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An Experimental and Numerical Investigation on Gas Hydrate Plug Flow in the Inclined Pipes and Bends

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***Abstract*—**Gas hydrates can agglomerate and block multiphase oil and gas pipelines when water is present at hydrate forming conditions. Using "Cold Flow Technology", the aim is to condition gas hydrates so that they can be transported as a slurry mixture without a risk of agglomeration. During the pipeline shut down however, hydrate particles may settle in bends and build hydrate plugs. An experimental setup has been designed and constructed to study the flow of such plugs at start up operations. Experiments have been performed using model fluid and model hydrate particles. The propagations of initial plugs in a bend were recorded with impedance probes along the pipe. The experimental results show a dispersion of the plug front. A peak in pressure drop was also recorded when the plugs were passing the bend. The evolutions of the plugs have been simulated by numerical integration of the incompressible mass balance equations, with an imposed mixture velocity. The slip between particles and carrier fluid has been calculated using a drag relation together with a particle-fluid force balance.

***Keywords*—**Cold Flow Technology, Gas Hydrate Plug Flow Experiments, One Dimensional Incompressible Two Fluid Model, Slurry Flow in Inclined Pipes and Bends, Transient Slurry Flow.

I. INTRODUCTION

GAS hydrates, are crystalline water based solids with appearance similar to ice, in which guest molecules can stabilize a lattice of hydrogen bonded water molecules. Most light gases as well as some higher molecular weight hydrocarbons like ethane, propane, and butane can form hydrates for sufficiently low temperatures and high pressures. More details about gas hydrates can be found in the references [1], [2].

Thermodynamic conditions favoring hydrate formation are often found in the hydrocarbon transport pipelines carrying multiphase mixtures of water and hydrocarbons. This is highly undesirable because gas hydrates may agglomerate in flow-lines and other equipment and block the pipeline flow. Remediation procedures for hydrate plugs are often costly, difficult and hazardous.

Currently, different methods including water removal, insulation, heating, and inhibitor injection are employed to prevent or manage hydrate formation phenomenon. In addition, a method called *CFT* "Cold Flow Technology" is being developed as an alternative technology to deal with hydrate formation problem in sub-sea flowlines and pipelines. *CFT* is a very simple, inexpensive and environmentally friendly method based on direct conversion of produced water from oil wells to inert gas hydrate particles and transportation of produced slurry mixture without a risk of pipeline blockage. More information about this technology is available in the references [3]-[10].

The evaluation of operational aspects of cold flow systems includes both steady state conditions (pressure drop and particle concentration in slurry flows) as well as transient conditions.

The special case of shut down and start up of a pipeline is studied here, in which particles may slide towards lower elevation points (bends) during the shut down period. In such situations a plug of particles may form in bends resulting in pipeline blockage. During the restart operation, the plug should be flowed.

If transportation systems are to be designed with CFT, then prediction tools must be extended to model hydrate slurry flows and the plugging phenomenon. The current work provides some experimental data for model validation. At the moment no study is available for this transient problem since inclined slurry pipe flows are not the subject of extensive studies and most available investigations are presented for steady state flows. As a result, this work has been designed to experimentally study the flow and dispersion of gas hydrate plugs in pipes.

To perform the experiments, an experimental setup has been designed and constructed.

A V-shaped pipe has been equipped with pressure transducers and impedance ring probes for particle fraction measurement. A peristaltic pump has been selected to handle the slurry mixture. Experiments with real gas hydrated and hydrocarbons are costly due to the requirements of low

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temperature, elevated pressure and safety aspects. We have used model fluid (water) and model hydrate particles (surface modified polymeric particles) to simulate the condition of gas hydrate particles in oil flows.

II. Plug Flow Tests

A. Construction of the Experimental Setup

The following items were considered on designing an experimental setup for this work:

- Inlet section securing our control over the inlet particles concentration. It should also supply the required NPSH (Net Positive Suction Head) for the slurry pump.
- A pump capable for handling slurry mixtures.
- Transparent pipe enabling us to visually observe particles behavior.
- Required safety means and instrumentation devices to measure pressure, flow rate and particle concentration.
- Outlet section conditioning particles for recirculation.

Based on the economical and technical parameters and also the space limitation at the laboratory, the following solutions were concluded:

- The pipe section, (0.03 (m) I. D.) of the setup was considered to have a nonsymmetrical V shape with 2 (m) downward and 7 (m) upward lengths. The inclination of both sides of the pipe can be adjusted.
- Two tanks equipped with two impellers and electromotor were assembled to be installed at the inlet and outlet of the system. The volume of each tank is 200 (L).
- A peristaltic pump with maximum flow rate of 1700 (L.h^{-1}) capable to measure the flow rate was purchased. The pump is capable to operate in both clockwise and counterclockwise directions enabling us to recycle the slurry mixture.
- Three existing impedance rings used for gas-liquid two phase flows were modified to measure the particle fraction at three positions along the pipe.
- A safety valve and five pressure measuring elements were installed on the system.
- The setup was provided with connections to the laboratory air system, tap water and the laboratory main multiphase flow loop. Air is necessary to dry the setup after the tests and the tap water may be required to flash the system after some experiments.

Fig. 1 shows a schematic drawing of the setup.

B. Model Particle Preparation

Model hydrate particles were made in collaboration with *SINTEF* Materials and Chemistry, and the ongoing hydrate research at *SINTEF* Petroleum Research. In order to find the best option, different model particles were experimentally studied in the presence of water, salty water and oily water to observe and compare their performances. The main criteria were density, availability, price and surface properties as real hydrate particles are thought to be highly hydrophilic. The best option regarding the density, availability and price had a hydrophobic surface; for this reason, further chemical surface treatment was performed to make its surface hydrophilic. The surface treatment recipe was provided by *SINTEF* Materials

and Chemistry Group. As it was designed for small scale treatments, the recipe was modified by running a series of small scale experiments. The objective of the experiments was to significantly decrease the ratio of the required chemicals per particle volume and increase the rate of reaction by

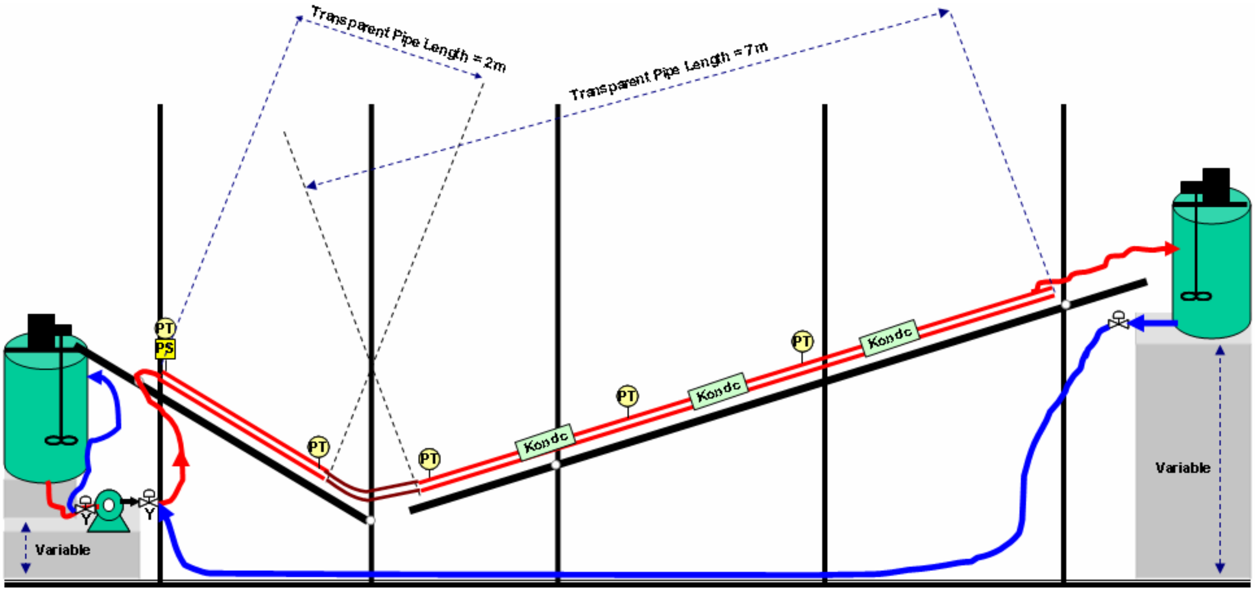

Fig. 1 A schematic drawing of the setup.

temperature adjusting.

To prepare model particle, 150 (kg) of original particles were purchased. Then, the particles were sieved in order to find the appropriate size range (i.e. 160-1000 microns and average size of 580 microns). Finally, around 60 (kg) of the particles were treated using the modified recipe.

C. Plug Flow Experiments

Plug flow experiments were made at a bend with 25 degree curvature and with equal inclination at its downward and upward sides. We studied the development of gas hydrate plugs with three different lengths (2, 1 and 0.5 meters) at different velocities. In order to make a plug, we had to dismantle the setup and place the particles into the bend with the aid of a piston. Then we had to assemble the setup again and fill it with water balancing the water levels at its both sides in order to keep the plug shape intact. The chance to have a successful preparation process was around 50 (%).

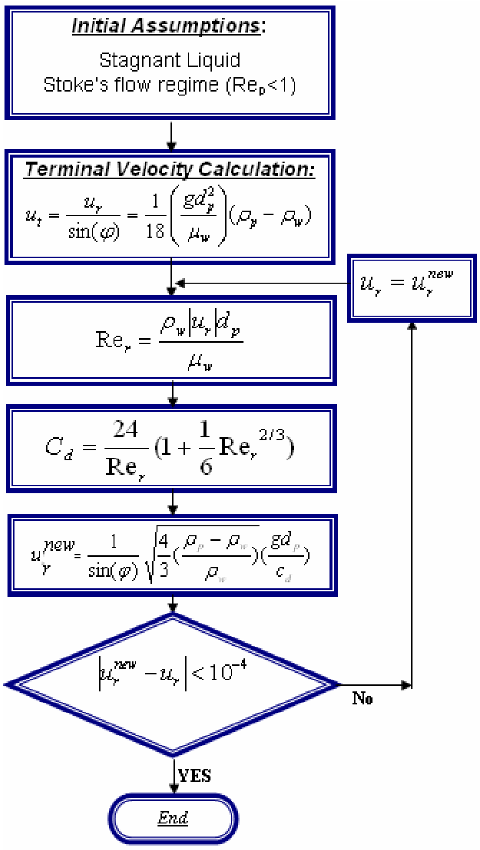

Fig. 2 The proposed scheme to calculate the relative velocity, u_r.

III. A INCOMPRESSIBLE FLOW MODEL

The purpose of the flow model is to investigate the dispersion of the hydrate plugs. The mass balance equations are integrated in time and space for an imposed mixture flow rate from the pump. This gives the evolution of an initial plug in a bend as if propagates out of the pipe. More details about different approaches to deal with fluid-particle systems can be found at the references [11], [12]. Using w and p for *liquid* and *particle* phases, the one-dimensional continuity equations for *water* and *particle* phases are [12]:

$$\frac{\partial}{\partial t}(\rho_w \alpha_w) + \frac{\partial}{\partial x}(\rho_w \alpha_w u_w) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_p \alpha_p) + \frac{\partial}{\partial x}(\rho_p \alpha_p u_p) = 0 \tag{2}$$

Where

$$\alpha_k = \frac{A_k}{A} \tag{3}$$

$$\alpha_w + \alpha_p = 1 \tag{4}$$

α is the phase volume fraction. The mixture velocity is defined as:

$$u_m = u_w \alpha_w + u_p \alpha_p \tag{5}$$

u stands for phase velocities. If we define the *relative velocity* as:

$$u_r = u_w - u_p \tag{6}$$

The phase velocities are:

$$u_w = u_r \alpha_p + u_m \tag{7}$$

$$u_p = -u_r (1 - \alpha_p) + u_m \tag{8}$$

Considering above equations, the continuity equations for *water* and *particle* phases can be written using α_p and u_r:

$$\frac{\partial}{\partial t}(1-\alpha_p) - \frac{\partial}{\partial x}\{\alpha_p (1-\alpha_p) u_r - (1-\alpha_p) u_m\} = 0 \tag{9}$$

$$\frac{\partial}{\partial t}(\alpha_p) + \frac{\partial}{\partial x}\{\alpha_p (1-\alpha_p) u_r + \alpha_p u_m\} = 0 \tag{10}$$

If we introduce a relation for u_r, we can integrate α_p numerically. The relative velocity u_r can be determined either from an empirical slip relation or from a drag relation together with a particle-fluid force balance.

Fig. 2 shows an iterative scheme for the case of a drag relation.

In order to calculate the pressure drop, the momentum equations for *water* and *particle* phases are written as:

$$\frac{\partial}{\partial t}(\rho_w \alpha_w u_w) + \frac{\partial}{\partial x}(\rho_w \alpha_w u_w^2) + \alpha_w \frac{\partial}{\partial x} p = -\tau_w \frac{S_w}{A} - \tau_i \frac{S_i}{A} - \rho_w \alpha_w g \sin(\varphi) \quad (11)$$

$$\frac{\partial}{\partial t}(\rho_p \alpha_p u_p) + \frac{\partial}{\partial x}(\rho_p \alpha_p u_p^2) + \alpha_p \frac{\partial}{\partial x} p = -\tau_p \frac{S_p}{A} + \tau_i \frac{S_i}{A} - \rho_p \alpha_p g \sin(\varphi) \quad (12)$$

τ_w is the wall shear stress from the liquid. τ_i represents the shear stress between the particles and liquid. τ_p is the wall shear stress from the particles. S is the wetted perimeter, A pipe area and φ pipe inclination with the horizon.

Two momentum equations can be used for layered flows, but for dispersed flows a mixture formulation is often used.

The total pressure drop can then be obtained by taking the sum of these two momentum balances which gives:

$$\frac{\partial}{\partial x} p = -\frac{\partial}{\partial t}(\rho_w \alpha_w u_w + \rho_p \alpha_p u_p) - \frac{\partial}{\partial x}(\rho_w \alpha_w u_w^2 + \rho_p \alpha_p u_p^2) - \tau_w \frac{S_w}{A} - \tau_p \frac{S_p}{A} - (\rho_w \alpha_w + \rho_p \alpha_p) g \sin(\varphi) \quad (13)$$

In this work, the wall friction is calculated as:

$$\tau_w = (\frac{1}{2}) f \rho_m u_m^2 \quad (14)$$

Where ρ_m is the mixture density and f is the friction factor calculated by a modified Churchil model [13] for slurry systems. We use slurry density and viscosity to calculate the friction factor. The slurry mixture viscosity is calculated by using an equation provided by Thomas [14].

To execute the proposed model, we firstly solve the continuity equations with given u_m, initial values and boundary conditions. We use a staggered scheme to solve the equations which are upwind in space and forward in time.

The discrete continuity equation used in this work is based on the approach proposed by Wangensteen [15]:

$$\frac{[\alpha_p]_j^{n+1} - [\alpha_p]_j^n}{\Delta t} + \frac{1}{\Delta x}\left([F_p]_{j+1/2} - [F_p]_{j-1/2}\right) = 0 \quad (15)$$

$$[F_p]_{j+1/2} = -[u_r]_{j+1/2}\left(\left\{[\alpha_p]_{j+1}^{n+1}[\alpha_w]_j^n\right\}^+ + \left\{[\alpha_p]_j^{n+1}[\alpha_w]_{j+1}^n\right\}^-\right) + u_m[\alpha_p]_j^{n+1} \quad (16)$$

$$[F_p]_{j-1/2} = -[u_r]_{j-1/2}\left(\left\{[\alpha_p]_j^{n+1}[\alpha_w]_{j-1}^n\right\}^+ + \left\{[\alpha_p]_{j-1}^{n+1}[\alpha_w]_j^n\right\}^-\right) + u_m[\alpha_p]_{j-1}^{n+1} \quad (17)$$

At above equations, j and n refer to cell number and time step, respectively.

It should be noted that on the calculation of $[F_p]_{j+1/2}$ and $[F_p]_{j-1/2}$ and depending on the sign of $[u_r]_{j+1/2}$ and $[u_r]_{j-1/2}$, only one of the brackets with (+) and (–) superscripts are used:

(+): when $[u_r]_{j+1/2}$ and $[u_r]_{j-1/2}$ are negative.

(–): when $[u_r]_{j+1/2}$ and $[u_r]_{j-1/2}$ are positive.

$[u_r]_{j+1/2}$ and $[u_r]_{j-1/2}$ are obtained taking the following relations:

$$[u_r]_{j+1/2} = 1/2\left([u_r]_j + [u_r]_{j+1}\right) \quad (18)$$

$$[u_r]_{j-1/2} = 1/2\left([u_r]_j + [u_r]_{j-1}\right) \quad (19)$$

When the entire variables at time $n+1$ are calculated, the pressure drop will be calculated using the following discrete equation:

$$\frac{[p]_{j+1}^{n+1} - [p]_j^{n+1}}{\Delta x} = -\frac{[\rho_w \alpha_w u_w + \rho_p \alpha_p u_p]_j^{n+1} - [\rho_w \alpha_w u_w + \rho_p \alpha_p u_p]_j^n}{\Delta t} - \frac{[\rho_w \alpha_w u_w^2 + \rho_p \alpha_p u_p^2]_{j+1}^{n+1} - [\rho_w \alpha_w u_w^2 + \rho_p \alpha_p u_p^2]_j^{n+1}}{\Delta x} + \left[-\tau_w \frac{S_w}{A} - (\rho_w \alpha_w + \rho_p \alpha_p) g \sin(\varphi)\right]_j^{n+1} \quad (20)$$

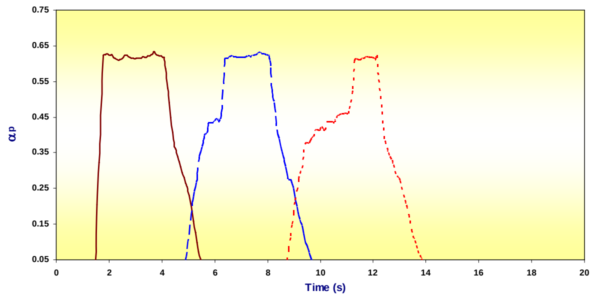

Fig. 3 The time variation of particles fraction passing the impedance rings with a 2 (m) plug at 0.66 (m.s^{-1}) mixture velocity. (—) first ring, (– –) second ring, and (…) third ring outputs.

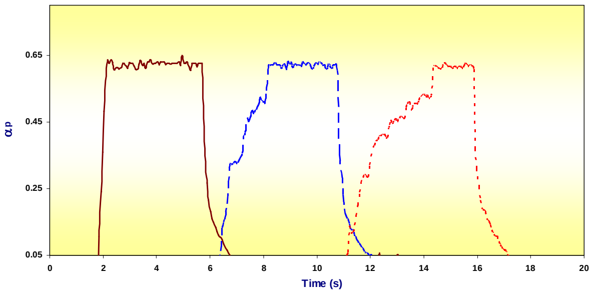

Fig. 4 The time variation of particles fraction passing the impedance rings with a 2 (m) plug at 0.50 (m.s^{-1}) mixture velocity. (—) first ring, (– –) second ring, and (…) third ring outputs.

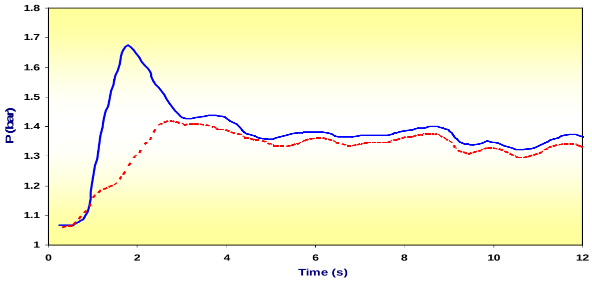

Fig. 5 The time dependent pressure variations before and after the bend with a 2 (m) plug at 0.66 (m.s^{-1}) mixture velocity. (—) before the bend, (– –) after the bend.

IV. Results and Discission

A. Experiments

Figs. 3 and 4 illustrate the time variation of particles fraction passing the impedance rings at three different locations with a 2 (m) plug at 0.66 and 0.50 (m.s^{-1}) mixture velocities. As it can be seen in those figures, we have a sort of mixing at the front of the plugs giving increased plug length. The shape of the plug tail keeps almost identical. A little mixing seen in the tail has been visually observed to be created when the tail passes the bend.

In the case of 0.25 (m.s^{-1}), the mixture velocity was not high enough to keep all particles dispersed and a layer of particles was built. It should be noted that the impedance rings are calibrated to measure the particle fraction in a well dispersed systems. In conclusion, we can not rely on the outputs of the rings, though they give us a qualitative overview of the flow.

Fig. 5 shows the time dependent pressure variations before and after the bend in the case of a 2 (m) long hydrate plug at 0.66 (m.s^{-1}). The pressure curves have been smoothed using a 3-point moving averaging method. It can be observed that the upstream pressure of the bend experiences a peak when the plug passes the bend. The same behavior has been recorded at all other experiments confirming this point that the pressure is significantly increased when a plug passes a bend.

B. Modeling

Fig. 6 presents the results of the model on the simulation of the case shown in Fig. 3. The computational examples are made with a fine grid to reduce the numerical diffusion. More physical details should be added to the model in order to improve its performance.

Fig. 7 presents the results of the model for pressure calculation of the case shown in Fig. 5. The results of the pressure computation show that increased pressure drop in bends needs to be included.

Another modeling approach could be to use a grid moving with the front which has been used for simulation of slug flow [17], [18]. The flow model may be extended for layered flow using two-layer [19], [20] or three-layer [21]-[23] approaches. At the two-layer approach there is a moving particle layer whereas, at the three-layer model the particle layer is divided into a static and a moving layer. The advantage of such an improvement may be essential since none of available two and three-layer models are capable to study transient systems.

C. Uncertainties

Impedance rings have been successfully used to measure slurry concentration [24]. One weakness of impedance ring techniques is that the response is flow regime dependent.

The rings may work for our case of homogeneous particle plugs, but other methods should be applied for layered or non-symmetric particles cross section distributions. The pressure response shows some systematic fluctuations. Although care was taken to remove all gas bubbles from the system, some residual gas may be left in the pipe fittings. Trapped gas may cause flow and pressure oscillations. The mass balance of the particles passing the impedance rings was satisfied with an absolute deviation of around 5 (%).

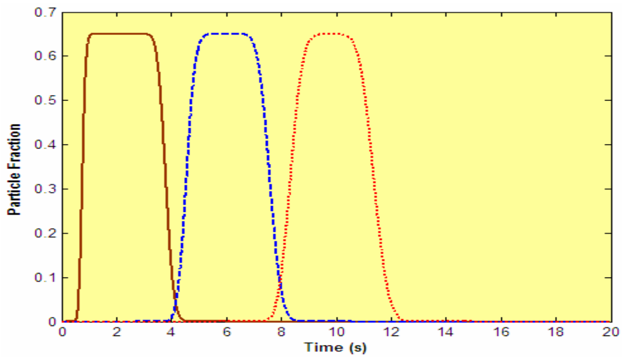

Fig. 6 Computational results for the time variation of particles fraction passing through the impedance rings with a 2 (m) plug at 0.66 (m.s^{-1}) mixture velocity. (—) first ring, (– –) second ring, and (…) third ring simulated outputs.

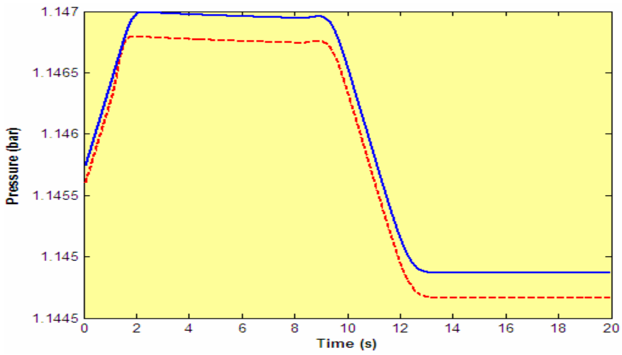

Fig. 7 Computational results for the time variation of the pipe pressure before and after the bend with a 2 (m) plug at 0.66 (m.s^{-1}) mixture velocity. (—) before the bend, (– –) after the bend.

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