient hydrate particles size and growth rate; and the deposition of the gas/particle flow is proposed using the concept of the particle deposition velocity. These components are integrated in comprehended model to locate the hydrate deposition in natural gas flowlines. The present research is prepared to foresee the hydrate deposition location that could occur in a real application in Compressed Natural Gas loading and offloading. A pipeline with 120 m length and different sizes carried a natural gas is taken in the study. The location of hydrate deposition formed as a result of restriction is determined based on the procedure mentioned earlier and the effect of water content and downstream pressure is studied. The critical flow speed that prevents hydrate to accumulate in the certain pipe length is also addressed.

Keywords: Hydrate deposition, Natural gas, CFD, Multiphase flow

1. Introduction

In Compressed Natural gas flow, the formation of hydrate is likely common, particularly in loading and offloading operation. The pipe that connects the offshore terminal with the custom CNG ship merges in the sea water and carries high pressure gas. Since the sea temperature is relatively low, the hydrate could form and accumulate somewhere in the pipe resulting a partial blockage which eventually could plug the pipe and completely interrupt the flow (Jassim et al., 2010).

The transmission system must operate in a safe, efficient, and reliable manner throughout the design life. Failure to do so has significant economic consequences, particularly for offshore gas production and transportation system. The avoidance or remediation of hydrate problems is the key aspect of flow assurance that enables the design engineer to optimize the production system and to develop safe and cost-effect operating strategies for the range of expected conditions, including start-up, shutdown, and turndown scenarios.

Annually, an operating expense greater than $500 million is devoted to hydrate prevention, almost half of that is devoted for hydrate inhibition (Sloan, 2003). In addition, offshore operations spend approximately $1,000,000 per mile for insulation of subsea pipelines to prevent hydrates.

The aim of the research is to integrate a comprehensive model in order to identify the locations where hydrate accumulation would most likely occur, to study the size distribution of particles, to model the particle-wall interaction, to simulate the deposition process based on forces balance, and to study the influence of some parameters on the location of the deposition such as flow conditions.

The comprehensive models capable to predict particle deposition and accumulation in fluids have been successfully implemented (Chen et al, 1997; Joseph, et al, 2001; Kvasnak et al, 1993; Legendre, 2005; Tian and Ahmadi, 2007). However, based on our extensive literature survey and best knowledge, models specifically developed to predict the most probable location for hydrate deposition under conditions where natural gas flows through restrictions in pipeline systems are still unavailable and need to be developed.

The proposed model consists of the following components:

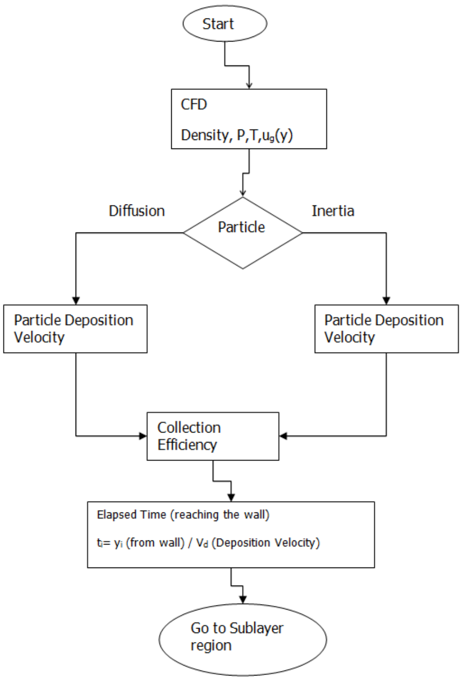
i. The computational fluid dynamic (CFD) technique to configure the flow field;
ii. A new correlation for hydrate growth and distribution based on the satisfaction of the Law of Mass action to predict the incipient hydrate particles size and growth rate;
iii. The inclusion of the concept of particle deposition velocity to track the particle motion in the turbulent regime; and
iv. A novel approach to describe the particle behaviour near wall region.

2. Summary of the Model

The flowchart presented in Fig (2.1) summarizes the procedure of the particle migration and process of deposition in turbulent flow. Further details can be found in (Jassim, 2008).

As particles travel in the fully turbulent region, deposition velocity is evaluated (depending on their sizes) and used to determine collection factor and the number of particles at the wall at each time step.

In the sublayer region, the particle size is used to relate the phenomena of the deposition to the proper model of deposition process, which is either the balance of the forces experienced by the particle(Cherukat et al, 1994; Jassim et al, 2010; Fan and Ahmadi, 1993; Kvasnak et al, 1993; Li and Ahmadi, 1993; Shams and Ahmadi, 2000; Tian and Ahmadi, 2007; Wang and Levy, 2003) or the probability of bouncing (Gondret et al, 2002; Jassim et al, 2010; Legendre et al, 2006; Legendre et al, 2005; Wang and Levy, 2003).



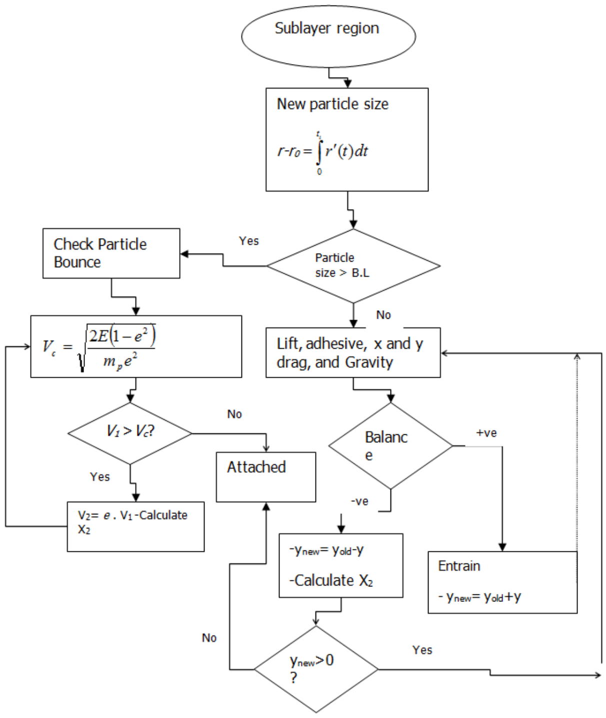


Figure (2.1). *Flowchart of deposition model*

3. Case Study

The following information pertaining to a near real application was used for this study to predict the deposition of the hydrate particle in a flexible loading line to a CNG ship:

Pipe length: L=120 m;

Gas water content = 160, 64, 16 mg/m^3 of wet gas;

Line pressures: P = 345 and 690 kPa ;

Pipe diameters: D_{pipe} = 25.4, 50.8, 101.6, 152.4, 203.2, and 254 mm (1, 2, 4, 6, 8, 10 inches) Flow rate was calculated as follows:

$$Q=\frac{\pi U_g D_{pipe}^2}{4} \quad \text{where } U_g=\sqrt{\frac{150}{\rho_g}} \text{ (m/s);}$$

These are the limits of erosion velocity prediction based on API 14E guidelines used in the study to predict the flow rates in the flow line.

Using the diagram of water content in hydrocarbon gas (Engineering Data Book GPSA), the temperature of the gas could be predicted. The pipeline was assumed to be in thermal balance with the chamber environment.

3.1. Calculating the Distance of the Deposition

According to the proposed model, the procedure for calculating the distance traveled by a single particle before being deposited on the wall could be summarized as follows:

- The deposition velocity is first determined using the model of Wells and Friedlander (Wells and Chamberlain, 1967; Crowe, 2006).
- The time required for the particle to reach the sublayer

region can be found from:

$$t = \frac{y_i}{V_d} \tag{3.1}$$

Where, y_i, the distance between the local position of the particle and the wall, is measured from the tube wall.

- The traveling distance in the turbulent region, assuming the initial velocity of the particle is equal to the fluid velocity, becomes:

$$X_1 = u(y_i).\frac{y_i}{V_d} \text{; where, } \frac{U_\infty - u(y_i)}{u^*} = 2.5 \ln \frac{R}{y_i} \tag{3.2}$$

- In the sublayer region, the particles smaller than the thickness of the boundary layer could migrate further as a result of external forces. Hence, the total distance from the initial position would be:

$$X_t = X_1 + X_\delta \tag{3.3}$$

- For particles larger than the sublayer thickness, the bouncing distance (X_B), the distance taken by the particle to settle as a result of rebound, is added to the distance traveled in the turbulent region.

$$X_t = X_1 + X_B \tag{3.4}$$

3.2. The Deposition Distance

Figure (3.1) shows the distance from the spot of particle formation to the location of deposition as a function of Reynolds number. The graph concludes that the deposition distance increases with increasing in Reynolds number. The trend is almost linear.

It is important to note here that the distance of particle deposition, called the "critical distance", is defined as the distance between the spot of hydrate formation to the location where the particles settle on the wall. The minimum size of the particle that deposit in a critical distances, is called the critical size. Hence all sizes equal or larger than the critical size will deposit in the same distance while smaller particles will be settled somewhere further ahead in the line.

Figure (3.2) illustrates such critical sizes with respect to Reynolds number. The figure shows that each value of Reynolds number is designated with a certain critical size of hydrate. The larger the magnitude of Reynolds number is, the smaller is the particle critical size.

3.3. Effect of Pressure

Pressure of the pipeline could change the distance of the deposition and the smallest particle size deposited (critical size). Figure (3.3) illustrates the critical size of hydrate particles as a function of Reynolds number for different flowline pressures. For each particular Reynolds number, the minimum size of hydrate deposited on the wall increases when the pressure inside the pipeline decreases.

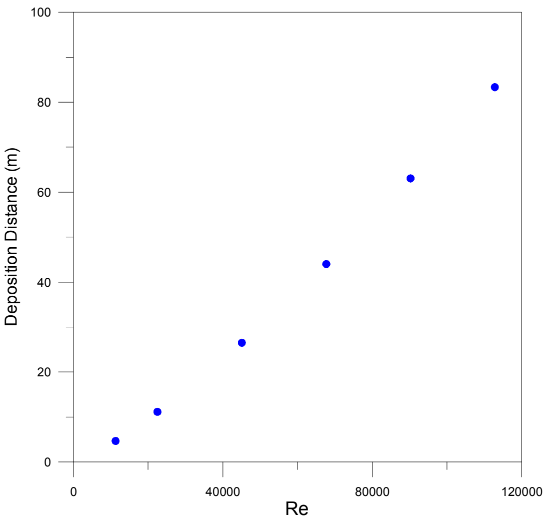


Figure (3.1). *Deposition distance versus flow Reynolds number*

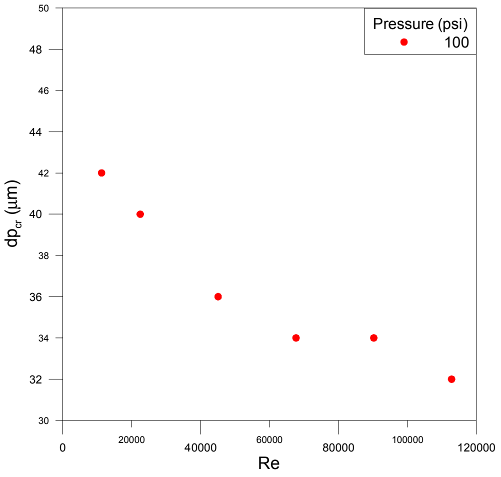


Figure (3.2). *Critical particle size deposit as a function of Reynolds number*

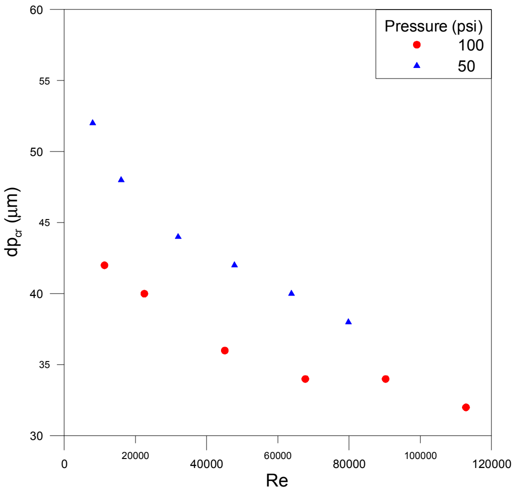


Figure (3.3). *Influence of pipeline pressure on the critical size of hydrate*

The deposition distance is also influenced by the pressure variation inside the pipe. Figure (3.4) shows that the deposition distance increases as the pressure inside the pipe decrease. Such discrepancy becomes more pronounced for higher Reynolds number.

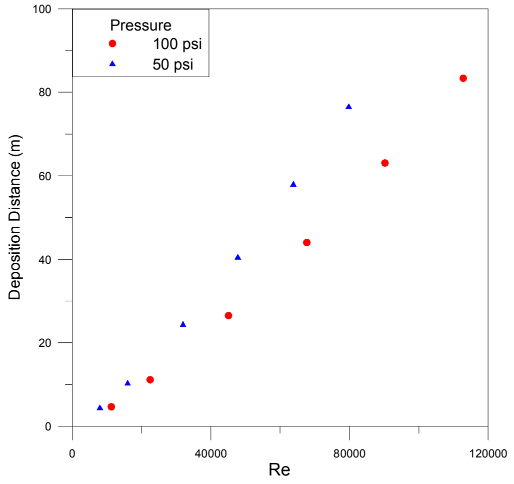


Figure (3.4). *Influence of pipeline pressure on the deposition distance*

3.4. Effect of Water Content

Another factor studied in this sample case was the amount of natural gas water content. Three values were chosen to present the effect of the water content on the deposition distance. Figure (3.5) demonstrates such effect. It can be observed that there are significant differences in the deposition distance as a result of water contents in natural gas flow, specifically at high Reynolds number. This trend comes from the fact that with increase in water content, the fugacity of water in gas phases increases and the driving force for mass transfer increases too. Hence, the rate of hydrate growth increases.

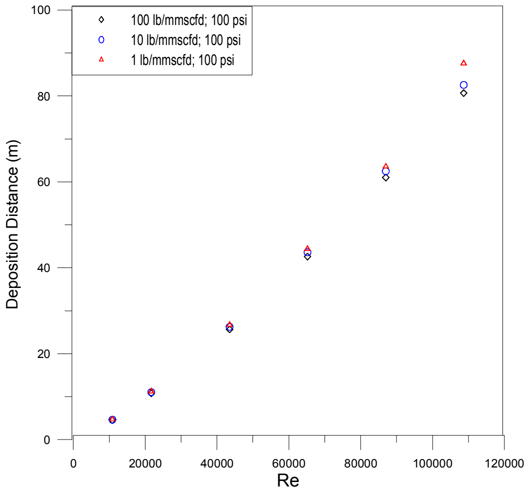


Figure (3.5). *Effect of water content on the deposition distance*

3.5. The Near Wall Effect

As the model considers the particle behaviour inside the sublayer region, it would be appropriate to illustrate the influence of such behaviour by comparing the deposition distance with and without particle-wall interaction.

Figure (3.6) shows the difference in the deposition distance (Δx) as a function of Reynolds number for different flow pressure and water contents. It could be concluded that the difference in the deposition distance increases with the increase in Reynolds number.

Figure (3.7) was developed to show the significance of this trend. The graph represents the distance the particle moves in the sublayer region as a fraction of total deposition distance the. From the figure, it can be seen the distance fraction decreases as the Reynolds number increases. That means that the particle-wall effect becomes significant at relatively low Reynolds number despite that the difference in the deposition distance is higher for high Reynolds number.

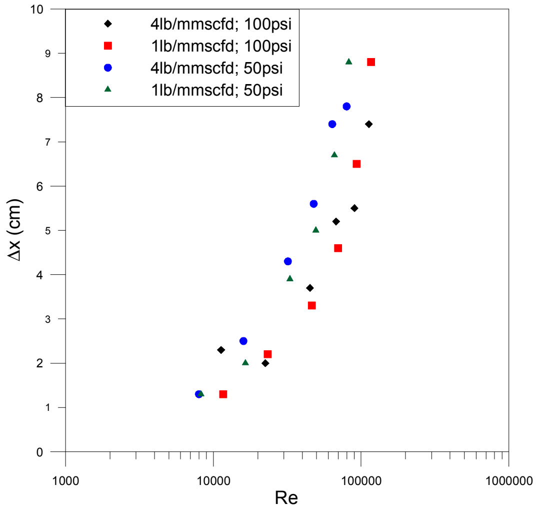


Figure (3.6). *the increment in the deposition distance resulted by wall effect*

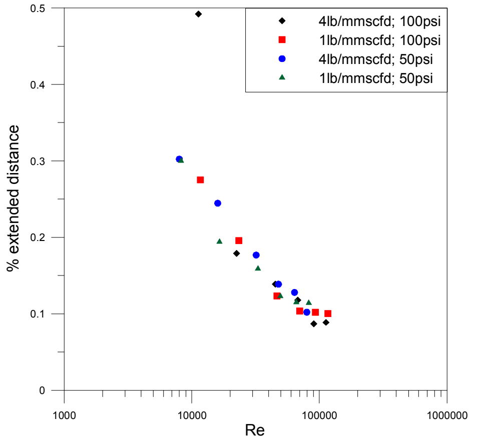


Figure (3.7). *the significance of near wall effect as a function of Reynolds number*

3.6. The Critical Speed

This section presents the speed required by the natural gas to flow so that no accumulation may occur within the pipeline. In other words, all the solid particles will move outside the pipeline and no deposition occurs on the pipe wall. Table (1) shows such velocities for the following constraints: P= 690 Kpa (100 psi), Water content= 160 mg/m^3 (10 lb/mmscfd). It is shown that small pipe size needs more gas speed to force the particles outside the line. This is because the distance to the wall is smaller and less time is required to get the particles travel towards the wall.

Table (1). *Minimum flow velocity required to prevent accumulation*

Line size (ID)	Velocity (m/s)	Re	Lc (m)
1”	26 100	8.3874×10^7	120.31
2”	2950	1.896×10^7	120.83
4”	1500	1.928×10^7	120.54
6”	200	3.856×10^6	120.92
8”	47	1.21×10^6	120.62
10”	15.2	488 461	120.23

4. Conclusion

A new approach is developed to locate the hydrate deposition in a natural gas pipeline. The concept of the particle deposition velocity is introduced to help to predict the trajectory of the particle motion in the turbulent region. The model presented in this research proposes a new approach to track the particle motion merged in the sublayer region using the forces acting on the particle. For particles with sizes larger than the sublayer thickness, the model introduces the influence of the bouncing concept to explain the near wall effects.

The main conclusions of the research can be summarized as follows:

1 The continuum equations should be corrected when the motion of submicron particles is addressed. Since very tiny particles behave as fluid particles, Brownian effect is taken into account by including the slip correction factor in the continuum equations.

2 The study showed that the distance of deposition decreases as the particle size increases. However, the analysis has introduced a certain size of particle in which further particle growth has no effect on the distance of deposition. Such size was called “deposition critical size”.

3 Deposition distance increases with the decreasing of pipeline pressure.

4 Water content in the natural gas has significant influence on the deposition distance particularly at high Reynolds number. The particles deposit faster when the content of water in the natural gas increases.

5 Increasing in Reynolds number reduces the effect of the distance that occurs as a result of near wall effect, i.e. the distance traveled by the particle in the boundary layer region.

6 More speed required by the smaller pipe size to prevent hydrate accumulation.

Nomenclature

D_{pipe}	Pipe diameter
d_p	Particle diameter
E	Particle Energy
e	Coefficient of restitution
L	Pipe length
m_p	Mass of Particle
P	Pressure
Q	Flowrate
R	Pipe Radius
r	Particle Radius
Re	Reynolds Number
t	time
T	Temperature
U_g	Fluid Velocity
u_*	friction velocity
V_d	Deposition Velocity
V_c	Critical Velocity
V	Particle Velocity
X	deposition distance
y	distance perpendicular to the wall
ρ	density

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