Petroleum and Coal

Analytical Modelling of Thermal Gas Hydrate Dissociation in Horizontal Pipelines

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Abstract

In this work, an analytical model describing thermal gas hydrate plug dissociation in horizontal natural gas pipelines has been developed. This was done by carrying out an energy balance on infinitesimal gas hydrate plug elements in cylindrical coordinates. Some of the assumptions used include that heat transfer was the dominant dissociation mechanism at play and heat was conducted through the hydrate plug by conduction in the redial direction only. In the end, it was ascertained that gas hydrate percentage dissociation was directly proportional to the quantity of heat needed to dissociate it. Also, dissociation depth was inversely proportional to quantity of heat needed to dissociate a gas hydrate plug. In addition, there exists a direct proportionality between gas hydrate plug length and the quantity of heat needed to dissociate it. And the difference between hydrate surface and inner temperatures of gas hydrate plugs varies directly with the quantity of heat needed to dissociate them. The model had a hydrate plug dissociation heat energy requirement per unit length of 101.87W/m when compared with data from Polarrev field direct electrical heating (DEH) installation in Norway which had a hydrate plug dissociation heat energy requirement per unit length of 96.4W/m, with an average error percentage of 4.55%.

Keywords: *Gas Hydrates; Modelling; Natural Gas; Hydrate dissociation; Pipelines.*

1. Introduction

Gas hydrates also referred to as clathrate hydrates exist as ice-like crystalline structures at low temperature and high pressure; they are composed of low molecular weight gas molecules encapsulated by molecules of water [1]. They are usually formed in different fundamental structures such as Structure I (sI), Structure II (sII) and Structure H (sH) [2]. Presence of natural gas hydrates (NGH) in pipelines and wellbores constitutes flow assurance problems offshore and impede proper operation of process facilities onshore [3] through formation hydrate plugs. In addition, release of methane from NGH presents dire environmental degradation problems as its global warming effect is 21 times higher than carbon (IV) oxide [4]. However, presence of huge deposits of NGH also presents a clean and abundant energy source to ever increasing global energy demand; this can be attributed to the wide range of distribution of NGH, their existence at shallow depth, huge reserves, high energy density and low environmental polluting components during combustion [5]. Therefore, this necessitates the need to produce NGH from environments such as continental margins located between 300 – 500m water depth and permafrost regions to meet the world's growing energy needs and facilitate environmental sustainability – successful NGH deposits production pilot tests have been carried out in countries such as China and Japan. Consequently, dissociation for NGH becomes imperative for improved process efficiency or as a source of primary energy.

Different methods such as depressurization, thermal stimulation and chemical/inhibitor injection have been independently or jointly applied for disintegration/dissociation of NGH [4]; these dissociation methods are usually based on disturbance of the thermal equilibrium

curve of NGH as shown in [1]. Hydrate dissociation methods are endothermic based processes therefore, involve use of an external source of energy for facilitation of the disintegration process. On the other hand, depressurization involves reduction of pressure of the guest-host molecule system/reservoir through supply of heat energy to hydrate bearing sediments which results in liberation of free gas and reduction in the pressure and temperature of the system; subsequently, this results in destabilization of the hydrate system. Furthermore, inhibitor injection involves use of chemicals [such as Thermodynamic Inhibitor (THI) and Low Density Hydrate Inhibitors - Kinetic Hydrate Inhibitor (KHI) and Anti-Agglomeration] into the reservoir of process systems so to prevent of hydrates – THI shifts hydrate phase equilibrium to regions of higher pressures at specific temperatures or low temperatures at specific pressures, KHI reduce nucleation and formation of hydrates without shifting phase equilibrium of hydrates while anti-agglomerants prevents agglomeration of hydrate crystals into larger sizes [3-4]. Finally, thermal stimulation entails heat transfer to the hydrate system/reservoir so as to destabilize and facilitate kinetic dissociation of the guest-host molecule system which consequently increases the pressure-temperature condition of the system.

1.1. Hydrate dissociation kinetic models

Amongst these hydrate dissociation methods, depressurization and inhibitor injection are the most applied commercially and industrially [2,4]. Hence, different theoretical, numerical and analytical models and simulation studies have been carried out on these hydrate dissociation methods. Notably, theoretical solutions are derived in the absence of semi-empirical data, numerical solutions apply method of discretization to solving differential equations – numerical solutions are usually affected by space and time while analytical solutions are provide closed-form of solutions when they are applied to solve hydrate dissociation modelling differential equations [5]. These kinetic models which relate hydrate dissociation of NGH to time provide advantages in two ways; they are (i) facilitate increased rate of formation of NGH especially in energy storage applications (ii) inhibit formation of hydrate plugs in flow systems during natural gas production and transportation. However, analytical solutions derived for modelling hydrate dissociation would be briefly discussed in this section.

Selim and Sloan [6] developed a mathematical model for hydrate dissociation under thermal stimulation. Their model assumed the decomposition of a pure hydrate block using a constant heat flux employed on a planar semi-infinite medium with constant physical properties. With the critical assumption that water formed during the dissociation process was blown away by the gas, the dissociation process was treated as a moving-boundary ablation problem and there would be no liquid phase over the dissociation surface. Based on their own model, Selim and Sloan extended the mathematical model to describe hydrate dissociation under thermal stimulation in porous media. The model viewed the dissociation as a process whereby gas and water were produced at a moving boundary. This boundary separated the dissociated zone (containing gas and water) from the un-dissociated zone (containing hydrate). One major assumption of the model is that water remained motionless within the pores of the dissociated zone. This assumption limited the model analysis to hydrate saturation values of about 0.3. Besides, the thermo-physical properties of each phase were assumed to be constant. Viscous dissipation, reversible work of compression, inertial effects and the possibility of mutual or external energy transmission were all neglected for simplicity. Kim *et al.* [7] conducted experiments to study the kinetics of methane hydrate decomposition using a semi-batch stirred-tank reactor and proposed a mathematical model to simulate hydrate decomposition. Hydrate decomposition was accomplished by reducing the pressure on hydrate slurry in water isothermally. The proposed model correlated the decomposition rate with hydrate particle surface area and the difference in fugacity of methane at equilibrium pressure and the decomposition pressure. Tsypkin [8] suggested a complete system of equations to correlate the phenomena of heat and mass transfer with gas hydrate dissociation. The formulation of the model allowed the existence of hydrate dissociation and phase transition fronts. The advantage of this model is that by including the moving boundary, it allows the formation of an extended dissociation zone or formation of an ice-gas region

located between hydrate dissociation and ice melting fronts when describing the dissociation process, which most numerical and analytical models may not account for.

Makogon [9] published his model of hydrate decomposition in porous medium during depressurization. In this work, Makogon described that the decomposition of hydrates in porous medium happened in a certain narrow zone which was treated as a surface, rather than the whole volume. However, it was believed that the rate of hydrate decomposition was determined by the movement of the decomposition front, but not by the kinetics of the process, which is controversial to the intrinsic kinetic model proposed by Kim *et al.* [7]. The movement of the front depends on the magnitude of heat flow through it and on the specific heat of hydrate formation. Thus, Makogon [9] first addressed the problem of hydrate decomposition by a pressure decrease using an analogy of the classical Stefan's problem for melting with a self-similar solution obtained after linearization of equations of the gas filtration. Hong *et al.* [10] presented a simple analytical model to simulate gas production from hydrate decomposition in porous media by depressurization method. Heat transfer to the decomposing zone, intrinsic kinetics of hydrate decomposition and gas-water two-phase flow were considered as the three primary mechanisms involved during hydrate decomposition in porous media. In the study, the decomposition rates controlled by heat transfer, intrinsic kinetics and by fluid flow were quantified respectively to determine which of these mechanisms was the rate controlling steps in realistic range of physical properties of hydrate reservoir.

A critical review of these studies reveals that there is scarce literature for analytical modelling of gas hydrate dissociation in horizontal gas wells. In this intent, this paper aims to derive an analytical model for evaluation of gas hydrate dissociation in horizontal natural gas pipelines when exposed to heat until steady state is achieved. Though it is assumed in line literature that hydrate dissociation is controlled by intrinsic kinetics when dissociation rate is small compared to the rate of heat transfer rate and that kinetics is negligible or intrinsic kinetics is extremely fast when interface fugacity becomes nearly equal to equilibrium fugacity [6]. Also, it is postulated that dissociation is controlled by heat transfer hence; heat transfer equation was employed to determine the dissociation rate of the hydrate plug. In addition, hydrate plug is assumed to attain extremely fast interface temperature. Even though the gas phase has a much higher resistance than the liquid phase, it was generally assumed that heat absorbed by the dissociating hydrate at the hydrate-water interface is conducted only through the water from the pipe wall.

2.1. Methodology

Since gas hydrates dissociation is controlled basically by heat conduction in pipes, the starting point for the model was Fourier's heat conduction in cylindrical co-ordinates. Then the physical realities of the system were then imposed on the derived equation in order to better represent the condition being modeled. These imposed realities were also valid assumptions taken in order to make an analytical solution to the model possible. For example, the first assumption taken was that heat conduction is only in the radial direction. This assumption is valid since heat is conducted primarily through the pipe wall, and considering the geometry a greater percentage of heat is carried in the radial direction.

Also, another assumption was that the system operates under steady state heat conduction. This assumption typifies gas hydrates dissociation by thermal treatment where heat is supplied to a gas hydrates system using different sources of heat like microwave, electrical heating etc. In addition, in order to achieve maximum gas hydrates dissociation effects, the source of heat is sustained for long periods until target dissociation is achieved, which approximates to steady state heat conduction. Another assumption is that at the gas hydrates completely blocked a perfectly cylindrical pipe section. Therefore, gas hydrates dissociation in partial pipe blockage situations might not be satisfactorily explained by the gas hydrates dissociation model presented here.

Above all, heat conduction through the gas hydrate plugs are only by conduction. There was no significant heat transfer by convection or radiation. And the gas hydrates parameter values used for this study were from Osokogwu and Ajienka [11].

2.2. Model development

Assuming heat conduction in gas hydrate plug is only by conduction; Fourier's heat conduction equation in cylindrical coordinates shown in Fig. 2 is given by:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\left(\frac{\partial T}{\partial r}\right) \qquad (1)$$

Considering heat conduction in the radial direction only, the above equation can further be simplified to:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\dot{q}}{k} = \frac{1}{\alpha}\left(\frac{\partial T}{\partial r}\right) \qquad (2)$$

Assuming steady state heat conduction,

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = -\frac{\dot{q}}{k}; \qquad \frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = -\frac{\dot{q}}{k}r \qquad (3)$$

On integrating the equation above:

$$r\frac{\partial T}{\partial r} = -\frac{\dot{q}}{2k}r^2 + C_1; \qquad \frac{\partial T}{\partial r} = -\frac{\dot{q}}{2k}r + \frac{C_1}{r} \qquad T = -\frac{\dot{q}}{4k}r^2 + C_1 lnr + C_2 \quad (4)$$

Considering the following initial and boundary conditions: at r = 0, T = T_i and when r = π, T = T_s

$$C_1 = \frac{1}{ln\varpi}\left(T_s - T_i + \frac{\varpi^2}{4k}\right)T_s; \text{ and } C_2 = T_i \qquad (5)$$

Inserting back C_1 and C_2 into the equation,

$$T = -\frac{\dot{q}}{4k}r^2 + \frac{1}{ln\varpi}\left(T_s - T_i + \frac{\varpi^2}{4k}\right)lnr + T_i \qquad (6)$$

Making $\dot{q}$ the subject,

$$\frac{\dot{q}}{4k}r^2 = \frac{1}{ln\varpi}\left(T_s - T_i + \frac{\varpi^2}{4k}\right)lnr + T_i - T \qquad (7)$$

$$\dot{q} = \frac{4k}{r^2}\left[\frac{lnr}{ln\varpi}\left(T_s - T_i + \frac{\varpi^2}{4k}\right) + T_i - T\right]; \text{ but,} \qquad (8)$$

$$Q = \dot{q} \times V; \qquad Q = \dot{q} \times \pi r^2 L \qquad (9)$$

Total quantity of heat,

$$Q = 4\pi kL\left[\frac{lnr}{ln\varpi}\left(T_s - T_i + \frac{\varpi^2}{4k}\right) + T_i - T\right] \qquad (10)$$

Assuming gas hydrates surface temperature is always equal initial surface temperature during dissociation,

$$Q = 4\pi kL\left[\frac{lnr}{ln\varpi}\left(\Delta T + \frac{\varpi^2}{4k}\right) - \Delta T\right] \qquad (11)$$

To ensure calculated total heat supplied (Q) values are positive,

$$-Q = 4\pi kL\left[\frac{lnr}{ln\varpi}\left(\Delta T - \frac{\varpi^2}{4k}\right) + \Delta T\right] \qquad (12)$$

where: Q = total quantity of heat supplied (W); k = thermal conductivity (W/m.K); r = pipeline radius (m); L = pipeline length (m); T_s = hydrates surface temperature (°C); T_i = temperature at the core of gas hydrate plug (°C); ϖ = gas hydrates dissociation depth (m); ΔT = temperature difference between gas hydrates core and surface (K); V= gas hydrates volume.

2.2.1. Percentage dissociation

In order to ascertain the efficiency of hydrate dissociation, a measure of dissociated quantity of gas hydrates compared to the initial quantity is needed. A good measure of this parameter can be gotten using the percentage hydrates dissociation. Percentage dissociation used in this study was gotten from the following formula:

$$\% \text{ } dissociation = \left[\frac{initial - current \text{ } hydrate \text{ } plug \text{ } radius}{initial \text{ } hydrate \text{ } plug \text{ } radius}\right] \times 100 \qquad (13)$$

3. Results and discussion

In the study, results show variation of heat supplied with percentage dissociation for hydrate plugs of different lengths at various radii. Herein, it can be deduced that the gas hydrate percentage dissociation is directly proportional to the quantity of heat needed to dissociate it. What this means is that as the target or desired gas hydrate dissociation percentage increases, so will the quantity of heat needed to dissociate it. This agrees with expected reality in that if higher gas hydrates dissociation is needed, then the higher the quantity of heat needed to raise the temperature of the gas hydrate plug higher enough to exit the gas

hydrate formation zone. This scenario is shown graphically in Figures 1 - 3, where the positive slopes of the straight lines in each graph clearly depict direct proportionality between percentage and quantity of heat needed for dissociating hydrate plugs in gas pipelines.
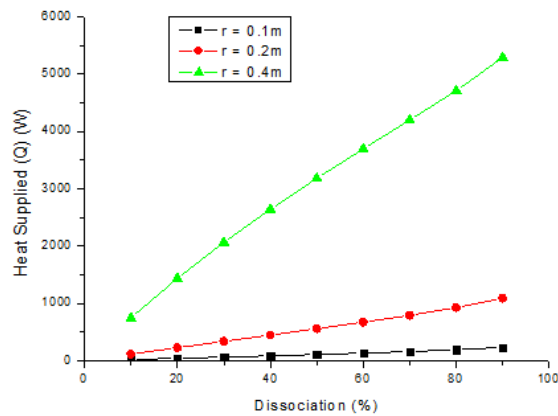

Fig. 1. Variation of heat supplied with percentage dissociation for a 50m hydrate plug at various radii
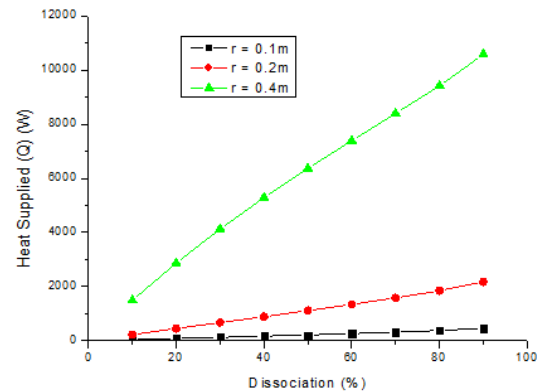

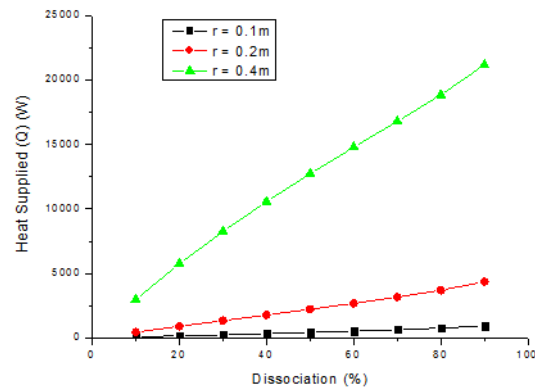Fig. 2. Variation of heat supplied with percentage dissociation for a 100m hydrate plug at various radii

Fig. 3. Variation of heat supplied with percentage dissociation for a 200m hydrate plug at various radii
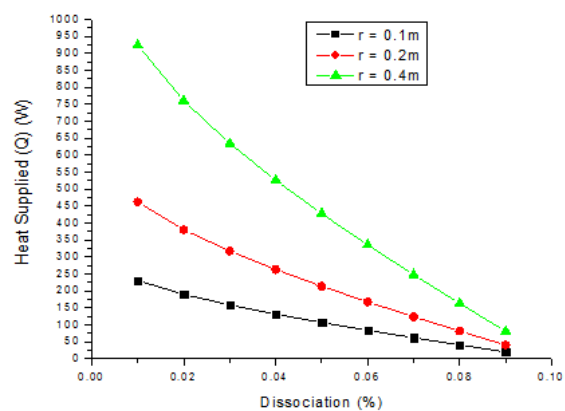

Fig. 4. Variation of heat supplied with dissociation depth for 0.1m hydrate plug radius at various lengths

In addition, results show variation of heat supplied with dissociation depth for different hydrate plug radii at varying lengths. Also, it is clear that dissociation depth is inversely proportional to quantity of heat needed to dissociate a gas hydrate plug. Hence, this means that as gas hydrate dissociation depth is increasing, the quantity of heat needed to dissociate it will be decreasing correspondingly. This phenomenon perfectly agrees with practical experience, because dissociated depth as used in this study measures the radius of the remaining gas hydrate plug after dissociation has started. Therefore, this parameter tends to decrease as dissociation increase, which explains the inverse proportionality between the parameter and quantity of heat needed for gas hydrate dissociation. This was captured graphically in Figures 4 - 6.

Similarly, results show the variation of heat supplied with hydrate plug length at various hydrate plug radii. Herein, it can be seen that there exists a direct proportionality between gas hydrate plug length and the quantity of heat needed to dissociate it. This signifies that as gas hydrate plug length is decreasing, so will the quantity of needed to dissociate correspondingly decrease. Consequently, this behavior however agrees with expected reality, since longer gas hydrate plugs implies larger gas hydrate volume. It is only natural that a higher quantity of heat be needed to dissociate it, compared to hydrate plugs of smaller

lengths. Also, this behavior was aptly depicted in Figure 7, which shows positive slopes of the straight lines in the graph clearly shows direct proportionality.
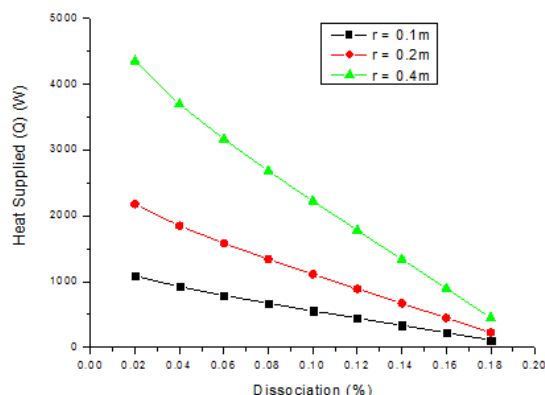

Fig. 5. Variation of heat supplied with dissociation depth for 0.2m hydrate plug radius at various lengths
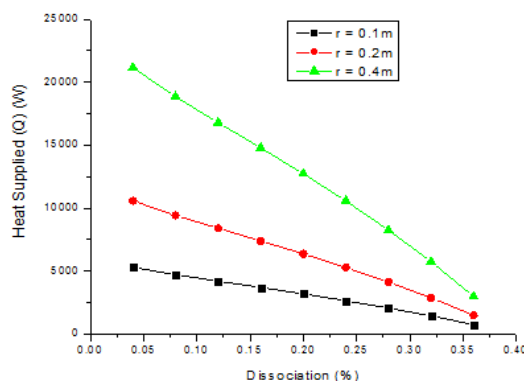

Fig. 6. Variation of heat supplied with dissociation depth for 0.4m hydrate plug radius at various lengths
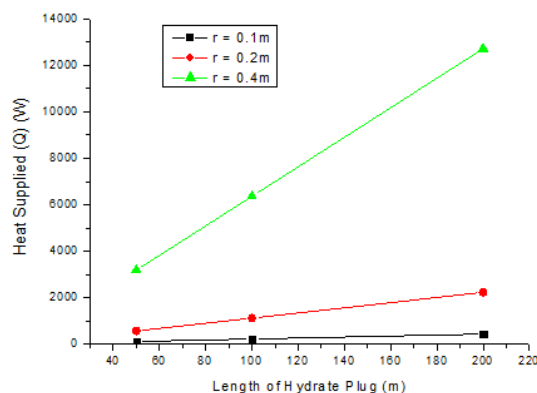

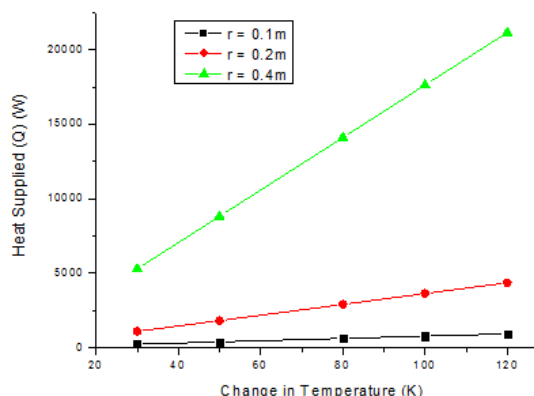Fig. 7. Variation of heat supplied with hydrate plug length at various radii

Fig. 8. Variation of heat supplied with difference between hydrate surface and core temperatures at various hydrate plug radii

Also, results show the variation of heat supplied with difference between hydrate surface and core temperatures at various hydrate plug radii. In addition, it is conspicuous that the difference between hydrate surface and core temperatures of gas hydrate plugs varies directly with the quantity of heat needed to dissociate them. This implies that as the difference between hydrate surface and core temperatures of gas hydrate plugs is increasing, so do the quantity of heat needed to dissociate the gas hydrate plugs. This behavior can be explained by the fact that higher difference hydrate surface and core temperatures lower both lower gas hydrate plug core temperatures and larger hydrate plug diameter. Hence, increasingly higher quantities of heat will be needed in order to dissociate the hydrate plugs. This behavior was represented graphically in Figure 8 for various hydrate plug radii. Similarly, the curve for each radius is actually a straight line sloping upwards. This signifies positive slopes, which thereby confirms the direct proportionality between hydrate surface and core temperatures of gas hydrate plugs and the quantity of heat needed to dissociate them. Furthermore, Figure 9 shows comparison of developed model with direct electrical heating (DEH) hydrates dissociation installations of some fields in Norway. From the Figure 9, it is obvious that the power rating of Polarrev field in offshore Norway closely matches the predictions of the developed model but the power rating of Kristin field was much higher. This can be explained by the remarkable differences between Polarrev and Kristin fields.

From the foregoing discussion, it is obvious that the model developed satisfactorily explains gas hydrate dissociation using thermal energy as provided by heat sources like microwave, electrical heaters etc. Hence, as long as it used for the prescribed conditions, it can be utilized with reasonable confidence.
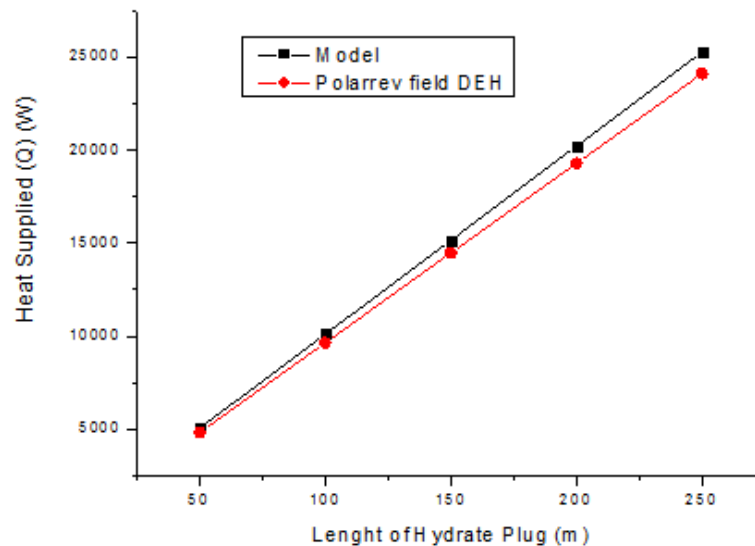

Fig. 9. Comparison of developed model with direct electrical heating hydrates dissociation ratings of Polarrev field DEH installation in Norway

4. Conclusion

Gas hydrate percentage dissociation is directly proportional to the quantity of heat needed to dissociate it. Hence, as the target or desired gas hydrate dissociation percentage increases, so will the quantity of heat needed to dissociate it.

Dissociation depth is inversely proportional to quantity of heat needed to dissociate a gas hydrate plug. Therefore, as gas hydrate dissociation depth is increasing, the quantity of heat needed to dissociate it will be decreasing correspondingly.

There exists a direct proportionality between gas hydrate plug length and the quantity of heat needed to dissociate it. This signifies that as gas hydrate plug length is decreasing, so will the quantity of needed to dissociate correspondingly decrease.

The difference between hydrate surface and inner temperatures of gas hydrate plugs varies directly with the quantity of heat needed to dissociate them. This implies that as the difference between hydrate surface and inner temperatures of gas hydrate plugs is increasing, so do the quantity of heat needed to dissociate the gas hydrate plugs.

Conflicts of interest

The authors do not declare any conflict of interest

Authors' contributions

Oghenegare Emmanuel Eyankware: Conceptualization, Formal Analysis, Methodology, Validation, Visualization and Writing – Original Draft Preparation. Henry Onokpasa Akpovi: Conceptualization & Formal Analysis. Idaereesoari Harriet Ateke: Writing – Review & Editing

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