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PHASE TRANSFORMATIONS IN PIPELINE GAS TRANSPORTATION AND METHODS TO PREVENT EMERGING COMPLICATIONS

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Abstract. *The current methods for prevention of problems in gas gathering, field preparation and transportation systems, as a rule, do not consider the joint effect of such processes as gas flow in the pipeline in case of phase transitions, accumulation of liquid in the pipeline cavity, heat exchange of the pipeline with the surrounding environment. The studies assessed the barodynamic factors and the component composition of gas, affecting hydrate formation, taking into account the complex effect of the processes involved in the operation of gas pipelines. The technological solution for gas pipeline cleaning by specially developed polymeric gel composition is proposed.*

Keywords: gas flow, heat transfer, condensation, moisture content, hydrate, viscous-elastic compound

Mathematics Subject Classification (2020): 76T10, 82B26, 80A05

1. Introduction

One of the most important problems in the gas pipeline operation is accumulation of liquid and gas hydrates generation. Hydrates deposited on the inner walls of pipes drastically reduce their flow capacity and can lead to an emergency shutdown of gas pipeline operation. Oil and gas companies' costs for preventing and controlling gas hydrates form a significant part of the operational expenses of gas fields and gas

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transportation. The reduction of operating costs for the prevention and control of fluid accumulation and hydrate generation in the field systems of gas production and further gas transportation is an urgent problem for the oil and gas industry.

2. Moisture Content

In the space of operated in-field and main gas pipelines there is a certain amount of moisture to some extent, since the gas extracted from the reservoir contains water in a certain concentrations [9], [11], [12], [19]. In the cold season the ground temperature is lower, which leads to a decrease in the temperature of the pipeline content. If the gas temperature falls below the saturation temperature corresponding to the water dew point, water vapor condensation will begin [4]. On straighter sections of the pipeline, the liquid begins to accumulate at the base of the pipe due to gravity. Accumulation can increase at the base of sagging pipeline sections located higher up the slope.

The moisture content depends on the gas composition, pressure, temperature, and physical and chemical properties of the condensed water with which the gas is in thermodynamic equilibrium. The temperature at which a gas becomes fully saturated with water vapor at a given water content in the gas is called the gas water dew point temperature at a given pressure.

The moisture content of the gas at a given pressure and temperature is calculated using the following equation [9]:

$$W_{Tzad} = (A/P_{zad} + B)\, C_{cp},$$

where A and B are temperature-dependent coefficients. At a given pressure, coinciding with the tabulated one, the constants A and B, coinciding with those given in the table [9] are used in the calculation.

If a gas pipeline is supplied with gas, the water content of which is such that by the conditions of its transport (change in pressure and temperature) the gas temperature does not decrease below the dew point, then in such a pipeline drip moisture does not fall out. If the dew point is above the temperature to which the gas in the pipeline can cool down, i.e. close to the ambient temperature, then water condensation will happen in such a pipeline [5], [9]. It should be noted that with decreasing pressure and increasing temperature the maximum content of water vapor in the gas increases. All transported gases under specific barothermal conditions of water accumulation, form gas hydrates, the structure of which depends on the gas structure, pressures and temperatures [16]. Clathrate hydrates are non-stoichiometric mixtures of water and natural gas in which gas molecules are trapped in a polygonal crystal structure composed of water molecules [17], [20]. Water molecules are arranged in an orderly fashion around the gas molecules, thereby trapping them.

Gas hydrates can form well above the freezing point of water at high pressures. The sequence of events leading to hydrate formation in gas pipelines includes condensation of water vapor, accumulation of water in the lower sections of the pipeline, nucleation and growth of hydrate particles, which eventually leads to blockage of the pipeline [16], [24]. However, various researchers have focused on different aspects of the flow of this process.

Bishnoi et al. [2] presented the kinetics of formation and decomposition of gas hydrates at the conceptual level, highlighting the different phases of formation. The authors [16] presented a critical review of the literature on the kinetics of hydrate formation, highlighting the efforts of various researchers on simulation. In an attempt to simulate the real conditions of these formations on an industrial scale, the flow loop experiments given in [6] and [7] were carried out. Water accumulation and gas hydrate generation can invariably be found over a wide range of pressures and temperatures.

3. Liquid Condensation

The equation of temperature change along the pipeline taking into account thermal effects of moisture vapor condensation can be written in the form [9]:

$$m_q C_p \frac{T_{qaz}}{dx} = \frac{m_q}{\rho_q} \frac{dp}{dx} + m_q l_v \frac{dk_1}{dx} - Q, \tag{1}$$

where C_p is the specific heat capacity of gas (J/K), l_w is the latent heat of vaporization of water, m_g is the mass flow rate of gas (kg/h), T_g is the gas temperature (K).

The intensity of heat removal is determined by equation (2):

$$Q = 2\pi d_j q \ , \tag{2}$$

where Q - heat removal intensity, q- heat removal intensity related accordingly to the pipeline length unit and its wall area unit.

As noted earlier, the formation of gas hydrate can take place in two ways [2], [17]. The first will be called the thermal balance mode, which is realized when the hydrate surface hydrate formers (gas and water) arrive in sufficient quantities. Therefore, the intensity of solid hydrate formation is limited only by the intensity of heat removal from the phase transition surface (hydrate surface) [18].

In this case, it is assumed that the temperature of the phase transition surface T_w(which is also the temperature of the inner wall of the pipeline at the section where the hydrate is deposited) is equal to the equilibrium temperature of hydrate formation Th, which is a function of gas pressure p in the flow $p\,(T_g = T_g(p))$. Consequently, the intensity of gas hydrate deposition in this mode will be determined by the thermal balance on the surface of the gas hydrate layer, which can be written by the following equation:

$$l_s j_h = q_1 - q, \tag{3}$$

where l_s is the specific heat of phase transition during hydrate formation, q_1 - heat flux from the inner surface of the gas hydrate layer into the sea water surrounding the pipeline.

It was assumed that throughout the pipeline, where the conditions of gas hydrate formation are met, deposition happens in accordance with the first mode [9], [11].

4. Evaluation of Hydrate Formation on the Inner Surface of The Pipe

The rate of increase in the size of hydrate crystals significantly depends on the rate of creation of the free surface of the gas-water contact, i.e., on the degree of turbulization of the gas-water flow [8], [17], [23].

If water vapor is in a single-phase saturated state (i.e., there is no contact between gas and water), the mechanism of hydrate formation has a slightly different character. Water vapor in the pre-condensation phase is also formed into clusters consisting of chains and cells of ice-like structure. Under appropriate thermodynamic conditions, water clusters enter into a fixed bond with gas molecules and among themselves, forming the base of crystallization germs. On the basis of nucleation nucleus formation there is an accumulation of hydrate [5], [10], [16].

The process of water accumulation and gas hydrates formation on the walls of the steel pipe takes place only due to cooling its inner surface. Processes of heat transfer on the pipe wall and in the hydrate layer we describe by the thermal conductivity equation with constant coefficients, written in a cylindrical coordinate system [19]:

$$r\frac{\partial T}{\partial t} + rv_r\frac{\partial T}{\partial r} = \frac{\partial}{\partial r}\left(\frac{r\lambda}{\rho c_p}\frac{\partial T}{\partial r}\right) , \tag{4}$$

where t- time, r - radial coordinate counted from the pipe axis, λ - heat conductivity coefficient, ρ - density, c_p - specific heat capacity, T - temperature, v_g - speed of motion. At the initial moment of time, the wall temperature is assumed constant and equal to the temperature of the gas flow:

$$T_{t=0} = T_0 \ . \tag{5}$$

On the outer surface of the pipe the boundary conditions of 1 - 3 kind are set, written in generalized form:

$$\alpha_w\left(r\lambda\frac{\partial T}{\partial r}\right) + \beta_w\ T|_{r=r_w} = f_w. \tag{6}$$

In particular, if the pipeline is located in the ground or in the water, the boundary condition of the 1st kind is set:

$$\alpha_w = 0,\ \ \beta_w = 1\ ,\qquad f_w = T_w. \tag{7}$$

At the interface "pipe - hydrate layer" conjugation conditions (equality of heat flows and temperatures) are exhibited:

$$\lambda_i\ \frac{\partial T}{\partial x}\bigg|_{x=x_i-0} = \lambda_{i+1}\ \frac{\partial T}{\partial x}\bigg|_{x=x_i+0},$$

$$T|_{x=x_i-0} = T|_{x=x_i+0}\ \ ,\qquad i=\overline{1,N-1}. \tag{8}$$

On the surface of the hydrate layer, the condition of the 1st kind is set, and the velocity of the boundary of the hydrate layer is determined from the Stefan equation:

$$T|_{r=r_c} = T_e,$$

$$v_g = -\frac{\lambda_g}{\rho_g Q_g} \left. \frac{\partial T}{\partial r} \right|_{r=r_c}, \qquad (9)$$

where v_g, λ_g, ρ_g, Q_g- linear velocity of hydrate formation, coefficient of thermal conductivity of hydrates, density of hydrates, specific heat of hydrate formation. Indexes "w", "e" define the outer surface of the pipe and the inner layer of gas hydrates.

According to the following parameters of gas flow $v_r = 10m/s; r = 0,55m;$; $\rho = 0,4kg/m^3$; $c_p = 2483J/kg{\cdot}K$; $\lambda = 0,0307Vt/m{\cdot}K$ the two- and three-dimensional graphs of temperature dependence on time $T = 0; 0.5; 1; 1.5; ...$ were built using MATLAB software (Fig. 1).

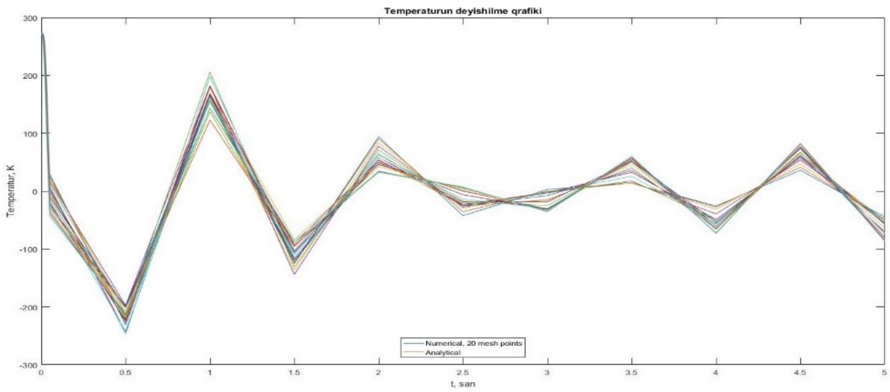

Fig. 1. Temperature change over time (2D image

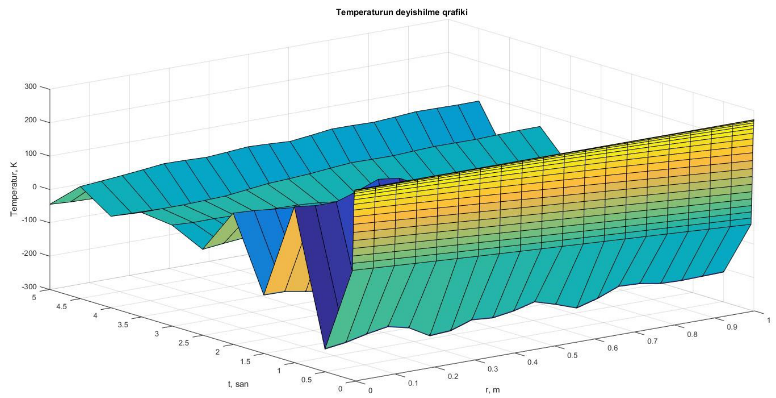

Fig. 2. Temperature variation in time and length in the radial direction (in the 3D case)

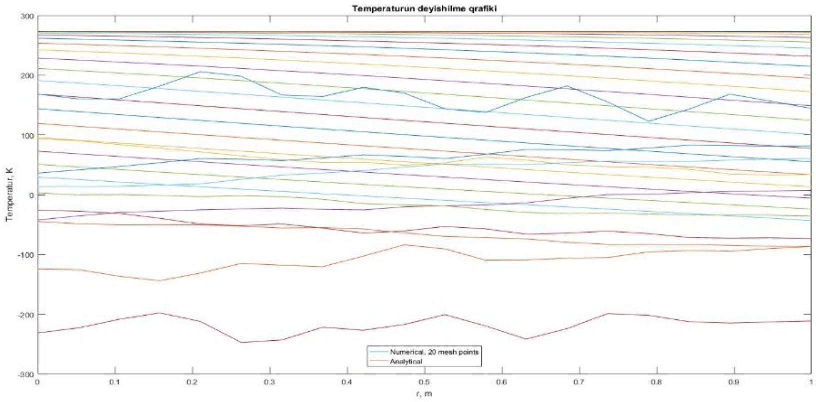

Fig. 3. Temperature variation along the cross section of the gas pipeline

5. Methods to Prevent Hydrate Formation in Pipelines

Currently, gas pipelines in long-term operation are constantly exposed to internal corrosion under the influence of aggressive components (H_2S, CO_2, O_2, etc.) contained in aqueous solutions of hydrocarbon condensate [1], [24]. Consequently, trapping condensate and drop moisture removal from gas pipelines of external gas transport is the main task of the technological process, providing trouble-free gas transport to consumers in compliance with sanitary norms and safety conditions [21].

In addition, one of the main reasons for this phenomenon lies in the fact that on the inner surface of the pipe wall there are almost always film formations of sorbed water, which passes into the gas pipeline of dry gas and saturates gas with liquid to equilibrium values. When identifying violations of the operating regime of the gas pipeline, the consequence of which is the formation of solid hydrate plug, it is necessary to begin measures for their removal, not allowing the complete blockage of the gas pipeline hydrates, as a complete overlap of the section - one of the most difficult to eliminate a very dangerous emergency situations [6].

The accumulation of water and hydrate formation makes it difficult to transport gas through long pipelines, particularly in areas where flow velocity is high. These deposits can also plug all or part of the pipe cross-section, which, in turn, reduces the flow capacity of the pipeline and contributes to the emergence of high-pressure zones. Due to the fact that such deposits lead to significant complications in the course of operation of main gas pipelines and gas fields, as well as the origin of major accidents, the issues of prevention of these complications at relatively low costs are currently one of the urgent scientific, technical and production issues [3], [15], [21].

Hydrates formed from hydrocarbon gases are unstable in their structure compounds of hydrocarbons with water. Technological conditions affecting the formation of hydrates include: a) careless blowdown of the pipeline before starting the pipeline; b) lack of condensate collectors and blowdown nozzles in the areas of pipeline drawdown or not constant removal from the accumulated liquid; c) incomplete purification of gas before supplying it into the main pipeline.

Recently, the technology of cleaning the inner cavity of gas pipelines with the help of cleaning devices of various designs and operating principles has been dominating [18], [19], [23]. Technological process of gas pipeline cleaning is carried out without stopping its work and consists of three main elements: the process of starting the cleaning device, control process of its passage through the cleaned section, receiving cleaning products and cleaning device at the end of the cleaned section. To start up and receive the cleanup devices, special devices are constructed, including launching and receiving chambers, signaling system, disposal tanks, lifting mechanisms of cleanup devices, technological piping and other equipment. Variable cross-section of pipelines, availability of bends, overhead clamps, etc. limit the possibility of using pigs and special balls of various shapes and designs.

In order to effectively clean gas pipelines from various deposits, this paper proposes the use of water-based viscoelastic compositions, providing recovery of pipeline capacity and reducing pressure losses. Unlike known systems, viscoelastic compositions sufficiently satisfy a set of requirements and have the following adjustable properties: relaxation, thixotropy, viscoelasticity, as well as dynamic hysteresis. The technological approach aims to ensure the removal of water, condensate and solid accumulations from the pipeline by pushing a freshly prepared visco-elastic composition into the space and pushing it through the transported product.

The proposed concept is based on the selection of viscoelastic compositions for cleaning gas pipelines and the generation of a layer on the wall of the gas pipeline to improve the efficiency of the pipeline system. During the technological operation of pipeline cleaning, the necessary volume of the viscoelastic composition is calculated depending on the pipeline geometry parameters. The volume of the composition is prepared right before application in a special container. The prepared composition is pumped under pressure into the pipeline and then the counterpressure is sequentially created to ensure the movement of the composition in the pipeline space and the formation of a viscoelastic layer along the internal surface of the pipeline.

It is shown that by technological methods it is also possible to regulate, and in some cases to exclude pressure oscillations in the main gas pipelines. This can be reached both by the choice of the material of the pipe itself, and by the internal coating of the pipe with a viscoelastic material.

Consider a gas-liquid mixture consisting of a carrying phase (gas) and a liquid phase weighted in it. Let us assume that the volume concentration of condensate is low, and the entire mixture is a continuous medium [22]. With the above assumptions, the problem in linear approximation is reduced to the Bürgers-Cortweg de Fries equation [21]:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial z} = \mu_1 \frac{\partial^2 u}{\partial z^2} + \beta \frac{\partial^2 u}{\partial z^3} = 0, \tag{10}$$

where $\mu_1 = \frac{2\mu}{3\alpha_1 \cdot \alpha_2 \rho_1^0}$; $\beta = \frac{\theta_0^2 \cdot c_l}{6\alpha_1 \cdot \alpha_2}$; $c_l^2 = \frac{\gamma \cdot p_0}{\alpha_1 \cdot \alpha_2 \rho_1^0}$; $z = x - c_l t$;

ρ_1^0 - gas density; α_1, α_2 - volume concentrations of gas and condensate fraction; p_0, θ_0- initial values of pressure and concentration of condensate; A_l - speed of sound propagation in the mixture.

Taking into account the elasticity of the inner sublayer of the pipe, the equation relating the radius to the fluid pressure will look like [21]:

$$p' = \frac{h \cdot \sigma}{r_0}, \tag{11}$$

where h - thickness of the viscoelastic sublayer; $r_0 = r - h$ - actual tube radius; σ - longitudinal stresses in the tube.

To determine σ, we use the viscoelastic body model:

$$\frac{\partial \rho r^2}{\partial t} + \frac{\partial \rho r^2 u}{\partial x} = 0; \frac{d\sigma}{dt} + \frac{\sigma}{\theta} = \frac{E_\infty(r')}{r_0}\frac{dr}{dt} + \frac{E_0(r')}{r_0}\frac{r'}{\theta}. \tag{12}$$

Here θ is the characteristic relaxation time; $r' = r - r_0$.

In (11) it is taken into account that at low loading rates the stresses are determined mainly by the Young's modulus $E_0(r')$, and at high loading rates by the Young's modulus $E_\infty(r')$, equation (11) is easily solved relative to [11]:

$$\sigma = e_0 \cdot \left\{ r' + \frac{e_\infty - e_0}{e_0} \cdot \int_{-\infty}^{t} \exp\left(-\frac{t-\xi}{\theta}\right) \cdot \left(\frac{dr'}{d\xi}\right) d\xi \right\}, \tag{13}$$

$$e_0 = E_0/r_0; \qquad e_\infty = E_\infty/r_0.$$

Thus, water contained in the flow will be consumed for mixing of viscoelastic polymer layer, but not for formation of gas hydrates in the pipeline. Then the equations of motion and continuity averaged over the cross section of the pipe taking into account changes in its radius can be presented in the following form:

$$\frac{\partial \rho r^2}{\partial t} + \frac{\partial \rho r^2 u}{\partial x} = 0;$$

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \frac{\partial p}{\partial x} = 0.$$

Using the same approximations as in the derivation of equation (10), taking into account (11) and (13), it is reduced to a differential equation of the form (10):

$$\frac{du}{dt} + (1+\alpha)\, u \frac{\partial u}{\partial z} - (\mu_1 + \mu_2) \frac{\partial^2 u}{\partial z^2} + \beta \frac{\partial^2 u}{\partial z^2} = 0, \tag{14}$$

where

$$\alpha = \frac{c^2}{2c_1^2} - \frac{c^4}{A_1^2 \cdot A_l^2}\left(1 + \frac{c_l^2}{4c_1^2}\right); \quad A = \frac{1}{\sqrt{A_4^{-2} + A_1^{-2}}};$$

$$c_1 = \frac{h \cdot e_0}{2\rho_1^2}; \qquad \mu_2 = \left[(e_0 - e_\infty)/e_0\right] \cdot \left(c^4/2 \cdot c_1^2\right) \cdot \Theta.$$

From (14) it can be seen that the sublayer with the selected characteristics can significantly increase the energy dissipation (due to μ_2). By changing the coefficient value α, the effect of nonlinearity can be reduced, resulting in the blurring of the wave front.

A specially designed composition [15] was applied at the 1500 m long section of the gas pipeline between the offshore platforms MSP-7 and MSP-5 at the field "White Dragon" of JV "Vietsovpetro". The operation of the offshore gas pipelines is one of the complex and critical components of the technological process of reservoir development. The maintenance of stable gas pipeline operation takes on a special urgency in critical conditions of offshore location of the pipeline, high corrosive activity of the medium and the transported product, reduction of pipeline capacity due to accumulation of liquid in the pipe space. Complicating factors of gas pipeline cleaning process in conditions of offshore oil and gas production are absence of special launching chambers for traditional mechanical cleaning pistons, complicated geometry of gas pipeline route, extended (70 m long) risers on platforms. The proposed innovative method is based on pumping a specially developed polymeric gel composition into the space of the gas pipeline, which allows to form a stable viscoelastic piston in the pipe cavity in the shortest time, which displaces the accumulated liquid into the collection and separation system on the offshore platform while moving in the pipeline.

In the process of gas pipeline cleaning about 8 cubic meters of water and condensate were displaced from the pipe space at a pressure of 5 atm, and the visco-elastic composition (gel piston) pumped on the MSP-7 platform was successfully accepted in the receiving unit on the MSP-5 platform (Fig. 4).

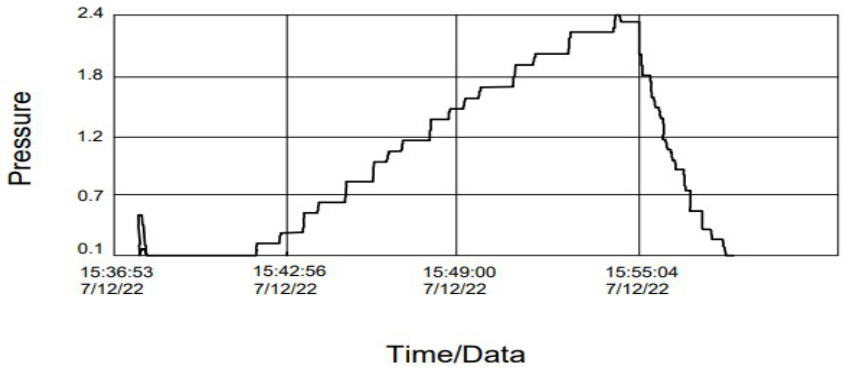

Fig. 4. Pressure dynamics during gas condensate displacement in the pipeline between offshore platforms MSP-7 and MSP-5 of White Tiger field, Vietnam (pressure sensor readings)

The results achieved can be used in the analysis and calculation of transient modes in gas pipeline systems in order to exclude emergency situations of gas transportation.

In gas pipelines transporting wet natural gas, there is often a negative phenomenon in formation of a layer of gas-hydrate deposits on the inner walls of the pipeline, which leads to partial or complete blocking of the flowing section, and as a consequence, to a decrease in the flow rate or even an emergency situation. In order to describe gas movement, to use stationary equations of nonisothermal gas flow in the channel in quasi-dimensional approximation [13], [14]. It was found that in the pulsation mode, changes in the gas and liquid flow rate, have a non-stationary nature and depend on the amplitude of the oscillation. We also evaluated the effect of inertia-free periodic intense disturbances on the flow of a gas-liquid flow with a variable structure in a circular cross-section pipe, determining the kinetics of changes in the structure and fluctuations of the pressure gradient, as well as on the gas-dynamic characteristics of the flow.

6. Conclusions

The influence of inertia-free periodic intensive disturbances on the gas-liquid flow with a variable structure in the pipe of circular cross-section, determining the kinetics of changes in the structure and pressure gradient fluctuations, has been estimated.

The technological solution for cleaning the gas pipeline cavity with specially developed polymeric gel composition is offered, allowing to form a stable viscoelastic piston in the pipe cavity in the shortest time, which displaces the accumulated liquid into the collection and separation system on the offshore gas production platform.

It was found that in the pulsation mode, variations in the flow rate of gas and liquid are non-stationary and depend on the amplitude of the oscillations.

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