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A. Yu. Dreus[1],
orcid.org/0000-0003-0598-9287,
O. I. Gubin[1],
orcid.org/0000-0001-5165-2226,
V. I. Bondarenko[2],
orcid.org/0000-0001-7552-0236,
Baochang Liu[3],
orcid.org/0000-0002-0185-3684,
V. I. Batuta[1],
orcid.org/0000-0001-8351-1751

1 – Oles Honchar Dnipro National University, Dnipro, Ukraine
2 – Dnipro University of Technology, Dnipro, Ukraine, e-mail: v_domna@yahoo.com
3 – College of Construction Engineering of Jilin University, Changchun, the People's Republic of China

NUMERICAL STUDY OF MICROWAVE IMPACT ON GAS HYDRATE PLUGS IN A PIPELINE

Purpose. Development of a technique for the numerical study on the decomposition of gas hydrate plugs in deep-water pipelines under microwave radiation using a coaxial source. Theoretical efficiency evaluation of using such an impact to unblock the pipelines.

Methodology. Mathematical modeling and computational experiment.

Findings. An original mathematical model is proposed to describe heat transfer processes during the decomposition of gas hydrates in a pipeline under the action of heat sources distributed over the volume. The non-stationary problem of heat transfer was considered in a one-dimensional formulation. An algorithm for numerical computation is proposed. A mathematical expression is obtained for distributed heat sources generated by the microwave radiation from a coaxially located SHF antenna. Parametric numerical studies on temperature fields and decomposition dynamics of a gas hydrate plug are performed for specified parameters of pipe and microwave radiation power. The boundaries of the decomposition area and the dynamics of change in this area are determined. The decomposition time of a gas hydrate plug with a diameter of 0.3 m was determined using a 300 W microwave source. The complete decomposition took approximately 40 hours.

Originality. The task of thermal decomposition of a cylindrical gas hydrate plug in a pipeline due to microwave heating using a coaxial microwave power source has been considered for the first time. The process is viewed as a sequence of several stages: heating, heating and decomposition, decomposition after complete heating of the gas hydrate layer. To model the volumetric dissociation of gas hydrate, it was proposed to use special functions that characterize the amount of decomposed gas hydrate. The introduction of such functions makes it possible to construct an efficient computational algorithm taking into account the action of volumetric sources in the decomposition area. The known models mainly consider only surface thermal effect or microwave impact on gas hydrate in porous mediums. The presented model allows describing the decomposition during volumetric heating of a solid hydrate adequately.

Practical value. Blocking plugs may occur due to hydrate formation when transporting gas through deep-water pipelines or through pipelines in cold environments. The elimination of such complications is a complex technical task. In particular, a special source of microwave radiation, which was proposed by the authors in previous works, can be used to unblock the pipeline. The device that makes the microwave radiation is located along the pipe axis. The results of this work allow us to evaluate the effectiveness of the microwave method for eliminating the gas hydrate plug. The mathematical model and computational method can be used in the development of appropriate technologies using a coaxial microwave heating source.

Keywords: *gas hydrates, pipeline blockage, microwave radiation, mathematical modeling, heat transfer*

Introduction. Currently, there is a growing interest in the development of natural deposits of gas hydrates, which represent significant energy reserves, all over the world [1]. Promising offshore deposits of gas hydrates are located, for example, in the waters of the Black Sea [2] and The South China Sea [3]. The development of such natural gas reserves is usually carried out by dissociating the hydrate into gas and water, followed by transportation of the gas through pipelines. It is known [4] that at great depths the thermodynamic conditions are rather complicated. One of the common complications during gas transportation through underwater pipelines is the reverse phase transition of gas into a hydrate form, resulting in a plug and channel blockage [5]. In winter similar problems arise in main pipelines located in regions with a cold climate [6], as well as in deep-water gas wells [7], which creates risks for operational safety.

To solve this problem, various technologies are used: the use of chemical inhibitors [8], pressure reduction in the pipeline [9], thermal and mechanical impact [10], the usage of acoustic, and radiation fields [11], and other physical fields [12]. The authors of [13] propose electric heating of hydrate-bearing deposits using direct currents or a high-voltage pulse discharge. Similar technologies are used in the oil and gas industry to reduce the viscosity of heavy oil and increase the efficiency of its transportation through pipelines [14]. Chemical inhibitors are the most used to remove gas hydrate plugs [15].

As shown in [16], one of the promising methods for influencing gas hydrates in order to decompose them is electromagnetic impact. SHF waves are a highly efficient source of thermal energy that ensures a stable dissociation process. The work [17] considers the use of microwave radiation for the development of natural deposits of gas hydrates. Numerical modeling is used as a tool for studying physical processes.

The possibility of using SHF waves to eliminate gas hydrate plugs in wells is considered in [18]. Moreover, casing pipes can be used as a waveguide. A similar approach can be applied to gas pipelines. However, in some cases, it is advisable to use an internal source of electromagnetic radiation to remove the resulting gas hydrate deposits. For example, in [19], a design of a microwave radiator was proposed for combating gas hydrate plugs in pipelines that transport gas. The proposed design uses a microwave radiator, which is coaxially located on the pipe axis. A review of the literature shows that usage of a coaxial radiation antenna for the decomposition of gas hydrates in pipelines is a new challenge. However, such devices

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are widely used in related areas, for example, to remove gas condensate [20]. Determining the effective parameters of the decomposition method of gas hydrates in pipelines requires the study on temperature fields, which are determined by the distribution of heat sources. This task can be solved with the help of mathematical modeling methods.

The purpose of this work is to develop a mathematical model for the decomposition of gas hydrate plugs under microwave radiation using a coaxial radiator and to theoretically evaluate the effectiveness of this method for unblocking. To achieve the purpose, the following tasks are formulated:

- to analyze modern computational approaches to modeling the processes of thermal decomposition of gas hydrates and justify the choice of a mathematical model for research;
- to develop a mathematical model for determining the power of volumetric heat release during microwave radiation using a coaxial energy source;
- to develop a mathematical model of thermal decomposition of gas hydrate in a pipe under the microwave radiation;
- to perform parametric numerical studies on temperature fields and temporal characteristics of the decomposition of the gas hydrate plug for specified geometric parameters of the pipeline and the power of the radiator.

Problem overview. The blocking of channels due to the formation of gas hydrates is the subject of a fairly large number of studies. The current state of the issue of such studies is given in [21]. Numerical methods are an effective tool for the theoretical study on heat and mass transfer processes during the dissociation of gas hydrates [22]. Currently, there are a large number of developed mathematical models that describe the processes of formation and decomposition of gas hydrates, from simple analytical solutions [23] to complex numerical multiphase models [24], for the implementation of which commercial CFD (Computer Fluid Dynamic) programs are used.

Simulation of electromagnetic impact on gas hydrates is characterized by a more complex problem statement than in case of traditional surface heating. The complexity of the statement is connected, first of all, with the need to solve the electromagnetic problem together with the problem of heat and mass transfer in a multiphase medium. In this regard, most of these formulations use a number of physical assumptions that allow us to simplify the physical and mathematical models. The main works in this direction are devoted to the problems of electromagnetic impact on porous hydrate-bearing rocks in order to extract gas.

CFD modeling of electromagnetic impact on porous hydrate-bearing rocks around the well was performed in [25]. In this model, the pipe is used as a cylindrical waveguide to provide electromagnetic radiation. When high-frequency electromagnetic radiation interacts with the gas hydrate medium, part of the microwave energy is converted into heat. Thus, there are thermal sources distributed over the volume, which can initiate the decomposition of the gas hydrate. The issues of modeling a volumetric source of heat release are considered.

Most natural deposits of gas hydrates are porous media. The study [26] simulated the processes of microwave impact on gas hydrates in a porous medium. The authors show that when decomposing gas hydrates in a porous body, it is necessary to use models with three characteristic zones: two homogeneous zones of a completely decomposed and completely integral gas hydrate, and a zone of phase transformation. This statement is due to the fact that during the development of productive formations there are long heating time periods. In this case, the width of the phase transition zone becomes much larger than the characteristic length of the electromagnetic radiation absorption region. At the same time, when considering the decomposition processes of gas hydrates in pipelines, the time scales are much less than when heating the formations.

In case of surface heating of gas hydrates, the assumption that the phase transformation happens on a surface of zero thickness is used more often. Mathematical models of such processes are based on the classical Stefan problem [27] and special numerical methods for its solution [28]. In particular, such a mathematical approach was applied to the problem of the formation of gas hydrates in [29]. However, the electromagnetic effect on gas hydrates is manifested as the action of volumetric heat sources. In this case, the usage of the Stefan model is not always justified. Thus, there is a need to model the distributed volumetric heat release and the laws of motion of the phase transition boundaries. This paper presents an approach to modeling the decomposition of a gas hydrate plug in a pipeline using a coaxial source of microwave radiation.

Problem statement. Let us consider the problem of microwave heating of a cylindrical plug of gas hydrate in a pipeline with radius R_2 when the radiation source is located coaxially on the pipe axis. Let us assume that thermodynamic conditions contribute to forming a hydrate plug at a certain section of the gas pipeline. To remove the plug, a microwave radiator is supplied, as shown in Fig. 1.

We will consider the problem under constant pressure. It is assumed that there is a zone free from gas hydrate on the pipe axis at the initial moment of time, where the radiation source is located. We will neglect the change in the electromagnetic and thermal characteristics of the gas hydrate. Thus, the model is limited only to electromagnetic and heat exchange processes. When the dissociation temperature is reached at some point, a region, in which the decomposition takes place directly, is beginning to form in the gas hydrate layer. The dimensions of this region change throughout the process.

The design scheme is presented in Fig. 2.

The thickness of the gas hydrate layer is h. From an electrodynamic point of view, a gas hydrate is a non-magnetic lossy dielectric characterized by a complex permittivity. The electrical properties of gas hydrates are well studied [30]. The power of internal heat sources arising in an undecomposed hy-

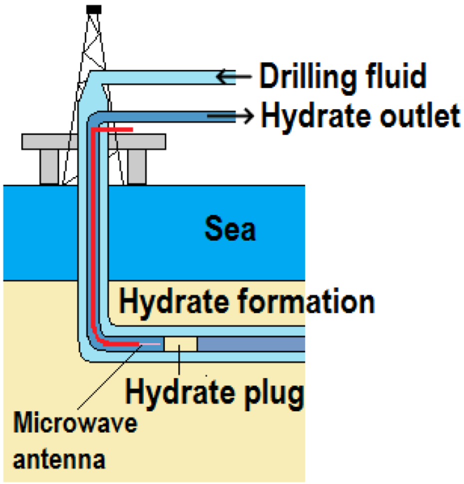

Fig. 1. Problem statement scheme

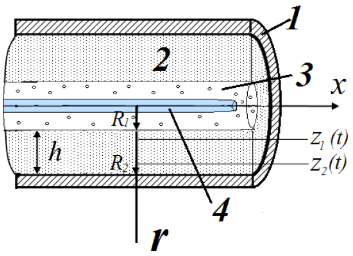

Fig. 2. Mathematical model scheme:

1 – pipe; 2 – gas hydrate layer; 3 – zone of homogeneous fully decomposed hydrate; 4 – microwave antenna drate due to the action of microwave waves is determined in accordance with the following expression [17]

$$q_v = \frac{1}{2}\pi f \varepsilon_0 \varepsilon' \left|E\right|^2 \tan\delta, \tag{1}$$

where f is the frequency; ε_0 is the electrical constant; ε' is the relative permittivity of the gas hydrate; $\tan\delta$ is the dielectric loss tangent; E is the complex amplitude of the radial component of the electric field intensity. Thus, to determine the heat release power, it is necessary to solve the problem of EM wave propagation in a multilayer dielectric medium. In the general case, such a task of the propagation of an EM wave in an inhomogeneous medium is rather complicated. In the case, when the EM field depends only on one radial coordinate, the problem can be simplified. Then, for a monochromatic plane wave, the wave equation has the form of

$$\frac{d^2E}{dr^2} + \frac{1}{r}\frac{dE}{dr} + k^2 \varepsilon E = 0, \tag{2}$$

where $k = 2\pi f\sqrt{\varepsilon_0 \mu_0}$ is the propagation coefficient of electromagnetic (EM) waves in vacuum; μ_0 is the magnetic constant. Equation (2) with the corresponding boundary conditions that determine the radiation conditions, as well as for various options for a multilayer structure, is considered in detail in (Nasyrov N. M., Nizaeva I. G., Sayakhov F. L., 1997). Let us write expression (1) taking into account the solution of (2) obtained in the work mentioned above

$$q_v(r) = \frac{\alpha N_0}{\pi r h} e^{-2\alpha(r-R_1)}, \tag{3}$$

where $\alpha = \frac{1}{2}k\sqrt{\varepsilon'}\tan\delta$ is the attenuation coefficient of EM waves, N_0 is the radiation power. It follows from the form of expression (3), that the heat source power exponentially reduces when the distance from the pipe axis is increasing.

From the point of view of heat transfer, the period of microwave radiation can be divided into several stages. We will assume that the decomposition products formed in the process are immediately removed from the surface. The first stage corresponds to the microwave heating of the gas hydrate up to the phase transition temperature T_f. The mathematical model for this stage is the heat-transfer equation and boundary conditions

$$c\rho\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[\lambda r\frac{\partial T}{\partial r}\right] + q_v(r); \tag{4}$$

$$R_1 < r < R_2; \quad 0 < t < t^*;$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=R_1} = 0; \quad \left.\frac{\partial T}{\partial r}\right|_{r=R_2} = 0; \tag{5}$$

$$T|_{t=0} = T_0, \tag{6}$$

where time t^* is determined by the condition $T(R_1, t^*) = T_f$; T_0 is the initial temperature; c is the heat capacity; ρ is the density; λ is the thermal conductivity of the gas hydrate solid phase.

Boundary conditions (5) for (4) assume that the pipe is thermally insulated and we neglect heat exchange with the environment on the free surface of the gas hydrate.

After reaching the temperature of the phase transformation value T_f, the second stage begins, during which the decomposition of the hydrate into gas and water begins. At the same time, a zone where the gas hydrate continues to warm up to the temperature T_f, and a zone where the heated gas hydrate dissociates are formed. To model the decomposition, we introduce the function $0 \le \psi \le 1$, which characterizes a part of the dissociated gas hydrate, and is determined by the equation

$$\rho L\frac{\partial \psi}{\partial t} = q_v(r, z_1(t)); \tag{7}$$

$$z_1(t) \le r \le z_2(t); \quad t^* < t \le t^{**},$$

where $z_1(t)$, $z_2(t)$ are functions that describe the position of the zone boundary in which the dissociation of the gas hydrate occurs, the moment of time t^{**} is determined from the equation $T(R_2, t^{**}) = T_f$. Thus, there are relations

$$\psi = 1, \quad R_1 \le r \le z_1(t); \tag{8}$$

$$y = 0, \quad z_2 \le r \le R_2; \tag{9}$$

$$z_1(t) = \max_{\psi=1} r; \tag{10}$$

$$z_2(t) = \max_{T=T_f} r. \tag{11}$$

Heat transfer in the zone where the gas hydrate has not yet reached the dissociation temperature is described by the following model

$$c\rho\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[\lambda r\frac{\partial T}{\partial r}\right] + q_v(r, z_1(t)); \tag{12}$$

$$z_2(t) \le r \le R_2; \quad t^* < t \le t^{**};$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=z2(t)} = 0; \quad \left.\frac{\partial T}{\partial r}\right|_{r=R_2} = 0; \tag{13}$$

$$q_v(r, z_1(t)) = \frac{\alpha N_0}{\pi r h} e^{-2\alpha(r - z_1(t))}.$$

At the final stage, the layer of incompletely decomposed gas hydrate is completely heated to the dissociation temperature and the decomposition occurs throughout the whole volume. This stage continues until the complete decomposition of the hydrate. The mathematical model describing the process of thermal decomposition takes the following form

$$\rho L\frac{\partial \psi}{\partial t} = q_v(r, z_1(t)); \tag{14}$$

$$T = T_f, \quad z_1(t) \le r \le R_2; \quad t^{**} < t \le t^{***}; \tag{15}$$

$$\psi = 1, \quad R_1 \le r \le z_1(t); \tag{16}$$

$$z_1(t) = \max_{\psi=1} r, \tag{17}$$

where the moment of time t^{***} is determined from the equation $\psi(R_2, t^{***}) = 1$.

Thus, the process of decomposition of a gas hydrate plug under electromagnetic radiation in a one-dimensional formulation is described by the system (1–17). The solution of the task is a sequential numerical solution of problems (4–6), then (7–11) and (12–13), then (14–17).

Results and discussion. Mathematical modeling of the decomposition of a gas hydrate plug in a pipeline under microwave radiation using a coaxially located antenna was performed on the basis of the model presented above for the initial values given in Table.

The power of the microwave source was taken in accordance with the data of [12]. Numerical integration of the system (4–17) was performed by the finite volume method.

As a result of numerical simulation, the dependences of temperature and functions ψ, z_1, z_2 on time were obtained at each stage of the process. Fig. 3 shows the results of the computations at the first stage: heating the gas hydrate before the start of the decomposition. The change in temperature from the initial value T_0 to the temperature corresponding to the beginning of the gas hydrate dissociation under given conditions is shown.

As can be seen from Fig. 3, the process of gas hydrate decomposition begins at the point where the influence of volumetric sources is maximal. The initial stage of heating is quite short compared to the subsequent stage of decomposition and is about 3.5 min after the start of microwave exposure. Fig. 4 shows further temperature change in the gas hydrate until complete heating to the dissociation temperature.

The data in Fig. 4 show that the complete heating of the gas hydrate to the dissociation temperature under the action of

Table

Initial data

Parameter	Value	Unit
N_0	300	W
ε′	4.17	–
ε_0	$8.85 \cdot 10^{-12}$	$F \cdot m^{-1}$
μ_0	$1.26 \cdot 10^{-6}$	$N \cdot A^{-1-}$
tan δ	0.1	–
f	2.45	GHh
R_1,	0.018	m
R_2,	0.15	m
L	$1 \cdot 10^6$	J/kg
ρ	900	kg/m^3
λ	2.11	W/(m · K)
c	2,500	J/(kg · K)
T_f	279	K
T_0	274	K

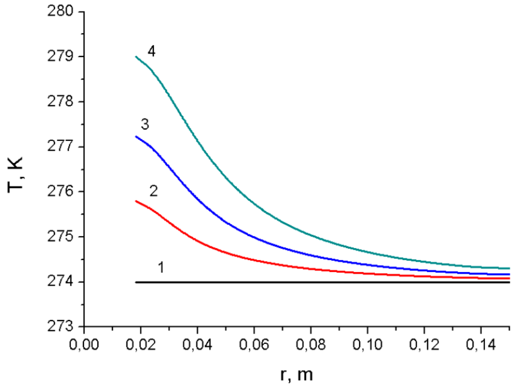

Fig. 3. Temperature field during the initial microwave heating of the gas hydrate plug:

1 – t = 0 *min; 2 – t* = 1 *min; 3 – t* = 2 *min; 4 –* 3.4 *min*

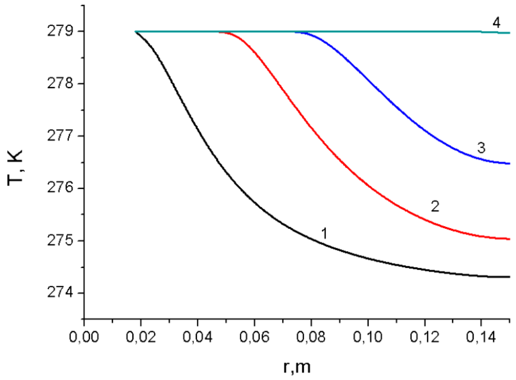

Fig. 4. Temperature field during the initial microwave heating of the gas hydrate plug:

1 – t = 3.4 *min; 2 – t* = 10 *min; 3 – t* = 20 *min; 4 –* 36 *min*

a microwave source of a given power is performed in 36 min. After this time, the dissociation of the gas hydrate in the entire volume begins, and the size of the plug decreases. Fig. 5 shows the change in the temperature field in the initial period of heating in the form of a distribution diagram of isotherms in coordinate system (*r, t*).

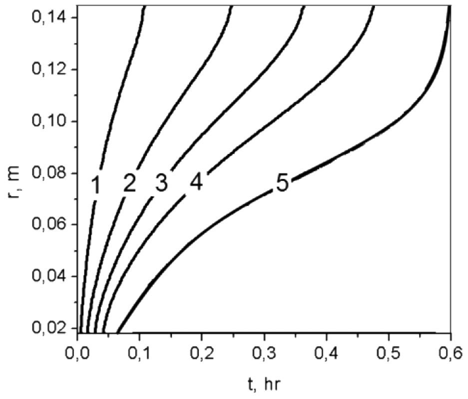

Fig. 5. Dynamics of the temperature field in the initial period of microwave heating: isotherms:

1 – 274.6 K; 2 – 276 K; 3 – 277 K; 4 – 278 K; 5 – 279 K

The dynamics of the decomposition of the gas hydrate can be carried out on the basis of the analysis of the change in the function ψ, Fig. 6.

Thus, as follows from the data in Fig. 6, the process of complete decomposition of the gas hydrate plug with the given geometry and parameters of microwave exposure will take approximately 40 hours. The duration of the dissociation stage compared to heating is explained by the high value of the heat of phase transformation and the exponential weakening of the effect of volumetric heat sources as the phase transition boundary moves away from the radiation source. The change in the region where the gas hydrate dissociation occurs under the action of volumetric heat sources is described by functions $z_1(t)$, $z_2(t)$. Fig. 7 shows graphs of these functions, where the time axis is shown in a log-log plot for convenience.

As can be seen from Fig. 7, function z_2, which describes the advancement of the temperature front T_f, changes rapidly in the initial period (about 36 minutes). After that, the dissociation of the hydrate begins in the entire volume. Function z_1 determines the boundary position of the decomposed gas hydrate and makes it possible to estimate the change in the size of the hydrate plug.

For a visual representation of the dynamics of changes in the gas hydrate area over time, Fig. 8 shows a diagram of change in the function of dissociated gas hydrate. The areas in Fig. 8 correspond to the following: ψ = 0 is the area of undecomposed gas hydrate, 0 < ψ < 1 is the area in which the decomposition of gas hydrate takes place, and ψ = 1 is the area of completely decomposed gas hydrate.

The diagram in Fig. 8 clearly demonstrates how the area in which the gas hydrate decomposes in the pipe changes with time under microwave exposure.

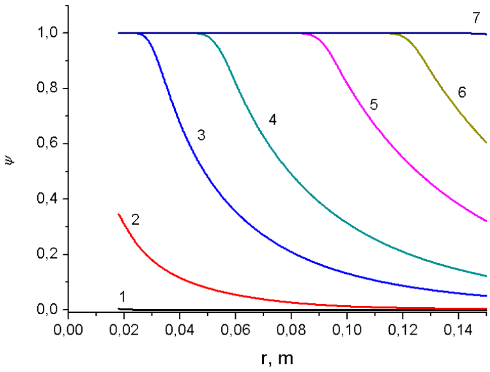

Fig. 6. Change in the function ψ along the radius r at different time moments:

1 – t = 3.4 min; 2 – t = 1 hr; 3 – t = 5 hrs; 4 – 10 hrs; 5 – 20 hrs; 6 – 30 hrs; 7 – 40 hrs

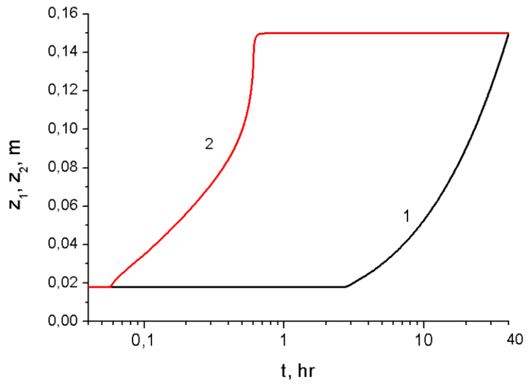

Fig. 7. Change in functions $z_1(t)$, $z_2(t)$ with time t:
1 – $z_1(t)$; 2 – $z_2(t)$

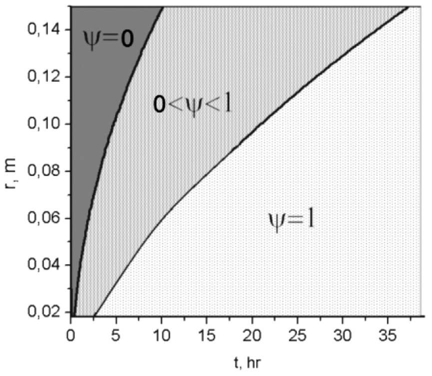

Fig. 8. Diagram of the change in the area of decomposed gas hydrate (function ψ) with time

Conclusions. A review of the known works shows that to date, the problem of thermal decomposition of a gas hydrate plug in pipes due to microwave radiation has not been studied enough. In particular, there are no mathematical models for the volumetric decomposition of gas hydrate in a pipe under the action of a coaxial radiator. In this work, a mathematical model is proposed for computing the process of volumetric heat release in a cylindrical layer of gas hydrate under the influence of electromagnetic energy from a coaxial source.

A mathematical model of heat transfer is proposed, which allows solving the task of the decomposition of a gas hydrate plug in a pipeline using microwave radiation, within the framework of heat conduction problem. The decomposition of a gas hydrate plug under microwave radiation can be divided into several non-equivalent stages: initial heating, joint heating and dissociation, volumetric dissociation after complete heating. To describe the volumetric dissociation of gas hydrate, it is proposed to use function ψ, which is related to the function of volumetric heat release. The volumetric heat release when using a coaxial radiation source will decay exponentially with moving away from the source. The results of the computations show that usage of a specific coaxial microwave radiator allows ensuring the removal of gas hydrate deposits in the pipeline, with the considered initial parameters. The time for complete decomposition of the gas hydrate was about 40 hours. The model can be used for further evaluation of the pipeline unblocking using microwave heating.

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Числове дослідження мікрохвильового впливу на газогідратні пробки у трубопроводі

А. Ю. Дреус[1], *О. І. Губін*[1], *В. І. Бондаренко*[2], *Баочанг Лю*[3], *В. І. Батюта*[1]

1 – Дніпровський національний університет імені Олеся Гончара, м. Дніпро, Україна

2 – Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна, e-mail: v_domna@yahoo.com

3 – Будівельний коледж Цзілінського університету, м. Чанчунь, Китайська Народна Республіка

Мета. Розробка методики чисельного дослідження процесів розкладання газогідратних пробок у глибоководних трубопроводах шляхом мікрохвильового впливу з використанням коаксіального джерела випромінювання. Теоретична оцінка ефективності використання такої дії задля ліквідації блокування трубопроводів.

Методика. Математичне моделювання та обчислювальний експеримент.

Результати. Запропонована оригінальна математична модель для опису теплообмінних процесів під час розкладання газових гідратів у трубопроводі під дією розподілених за обсягом джерел тепла. Нестаціонарна задача теплообміну розглядалася в одновимірній постановці. Запропоновано алгоритм чисельного розрахунку. Отримано математичний вираз для розподілених джерел тепла, що утворюються за рахунок мікрохвильового випромінювання від коаксіально розташованої НВЧ-антени. Виконані параметричні чисельні дослідження температурних полів і динаміки розкладання газогідратної пробки за заданих параметрів труби й потужності НВЧ-випромінювача. Визначені межі області розкладання й динаміка зміни цієї області. Визначено час розкладання пробки газового гідрату діаметром 0,3 м за потужності джерела випромінювання 300 Вт. Час повного розкладання становить близько 40 годин.

Наукова новизна. Уперше розглянута задача теплового розкладання циліндричної газогідратної пробки у трубопроводі за рахунок НВЧ-нагрівання при використанні коаксіального джерела мікрохвильової енергії. Процес розглядається як послідовність кількох етапів: нагріву, нагріву й розкладання, повного прогрівання шару газового гідрату. Для моделювання об'ємної дисоціації газового гідрату було запропоновано використовувати спеціальні функції, що характеризують кількість розкладеного газового гідрату. Уведення таких функцій дає змогу побудувати ефективний алгоритм розрахунку з урахуванням дії об'ємних джерел у зоні розкладання. Відомі моделі розглядають, головним чином, тільки поверхневий тепловий вплив або мікрохвильовий вплив на газові гідрати у пористому середовищі. Представлена модель дозволяє адекватно описувати процес розкладання при об'ємному нагріванні суцільного гідрату.

Практична значимість. При транспортуванні газу глибоководними трубопроводами або трубопроводами, що знаходяться в умовах холодного навколишнього середовища, можливе виникнення блокуючих пробок за рахунок гідратоутворення. Ліквідація таких ускладнень представляє складне технічне завдання. Зокрема, для усунення блокування трубопроводів можна використовувати спеціальне джерело мікрохвильового випромінювання, яке було запропоновано авторами в попередніх роботах. Пристрій, що реалізує випромінювання, підводиться до пробки по осі труби. Результати даної роботи дозволяють виконати оцінку ефективності НВЧ-методу ліквідації газогідратної пробки. Математична модель і методика розрахунку можуть бути використані при розробці відповідних технологій усунення блокування трубопроводів із використанням коаксіального джерела НВЧ-нагрівання.

Ключові слова: *газові гідрати, блокування трубопроводів, мікрохвильова дія, математичне моделювання, теплообмін*

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