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# Review of Gas Hydrate Plug Dissociation in Oil and Gas Pipeline: Downstream Pressure Reduction Approach

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## Abstract

*Hydrate plug dissociation in subsea pipelines is a challenging problem in oil and gas transport systems as limited options are available for remediation. Key concerns include technical, operational deferment and safety hazards that are associated with hydrate plug dissociation in oil and gas pipelines. This paper presents a comprehensive review of the physics of hydrate plugs remediation including a compilation of dissociation models, experimental work performed to date, and a detailed analysis on the problem of gas hydrate from a flow assurance perspective. Depressurization methods are critically reviewed, with influence of temperature, pressure, velocity and hydrate plug properties discussed with detail. Outstanding research questions for hydrate plug dissociation highlighted.*

## 1. Introduction

Since the discovery of gas hydrate plugs in transmission lines by Hammerschmidt in 1934 [1], hydrate plugs in subsea pipelines have been a major challenge, either partially or completely obstructing flow of produced hydrocarbon fluids.  Besides hindering the flow of hydrocarbon in transportation pipelines, hydrate plugs also pose a safety concern [1-3]. It's considered a major threat confronting and frustrating deep water/offshore oil and gas production operations. [4, 5] In-spite of mitigation techniques that have been developed owning to the occurrence of hydrate blockage in pipeline; pipeline plugs are not uncommon [6]. Comparatively less research has been carried out to determine hydrates plug dissociation strategies in oil and gas subsea pipelines when compared to hydrate formation; especially, as it pertains to downstream depressurization approaches. Historically, academic research related to gas hydrates has either been focused on the recovery or on the production of gases such as methane from natural reservoirs in the seabed or permafrost region [7-12] or on the inhibition of hydrate formation in pipelines and process facilities. [13-15] Both the thermodynamics [15-20] and kinetic of gas hydrates [21, 22] have received a considerable research attention. However, limited information exists in open literature for hydrate plug dissociation in pipelines. The choice and method to adopt for hydrate plug dissociation is limited, because remediation options may be dependent on the formation conditions and the hydrate plug characteristics. There are several dissociation techniques – chemical injection methods, thermal methods, mechanical methods [23-24] and depressurization techniques. For chemical, this involves the use of chemical inhibitors, such as methanol injection, and numerous other [18, 19, 22, 25, 26]. When a pipeline is completely blocked, the passage of chemical (methanol) to dissociate hydrate plugs is unrealistic, and this method could be cost ineffective. Thermal dissociation techniques involve active heating and Direct Electrical Heating (DEH) – increasing the temperature of the system above hydrate dissociation temperature, allowing significant heat flow to dissociate plugs. The application of this method is limited by a concern that the evolved gas from dissociating plugs may be trapped and eventually over-pressurize the pipeline system [27-28]. For mechanical methods, [23-24] the use of pigging, drilling or scraping is not advisable. This approach intends to compress the hydrate and increases the risk of pipe rupture. Depressurization method involves reducing the pressure of the hydrate plug below the hydrate equilibrium pressure, this would cause the hydrate phase to cool and dissociate until the new equilibrium state is reached. From Figure 1, the case of hydrate blockage between the reservoir (X-mass Tree) and platform can be envisaged

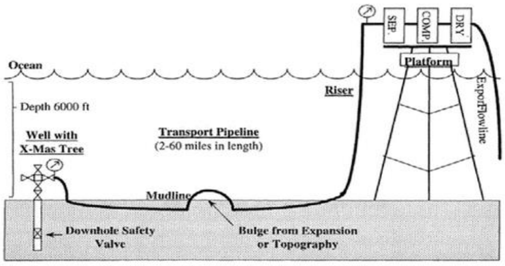

Figure 1. Schematic of typical Offshore Well, Production Pipeline and Platform [27]

The motivation to carry out research of gas hydrate plug dissociation in pipeline, is fundamentally driven by a desire to ensure uninterrupted transportation of produced hydrocarbon fluids via pipeline and process facilities. In this paper, we review various dissociation models and experimental studies on hydrate plug dissociation. Because of the limited availability of research data in this area, it is extremely important to review and concisely harmonized research investigations till date in hydrate plug dissociation in subsea pipeline.

## 1.1 Thermal Dissociation Techniques

As the name implies, this method involves the application of heat primarily to maintain the flowing of hydrocarbons outside the hydrate stable region [29]. In some deep offshore operations heating is considered to take the hydrate plug out of the hydrate stable region for dissociation to occur. Due to the large residual liquid head that may exist in some deep-water field development, heating of the flow line wall to dissociate the hydrate plug may be necessary in cases where depressurization alone is inadequate [30]. Flowline/pipeline heating technology application to prevent fluid cooling below the hydrate equilibrium temperature during pipeline shutdown has been investigated [31-33]. Methodologies for introducing heat in pipelines are categorized into direct electrical heating (DEH) and indirect heating [32, 34]. Indirect heating technology, an electrically heated warm fluid is circulated through a pipeline bundle [32], or electrical current is passed through heating elements which are in contact with the pipeline [33]. In the aforementioned electrical techniques, there exists conduction of electricity by the pipeline and the impedance of the material causes the pipeline heating [35]. Statoil-Hydro and Shell applied electrical heating technology on some subsea flow lines [28, 36]. The purpose is primarily to keep the hydrocarbon content above the hydrate formation temperature during shutdown or start-up operation. The Annular flow model developed by Mehta [37] employing uniform 'low' heat to dissociate hydrate plugs from pipelines is stated as a safe approach.

Recently, heating technology called Electrically Heat Tracing Pipe in Pipe (EHT-PiP) has been applied with success [38-41]. EHT-PiP involves active heating technology that maintain the hydrocarbon fluid temperature above hydrate formation temperature during normal operation or shut-in periods [42]. It was demonstrated that following the formation of a 200 kg hydrate plug in 18m 6” OD prototype ETH-PiP, the hydrate could be dissociated without local pressure build-up runway (i.e, without plug detachment or movement) using ETH-PiP [42]. The research on ETH-PiP for hydrate management and dissociation in full scale was tested by Technips France at French Research Institute’s Experimental Facilities in Solaize (France) in collaboration with Total E&P, ExxonMobil Development Company and Woodside Energy Limited[43]. The study indicated that EHT-PiP technology was a successful development of a simulation tool and performance monitoring system that represents the main safeguards, and could be used to demonstrate the safe dissociation of hydrate plugs in real offshore operation conditions.

The EHT-PiP technology is reported to have been implemented in the Dalia field operated by Total E&P Angola and Papa Terra field development [44]. The research study of 39 reported the first application of ETH-PiP technology on the Islay field in the North Sea UK. The working principle is based on the Joule resistive effect, which enhances active heating through the 3-phase electrical tracing cables [44]. Pipeline heating technologies may also allow for remediation of existing hydrate plugs by increasing the local pipeline temperature outside the hydrate equilibrium region [28] However, challenges already mentioned in previous sections are not completely alleviated. Also, another limitation to the applicability of this approach is that such technology is better introduced during the design phase of deep-water/offshore pipeline installation. In the author’s view, EHT-PiP technology may not easily be retrofitted into an existing subsea pipeline or offshore installations to dissociate hydrate plugs. Hence, the use of depressurization techniques to dissociate hydrate plugs in subsea pipeline is a better option.

In additional to the above-mentioned limitations for this method, the use of thermal dissociation techniques will largely be an issue by the tie back distance, nature of the fluid being conveyed in pipeline, design and installation cost, and technical challenges.

## 1.2 Thermodynamic/Chemical Dissociation Techniques

To support pressure reduction methods, chemicals may be injected to accelerate dissociation of a permeable hydrate plug, with methanol’s being commonly used. This approach involves thermodynamic inhibitor (THIs) and low dosage kinetic inhibitors (KI’s). Experimental results in the last decade have shown that KI’s can be applied at lower concentrations for hydrate inhibition, and this is considered advantageous in hydrate remediation [18, 19, 22]. Low dosage inhibitors work independently of water cut, which is the reason why KI’s are appropriate for a mature reservoir. Inhibitors are limited to low subcooling temperature, which may be insufficient for deep-water application 18, 19].

A recent study of Panter et al.[45] experimentally demonstrated that hydrate plugs can be dissociated using a nitrogen purge. The dissociation was shown to involve growing channels and significantly different from radial dissociation. Figure 2 shows that a hydrate plug dissociated through a small channel wherein. the plug crumbles into small fragments. Supporting the experiments shown in Figure 2, a numerical model was developed and solved by Panter et al [45] using an explicit numerical scheme to solve for methane concentration and amount of hydrate dissociated as shown in Equation (1).

$$\Delta n_i = KA\Delta t\left(C_{eq} - C_{i,t}\right) \tag{1}$$

where $\Delta n_i$ is the number of moles of methane released into the gas phase, $K$ is the overall mas-transfer coefficient, $A$ is the surface area, t is the time, and $C_{eq}$ is the thermodynamic concentration of methane, $C_i$ is the concentration of methane in segment $i$ of the channel. The numerical model predicted shorter dissociation time for **s**II hydrate plug when compared to experiment results.

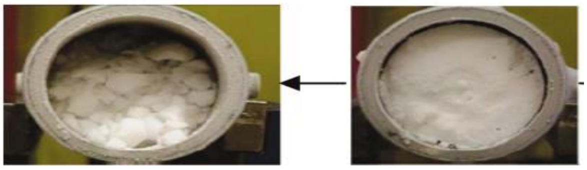

Figure 2. Methane hydrate plug dissociation using Nitrogen purge, (right image) before dissociation, (left image) after 1 hour [45]

In a field demonstrated application at Campos Basin's ultra-deep waters well (1541 m depth), a hydrate plug that completely blocked the locking mechanism of the Production Vertical Connection Mandrel (PVCM) of the Xmas tree was dissociated using Self-Generated Nitrogen (SGN) [46]. This principle is based on a heat-releasing fluid used to dissociate the hydrate plug. Petrobras [46] used this method to remediate the hydrate plug. However, one major challenge with this process is the ineffective reaction of SGN at a temperature below 10$^o$C. Hence, at the temperature on the deep-sea floor, SGN reaction rate is close to zero. The active rate reaction is required to dissociate the hydrate plug, and for that reaction to occur, a more cumbersome technical process is required to maintain the reaction. This can be achieved by either shortening the residence time of the SGN fluid in the pipe string by increasing the pumping rate or a thermal insulated pipe string should be available [46]. The study of Lederhos [47] also noted that environmentally acceptable hydrate inhibitors could be a technological challenge for the oil and gas production industry. In general, any chemical process of hydrate plug dissociation is associated with such environmental challenges.

### 1.3 Kinetics Dissociation Model

Dissociation kinetics of hydrates is of a significant importance for hydrate plug remediation in oil and gas pipelines. Some studies had been developed to broaden the understanding of intrinsic kinetics in hydrate dissociation. Kim et al.[48] developed a model for the intrinsic rate of gas hydrate dissociation, wherein the decomposition rate was proportional to the particle surface area, and the difference in the fugacity of gas at the equilibrium pressure and the decomposition pressure:

$$\left(\frac{dn}{dt}\right)_p = -K_d A_p (f_{eq} - f_g) \tag{2}$$

where $\left(\frac{dn}{dt}\right)$ is the decomposition rate, $A_p$ is the particle surface area, *Kd* is the decomposition rate constant and $f_{eq} - f_g$ is the difference in the fugacity of gas at the equilibrium pressure and the decomposition pressure. From experimental data for methane, the rate constant is given as

$$\frac{1}{K_d} = \frac{1}{k_r} + \frac{1}{k_m} \qquad (3)$$

where *k*r is the reaction rate constant and *k*m is the mass transfer coefficient. However, Gupta [49] studied the dissociation of methane hydrate using nuclear magnetic resonance and found out that intrinsic kinetics did not play a significant role in the overall dissociation process in their equipment. However, the formation temperature was below ice point. Makogon [50] noted that dissociation of hydrates in porous medium does not occur in the whole volume, but in a narrow region that can be referred to as a surface. During this process, the rate of dissociation is influenced by the movement of a decomposition front, and not by the kinetics of this process [50]. Makogon [50] affirms that the movement of this front depends on the magnitude of heat flow through it and the specific heat of the hydrate. Additional research [51-53] that has been developed on hydrate plug dissociation indicates that kinetics plays some role in the hydrate dissociation process. Not fewer than two dissociation rate processes possibly control hydrate plug decomposition: (i) the heat transfer process: A dissociation model based on external energy in the form of heat to melt the hydrate plug in an endothermic reaction. (ii) Intrinsic kinetic process: The reaction at the surface – interface base dissociate rate [54]

### 1.4 Intrinsic Kinetics Couple with Heat Transfer

The intrinsic kinetics and heat transfer was coupled by Jamaluddin et al [55] in a single model to simulate dissociation of a core methane hydrate. The intrinsic kinetic rate is given by Jamaluddin et al [55] as:

$$\frac{dS}{dt} = -\psi K_o e^{\frac{-E}{RT_s}} \left( f_s - f_\infty \right) \qquad (4)$$

The heat transfer rate equation is given by Jamaluddin et al [55] as:

$$q_s = k\left(\frac{\partial T}{\partial x}\right) + \rho_H M_H \lambda \frac{dS}{dt} \qquad (5)$$

Jamaluddin then coupled the aforementioned equations into a single model:

$$q_s = k\left(\frac{\partial T}{\partial x}\right) + \rho_H M_H \lambda \psi K_o e^{\frac{-E}{RT_s}} \left( f_s - f_\infty \right) \qquad (6)$$

where $S$ is noted as the thickness of the hydrate block; $\psi$ is dimensionless surface roughness factor which is given as the ratio of the actual surface area to the geometric area; $K_0$ is a constant; $E$ is activation energy of methane gas hydrate; $M_H$ is the molecular weight of hydrate; $Ts$ is the absolute decomposition surface temperature; $\lambda$ is the latent heat of dissociation of the hydrate; $f_s$ is the fugacity of methane at the hydrate interface; $f\infty$ is the fugacity of methane in the bulk. Jamaluddin et al.[55] implies that at slight activation energy, no significant effect of $\psi$ on the overall rate of decomposition occurs. However, when the activation energy was increased, the surface roughness factor has a significant effect on the overall rate of decomposition. As $\psi$ increases, the intrinsic decomposition rate increases. Hence, the kinetics becomes less determinant, and the overall rate of decomposition is gradually controlled by the heat transfer rates only. The rate of decomposition is also sensitive to the system pressure. Jamaluddin et al [55] found that by changing the system pressure, the decomposition process moved from a heat transfer controlled regime to a regime where both heat transfer and intrinsic kinetics had a significant effect on the global rate of decomposition.

It was not until after the work of Jamaluddin et al.[55] that several researchers began to explore further research on hydrate dissociation from a combination of heat transfer and intrinsic kinetic models. The research work of Vlasov [56] developed a model based on theory of chemical kinetics for the dissociation of gas hydrates. The driving force for dissociation (i.e., the fugacity difference) was highlighted in the model and the rate constant of the hydrate dissociation was found to be dependent on the temperature. Nihous et al. [57] analyzed methane hydrate dissociation behavior in the presence of thermodynamic inhibitors. Intrinsic dissociation kinetics and heat transfer dissociation models at the decomposing hydrate surface were investigated. It was found that when the convective heat transfer coefficient was expressed as a simple power of the dissociating front velocity, the agreement between data and calculations was further improved. The results of Nihous et al. [57] indicates that hydrate dissociation is controlled by heat and mass transfer at the interface.

Previous investigations that have coupled heat transfer and kinetics models have also considered the intrinsic kinetics at different temperature [57]. However, most of the hydrate dissociation models are heat transfer controlled in this particular experiment [58], indicating that intrinsic kinetics are limited. In the subsequent section, hydrate plug dissociation model and experiment studies involving pipeline depressurization techniques are discussed in detail.

### 1.5 Depressurization Models

The dissociation methods and models discussed above have some technical concerns and safety challenges that may limit their application for hydrate plug remediation in pipelines depending on the plug condition. Of all known hydrate plug remediation methods, depressurization techniques are the most commonly used and most viable option for hydrate plug dissociation [23, 59]. The use of depressurization techniques requires that the plug formation conditions and hydrate properties are known, essentially for modeling/prediction of plug remediation. Porosity and permeability of the hydrate plug are an important consideration for this dissociation strategy.

Significant effort has been made over the last two decades to gain insight into the physics of hydration plug remediation in pipeline using pressure reduction approaches. Depressurization methods are typically classified into two categories:

1. Double sided depressurization – Pressure reduction both upstream and downstream of the pipeline.

2. Single/one sided depressurization – Pressure decrease at the downstream end of the pipeline.

Several other models have been proposed for hydrate plug dissociation in pipeline using either double sided depressurization [59-66] or single sided [5, 67-69].

## 2. Double Sided Depressurization Techniques

Hydrate plug dissociation in pipelines was first modeled by Lysne et al.[60] and the subsequent work of Lysne [61]. Lysne studied 1-D steady state model. The model assumed that the energy required to decompose the plug was provided by heat flux through pipeline wall only. The convective heat transfer was considered negligible. As noted by Kelkar et al. [64] and Peter [62, 63] the model developed by Lynse et al was simplistic in its assumptions.

The formation of ice in the system during depressurization was one aspect that was not systemically examined and unaccounted for in the Lynse et al. study. Predominantly, at the onset of dissociation, the hydrate equilibrium temperature for the depressurized pipeline falls below the ice formation temperature, and thus the phenomena will result in some if not all water released from the decomposing hydrate plug to form ice crystals around the melting hydrate plug. Some researchers [62, 67, 68] recommend and consider the formation of ice during hydrate plug dissociation in pipelines as beneficial for the following the reasons:

a. High thermal diffusivity of ice gives high heat flux that aids the dissociation rate.

b. Latent heat that would be released from the freezing of water is able to improve hydrate dissociation rate.

However, there are opposing view(s) on the benefits of ice formation during dissociation; the research work of Lysne et al.[60] study also noted that ice formation may slow dissociation. Fide-Dufour et al.[70] study also noted that ice formation may slow dissociation.

Most models developed for hydrate plug dissociation in pipeline using depressurization method treat the process as heat transfer controlled and apply Fourier's law of heat transfer. Kelkar et al. [64] applied Fourier's law in rectilinear coordinate to formulate one of the first models to investigate hydrate plug dissociation in pipeline. Kelkar et al.[64] analytically solved a simplified partial differential equation for heat diffusion in rectilinear coordinates. The study assumed a pipe wall constant temperature and the energy needed to decompose the plug comes from heat flux through the pipeline wall. Contrast to Bovallaram's [67] research which is discussed in a subsequent section, Kelkar et al.[64] did not estimate hydrate plug length because the model assumed hydrate plug shrinks radially.

Kelkar et al.[64] assumed hydrate plugs are highly porous and able to transmit pressure across the plug length; this assumption was acknowledged in the subsequent research work of Austvik [6]. The 1-D transient model developed by Kelkar [64] had one major limitation. had one major limitation. The study neglected the effect of curvature in pipeline.

$$\frac{\partial T_w}{\partial t} = \alpha_w \frac{\partial^2 T_w}{\partial x^2} 0 < x < X_1 \tag{7}$$

$$\frac{\partial T_I}{\partial t} = \alpha_I \frac{\partial^2 T_I}{\partial x^2} X_1 < x < X_2 \tag{8}$$

Where $T_w$, $T_I$, $\alpha_w$, $\alpha_I$ is temperature of water, temperature of ice, thermal diffusivity of water & ice respectively, $x$ is the longitudinal direction along the pipe with $X_1$ and $X_2$ representing water-ice boundary and ice-hydrate boundary.

Some researchers extended the application of Fourier's law of heat transfer in cylindrical coordinates [62, 63, 67, 68] to develop a moving boundary model of hydrate and ice phases during plug dissociation in pipeline. Peters[62] performed two-sided depressurization experiments with methane hydrate and concluded that dissociation in the radial direction is dominant. The study noted that the ideal scenario for dissociating a plug in a pipeline would be when the downstream pressure is at a minimum, mostly likely, the atmospheric pressure. A numerical model was developed, the model assumed that hydrate dissociated as moving boundary to provide a shrinking core model.

The model developed by Peter [62] has two moving boundaries – water/ice boundary and ice/hydrate boundary. To validate the numerical model, experimental study was performed by Peter at a pressure range 0-21 MPa. This experiment was performed for ethane hydrate. Also, one objective of this model was an attempt to remove assumption used in Kelkar et al model and improved the applicability. However, this study did not account for mobility of water released from the dissociating hydrate plug in pipeline. Also, the prediction of the numerical model and experimental study did not agree on structure II (sII) gas hydrate dissociation. While the former predicted that it would take longer time for sII hydrates to dissociate, the later showed it will take less time. "This discrepancy maybe attributed to the role of kinetics in hydrate dissociation". However, the researcher concludes that dissociation is heat transfer limited [62]. Figure 3 shows that hydrate plug dissociated radially, shrinks from the pipeline wall to core.

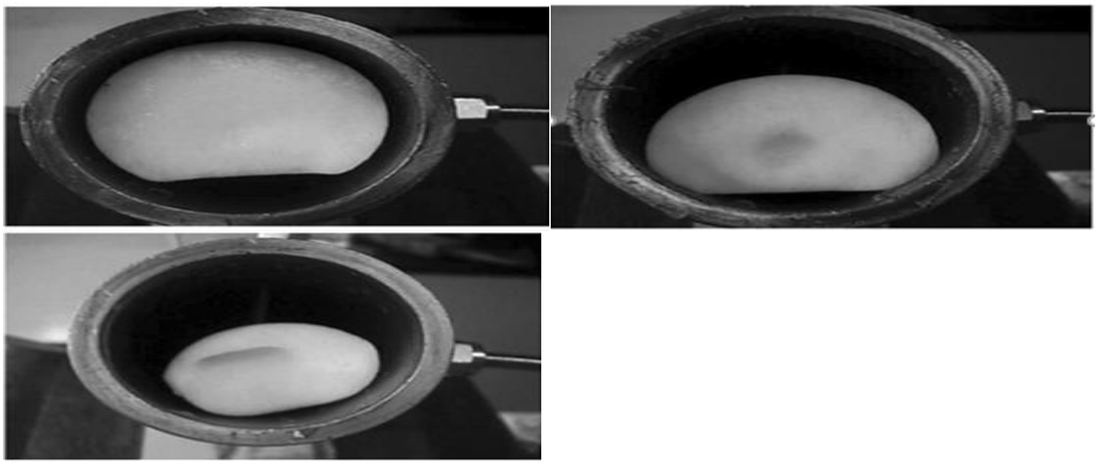

Figure 3. Hydrate dissociation by pressure reduction in descending order (a) 1h, (b) 2h, and (c) 3h [65]

Since the rate of change of temperature and size of the hydrate plug are slow after the pipeline pressure had been reduced, Kofoed [66, 71] model proposed quasi steady-state model (QSS) to simplify the transient model of Kelkar et al.64 and Peter,[62] without adversely affecting the predictive capabilities. QSS model streamlines the transient system into sub-systems, with the assumption that each sub-system is at steady-state. The main objective of the work was to obtain analytical solution to the numerical problem that was proposed by Peter [62]. The research concludes that the dissociation time predicted by the transient model are only satisfactory for hydrate dissociate temperatures just above and below the freezing point of water.

In 2010, Osokogwu [59], developed two-sided hydrate dissociation model, based on cubic-degree polynomial from Fourier laws of heat conduction. This study considered radial dissociation on a fixed boundary, which was programmed into PIPECLEAN software [59]. The research shows that it takes about 13 hours to dissociate a gas hydrate plugged production pipeline with a dissociation temperature and hydrate depth of penetration of approximately 295K and 32cm respectively. However, dissociation was reported to commence from a temperature of 285.7K and well above 13 hours duration to dissociate a pipeline that is plugged off by gas hydrate. The prediction model for dissociation temperature is as follows:

$$T_{(0,t)} = bT_a + C\frac{q_o\phi\gamma}{K\pi rL} \tag{9}$$

where $T_a$ is the initial temperature of the hydrate (K), $K$ thermal conductivity of the hydrate, $r$ is the radius, $\phi$ is the hydrate porosity, $L$ hydrate plug length, $C$ is a constant at point 1.22, $T_{(0,t)}$ is the temperature at the point dissociation commences, $q_o$ specified heat flux at the boundary surface. The hydrate penetration depth model (when to commence injection process for clean up of hydrate plug) proposed by Osokogwu [59] is given as:

$$\delta = C\frac{K\Delta T\phi\gamma}{q_o} \tag{10}$$

where $\delta$ is the penetration depth, other parameters are as noted in Equation (10). However, one major limitation of this work was the inability of the model to determine gas released during dissociation.

Additional research investigations on double sided dissociation of hydrate plugs in pipelines include Yousif [72] and Hong [73]. In Yousif [72] a 1-D moving boundary semi-infinite solution for linear and radial dissociation was developed. Yousif [72] also performed an experiment to validate the model. Yousif noted that depressurization method is a slow process when performed on low temperature and small pressure reduction. The study concluded that dissociation is heat and mass transfer controlled.

Hong [73] developed a numerical model in cylindrical coordinates based on enthalpy approach. Two modeling approaches were used, the first approach involved estimation of the quantity of hydrate during depressurization:

$$\psi = \frac{\Delta T(1-\varepsilon)\rho_H C_H + \varepsilon\rho_L C_L}{(1-\varepsilon)\left[\rho_H L_H + \Delta T(C_H\rho_H - C_L\rho_L)\right]} \tag{11}$$

Where $\psi$ is the mass fraction of dissociated hydrate during the depressurization, $\varepsilon$ is the porosity, $T$ is the temperature, $\rho_H$ density of hydrate, $C_H$ is heat capacity, $\rho_L$ density of liquid. Note subscript, H is hydrate, L is liquid. The second model used an enthalpy formulation to solve the problem of hydrate plugs dissociation. A differential equation describing the dissociation time (after depressurization) is given as:

$$\frac{\partial H}{\partial t} = K_L \left[ \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right] \qquad (12)$$

Where H is the enthalpy, $K$ is thermal conductivity, $T$ is temperature and $r$ is radial coordinate. The enthalpy model presented relates the numerical value of the enthalpy of the discretized equation at the nodes of the mesh to the position of boundary between solid and liquid phase. This research assumed that water formed from the dissociating hydrates occupies the external volume of the plug. In most cases, water release from dissociating hydrate plug may not be stationary.

## 3. Single Sided Depressurization Techniques

As descriptive as two-sided depressurization could be, in most industrial scenarios access to upstream end of the plug is restricted and it becomes unrealistic to reduce pressure from both sides. Therefore, single sided depressurization becomes the only viable option to be used [5, 74].

It was not until 2002 that Bollavaram [67] investigated one-sided depressurization for dissociation of hydrate plugs in pipelines. This study involved both experimental testing and numerical modeling. Bollavaram's model [67] split a hypothetical hydrate plug into sections and calculated the position of the hydrate and ice boundaries for each section based on local thermal equilibrium between the flow of gas and hydrate. The purpose of the study was to discover an optimal technique to depressurize a pipeline such that the hydrate plug will dissociate fastest and within a safety bound.

Also, in Bollavaram [67], a 1-D steady-state dissociation model, strength model and safety simulator model were developed as follows. The dissociation model with assumption of local thermal equilibrium is:

$$cpV_z \frac{\partial T}{\partial z} - \beta T_h V_z \left( \frac{\partial p}{\partial z} \right) = K_h \frac{\partial^2 T}{\partial z^2} \qquad [13]$$

Where $cp$ specific heat at constant pressure of the fluid, $T$ is the temperature, $k$ is the thermal conductivity, $\beta$ is the coefficient of volumetric thermal expansion, $V_z$ is the velocity in the axial direction and $p$ is pressure term. The velocity profile was modeled using Darcy's law, and the axial pressure profile in the upstream section was then modeled by assuming the downstream section was fixed. A combination of Darcy's law with the ideal gas equation was used to calculate the molar volume [65]. Figure 4 Illustrates the schematics of one-sided depressurization of hydrate plug in pipeline, the interphase dissociates both radially and axially.

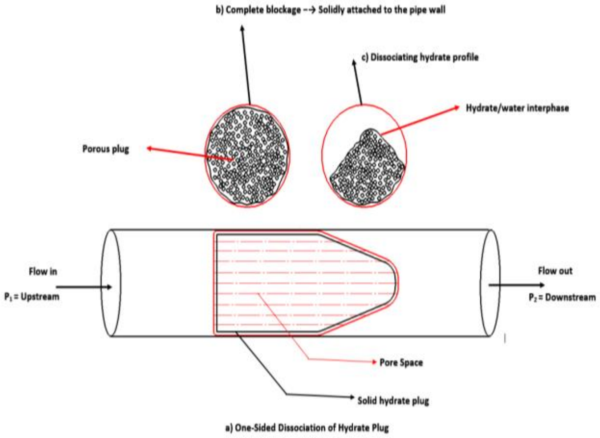

Figure 4. Schematic representation of single sided hydrate plug profile in pipeline

During dissociation, the source of energy to melt the hydrate plug comes from the surroundings and the pressure distribution across the plug is dependent on the permeability of the plug. Hence, pressure is not constant across the axial length of the plug and neither is temperature. Unlike the two-sided dissociation model, heat transfer by both convection and conduction was considered in axial direction (gas phase).

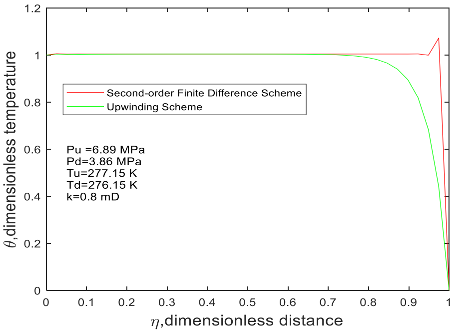

Figure 5. Upwind Scheme and Second order model for Equation 13 reproduced [67]

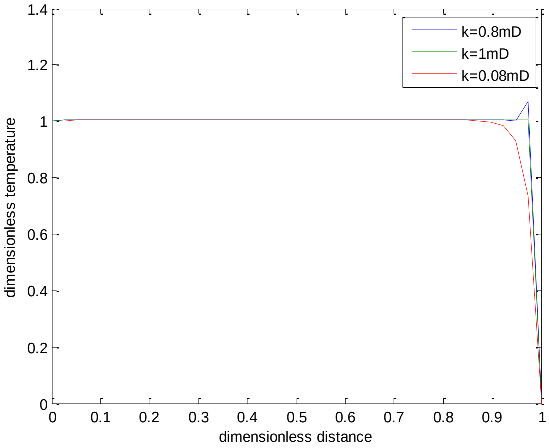

Figure 6. Second-order Finite Difference Solution for Temperature Distribution for Equation 13

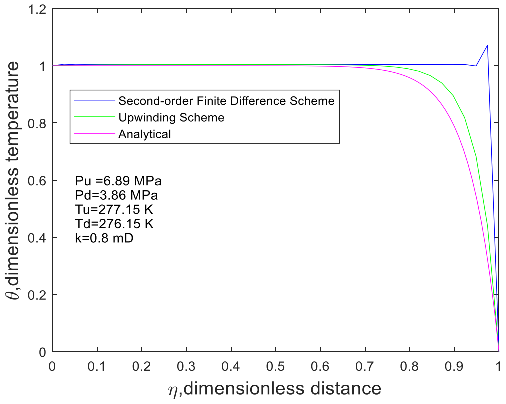

Figure 7. Temperature distribution profile Equation 13

In the single-sided depressurization model developed by Bollavaram [67], analytical solution was developed for the pressure profile and velocity profile as presented in Figure 8 and 9.

$$N = \frac{P_u}{P_d} \tag{14}$$

Where $P_u$ and $P_d$ defines the upstream pressure and downstream pressure respectively.

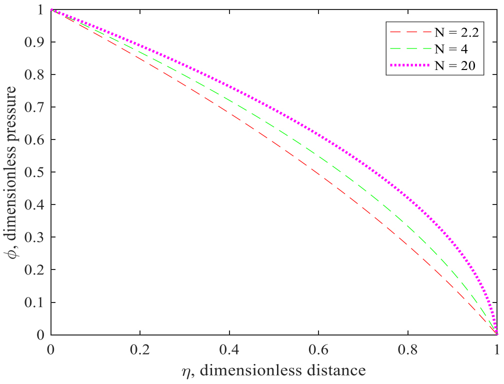

Figure 8. Dimensionless pressure distribution as a function of pressure ratio reproduced (The pressure distribution is a strong function of the pressure ratio N)

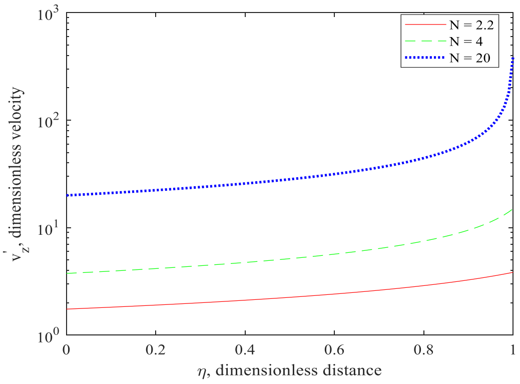

Figure 9. Dimensionless velocity as a function of dimensionless distance for three pressure ratios

The axial temperature profile was solved using two finite difference schemes implemented in CSMPlug software. In an effort to obtain data to validate the one-sided model and to compare Peter's model [63, 62], the following experiments were carried out – One sided depressurization, double sided depressurization and series of flow loop experiments. The results from the forced axial dissociation experiment indicates that axial dissociation is not the dominate factor for hydrate plug dissociation, this agrees with Peter's conclusion. Another finding from the forced axial experiment was that the data obtained supported the anomalous self-preservation of methane hydrates, which has been noted in a handful of independent studies [75-77]. Also, another key finding from Bollavaram studies is the effect of hydrate plug structural transition. Structure II hydrate takes about 30 percent longer to dissociate than sI hydrate plug [67]. Hydrate plugs structural transition had been reported to occur in natural gas pipeline [78]. Therefore, is of importance consideration for dissociation process. According to the study of Bollavaram [67]

According to the study of [67], the pipeline downstream pressure was reduced in a swift step-change. A slow step change as a function of time in the down pressure was not consider. Hence, it is unclear what difference this would have had in modeling hydrate plug dissociation. A maximum pressure range of 780 psig to 180 psig for upstream and downstream respectively were considered in the research. However, Berge et al [79] reported a pressure drop of 1000 psig (6.89 MPa).

## 4. Plug Detachment Prediction Model

An adhesive strength model was developed and implemented into a safety simulator, in order to find an optimal downstream pressure for operators to avoid pipeline rupture that would result from a detached hydrate plug. Bollavaram [67] attributed the driving force for plug movement to be pressure gradient between the upstream and downstream pressure.

$$F_{DP} = \left(P_u\left(t\right) - P_d\left(t\right)\pi r^2\right) \tag{15}$$

Where $F_{DP}$ is the pressure force, $P_u\left(t\right)$ and $P_d\left(t\right)$ are the upstream and downstream pressures at time $t$ and $r$ radius of the pipe. The simulator model was validated with Deep-Star Wyoming Field Trials reported by Xiao et al [80] using OLGA software.

One crucial factor that was left out of consideration is the effect of friction on hydrate plug movement. To what extent could frictional force impact on the speed of the moving plug remains a novel area to be investigated [80]. In the adhesive strength model the author [68] inferred that hydrate will detached and moves as a projectile when the adhesive force becomes weak compared to the pressure gradient force, the equations are given below.

$$F_{AD} = \tau_h(2\pi r L_c) \tag{16}$$

$$F_{DP} = \left(P_u - P_d\right)\pi r^2 \tag{17}$$

Where $F_{AD}$ is the adhesive force, $\tau_h$ is the adhesive strength of hydrate, $L_c$ is the contact length or undissociated part of the hydrate plug. Bondarev et al [81] gave the adhesive strength of hydrate on substrate pipes.

A major risk observed with this type of dissociation (one-sided depressurization) is that, energy flux is maximum at the pipe wall [82], it stands to reason that hydrate plugs at the outmost layer near the pipe wall dissociate first as a result projectile profile is formed in the pipeline, which is capable to cause serious incident when the plug detaches and rupture the pipeline [83-84]. Marcelo et al.[5,69] also investigated hydrate plug detachment during single sided depressurization and the safety implication. The model developed by Marcelo et al. [5, 69] was implemented as a finite volume transient simulator that determined the flow field coupled with the plug displacement dynamics after its detachment.

Some number of field trials have been performed to dissociate hydrate plugs in pipeline using depressurization method. Statoil in 1994 purposely formed and dissociated 17 hydrate plugs in 6" gas condensate line in the North Sea Tommeliten field [85]. Two were remediated through one-sided depressurization method. Davalath [86] provided update on 16 hydrate plug compilation for Deepstar IIA (A208-1, 1996). In February 1997, Kerr McGee performed field trial for hydrate plugs formation and there after dissociated the plugs, this was reported by SwRI as documented in [87]. One-sided depressurization method was used, and the plug velocity was reported to be as high as 82 m/s. Also, field trial experiment was performed by British Petroleum as documented in Corrigan et al. [88].

## 5. Challenges for Future Studies

Here are some challenges that could be difficult issues in gas hydrate plug remediation but do need further studies. Effects of friction was reported for plug detachment prediction model, hence it's worthwhile to investigate plug-fluid interaction and the analysis of such interaction on hydrate plugs remediation. This could be challenging to model, but the surmountable findings will advance hydrate dissociation knowledge. It important to verify existing one-sided depressurization numerical models on flow loop plugs. Additionally, no comprehensive model exists for 2-D dissociation modeling of hydrate plugs in pipelines that involve single-sided remediation. A single coupled equation with a moving boundary concept is worthy of investigation. This is anticipated to provide an improved representation of the physics involved in of single-sided depressurization techniques.

## 6. Conclusion

In most industrial scenarios involving hydrate plugs, access to the upstream end of the plug is restricted. One sided depressurization is most practical option to remediate hydrate plug. A careful risk analysis should be performed to avert projectile motion of plug during single sided depressurization. For hydrated blockage with unrestricted access to both ends, double sided decomposition is recommended. It stands to reason that the safety concern will be minimized if not eliminated. Radial dissociation is faster than linear dissociation.

A combination of techniques could be an alternative option to remediate hydrate plugs, if a pressure reduction approach is inadequate. However, its recommended that the strategies to be adopted should be fully analysed to obtain information on porosity and permeability of the plug. These maybe key factors to successfully dissociate hydrate plugs. The length of plug is not essential consideration for two-sided depressurization.

It's inherently known that during direct heating method, the risk of over-heating the flowline is a major concern. Hence, it is recommended that more experiment work be performed to establish how realistic is the safety of this techniques without impinging on huge design and installation cost. The importance of more experimental data to further verify one sided depressurization, especially the flow loop experiment cannot be over emphasized.

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