NUMERICAL SIMULATION OF GAS HYDRATE DECOMPOSITION IN POROUS MEDIA UNDER THE ACTION OF MICROWAVE HEATING

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ABSTRACT
Numerical studies were performed with the two-dimensional axisymmetric model of gas hydrate decomposition in porous media under the action of microwave heating. Electromagnetic waves propagate in a radial direction about the well; they are absorbed and volume heating of the reservoir and adjacent rock occurs. Thus, the system of equations describing the above process includes in the mass balance equations of gas, water and hydrate phases, the energy balance equation, generalized Darcy’s law for water and gas, Kim-Bishnoi kinetics equation for hydrate decomposition reaction. The system is closed by the condition of equilibrium of the mixture. The system of equations is reduced to four differential equations relative to temperature, pressure, volume hydrate and water saturation with appropriate boundary and initial conditions. Simulation of gas hydrate decomposition in porous media under the action of microwave heating was carried out by finite element method. Physical parameters characteristic of typical hydrate reservoir were used in the modeling. Heating time of reservoir was 30 days. A spatial and temporal distribution of temperature, pressure, hydrate and water saturation was obtained. The mass of gas evolved during hydrate dissociation was determined. The calculation of the energy efficiency of electromagnetic heating was carried out. These results are quite usable from a practical standpoint, and the electromagnetic heating method is technically achievable and competitive, for example, with the inhibitor injection method.

Keywords: numerical simulation, microwave heating, gas hydrates decomposition, gas production

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{HS}$</td>
<td>Constant determined by the ratio of surface area of hydrate spherical particles to pore volume [mm$^{-1}$]</td>
</tr>
<tr>
<td>$a$</td>
<td>Constant of condition of thermodynamic equilibrium of the mixture</td>
</tr>
<tr>
<td>$b$</td>
<td>Radius of the well [m]</td>
</tr>
<tr>
<td>$C$</td>
<td>Heat capacity [J/(kg·K)]</td>
</tr>
<tr>
<td>$f_{eq}$</td>
<td>Gas fugacity at equilibrium [MPa]</td>
</tr>
<tr>
<td>$f$</td>
<td>Gas fugacity in pore space [MPa]</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration of gravity [m/s$^2$]</td>
</tr>
</tbody>
</table>

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**INTRODUCTION**

Gas hydrate deposits are considered to be one of the most promising sources of natural gas in the future. The results of numerous theoretical and experimental research of the processes of hydrate formation and dissociation in natural reservoirs are presented in works [1,2]. For the production of gas from gas hydrate reservoirs, several recovery methods have been proposed, such as depressurization, thermal stimulation, the injection of hot fluid, use of inhibitors, pumping of carbon dioxide into the reservoir, or a combination of these methods [3]. One of the most promising methods is a thermal stimulation method, or its combination with other methods. However, the large heat losses to the surrounding rocks and the low permeability may restrict the application of the thermal stimulation method such as the injection of hot fluids. One of the promising methods of thermal treatment is an electromagnetic heating of the productive layers. Due to deep penetration and the volumetric heat release, and absence of coolant, electromagnetic radiation can provide (compared to traditional methods) high speed and uniform heating, the possibility of optimal control and automation of technological processes; virtually eliminate the harmful effects on the environment. The results of laboratory and field trials show perspective utility of this trend [4-11]. However, the effective realization of these opportunities is hindered by the lack of reliable data on the study of heat and mass transfer processes in multiphase media, typical for the oil and gas technologies, when subjected to these media microwave electromagnetic radiation. The main objective is to determine optimal modes of stimulation, namely: the frequency and power of a source of microwave radiation, the parameters of the antenna, the possibility of using nonlinear properties of the medium to enhance impact on the models as close as possible to real conditions. The theoretical study of heat and mass transfer in the oil stratum when it is heated by high-frequency electromagnetic radiation was performed on one- and two-dimensional models in research. The filtration processes in porous media filled with a solid gas hydrate or liquid, with depression and thermal effects (including the electromagnetic heating), which leads to phase transitions (gas hydrate decomposition, boiling liquid) were studied in research [12-21]. Overall, however, the problem is not well studied.

In present work, numerical studies were performed with the two-dimensional axisymmetric model of gas hydrate decomposition in porous media under the action of microwave heating.

**FOMULATION OF THE PROBLEM**

The problem of the decomposition of gas hydrates in a porous medium initially saturated with thermodynamic equilibrium mixture of methane hydrate, water and gas is considered in the
axisymmetric approximation. A horizontal layer of thickness \( H \) is located between two planes perpendicular to the axis \( z \) - top and bottom, which are impermeable and heat-insulated. A top and bottom layer is surrounded by the unbounded medium, the thermophysical characteristics of which differ from the characteristics of the reservoir. It is believed that the skeleton of porous rock and the gas hydrate incompressible and immobile, the gas is perfect, the water is incompressible, the motion of water and gas phase filtration is subordinated to the law of Darcy, capillary effects are not considered. In the well at the level of the reservoir the source emitting electromagnetic waves in a radial direction is placed. Due to bulk absorption of electromagnetic energy around the well heating of reservoir and surrounding rocks occurs, which leads to the decomposition of methane hydrate. Gas hydrate is decomposed into gas and water accordingly to the following pattern

\[
nH_{2}O \cdot CH_{4}(hydrate) \rightarrow nH_{2}O(water) + CH_{4}(gas)
\]

During the methane hydrate dissociation one gas molecule fits to 5,75 water molecules. Basic equations describing the dynamics of an equilibrium mixture of gas, water and gas hydrate in porous media, are laws of conservation of mass of gas, water mass, the mass of gas hydrate and the energy conservation law.

The law of conservation of the water mass has the form

\[
\frac{\partial}{\partial t} \left[ ms_{w} \rho_{w} \right] + \nabla \cdot \rho_{w} \vec{v}_{w} = q_{w}
\]

(1)

The law of conservation of the gas mass:

\[
\frac{\partial}{\partial t} \left[ m(1 - s_{w} - s_{h}) \rho_{g} \right] + \nabla \cdot \rho_{g} \vec{v}_{g} = q_{g}
\]

(2)

The law of conservation of the gas hydrate mass:

\[
\frac{\partial}{\partial t} \left[ ms_{h} \rho_{h} \right] = -q_{h}
\]

(3)

under the condition

\[
s_{h} + s_{w} + s_{g} = 1
\]

(4)

The filtration rate of water and gas are determined by Darcy's law:

\[
\vec{v}_{w} = -\frac{Kk_{w}}{\eta_{w}} \nabla \left( P - \rho_{w} g z \right)
\]

(5)

\[
\vec{v}_{g} = -\frac{Kk_{g}}{\eta_{g}} \nabla \left( P - \rho_{g} g z \right)
\]

(6)

The dependence of permeability on hydrate saturation of pore structure is defined as follows

\[
K = K_{0} \left( 1 - s_{h} \right)^{V}
\]

(7)

The amount of gas released during gas hydrate dissociation is determined according to the model proposed in work [22]

\[
q_{g} = K_{B} M_{g} A_{RS} s_{h} \left[ f_{eq}(T) - f \right]
\]

(8)

The dissociation rate constant is determined from the expression

\[
K_{B} = k_{B}^{0} e^{\frac{-\Delta E}{RT}}
\]

(9)

The condition of thermodynamic equilibrium of the mixture is written as follows

\[
T = a_{1} \ln P_{eq} + a_{2}
\]

(10)

Changing of the amount of water and hydrate in a unit of time is determined from the correlations

\[
q_{w} = M_{w} n_{g} q_{g} / M_{g}
\]

(11)

\[
q_{h} = M_{h} q_{g} / M_{g}
\]

(12)

The energy conservation law is written as follows

\[
\left( \rho C_{e} \right) \frac{\partial T}{\partial t} - mQ \rho_{h} \frac{\partial s_{h}}{\partial t} - m \left( 1 - s_{h} - s_{w} \right) \frac{\partial P}{\partial t} + \left( \rho_{w} \vec{v}_{w} \nabla C_{w} + \rho_{g} \vec{v}_{g} C_{g} \right) \nabla T + \vec{v}_{w} \nabla P = \nabla \left( \lambda_{e} \nabla T \right) + Q_{H}
\]

(13)

where
\[(\rho C)_v = (1-m)\rho_s C_s + ms_h \rho_s C_h + ms_w \rho_w C_w + m(1-s_h-s_w)\rho_g C_g\]  
\[\lambda_v = (1-m)\lambda_s + ms_h \lambda_h + ms_w \lambda_w + m(1-s_h-s_w)\lambda_g\]

The last term in expression (13) \(Q_H\) is the density of the volume heat release, resulting from the absorption of electromagnetic radiation (the law of Bouguer-Lambert, taking into account the geometric divergence):
\[Q_H = \frac{\alpha W \Psi(z)}{2\pi r} \exp[\alpha (b-r)]\]

where \(W\) - linear power of transmitter (watts per unit length along the axis \(z\)), the function \(\Psi(z)\) characterizes the distribution of power of electromagnetic radiation in height (pattern radiator). Ideally, when the electromagnetic wave is "channeling" along the layer without penetrating into the adjacent rock, the function \(\Psi(z)\) has the form:
\[\Psi(z)= \begin{cases} 1, & npu - H / 2 \leq z \leq H / 2, \\ 0, & npu z < -H / 2, \ z > H / 2. \end{cases}\]

The total absorption coefficient of radiation \(\alpha\) in a multiphase porous medium is determined as follows
\[\alpha = (1-m)\alpha_s + m \cdot s_h \cdot \alpha_h + m \cdot s_w \cdot \alpha_w + m \cdot s_g \cdot \alpha_g\]

Since \(\alpha_w \neq \alpha_s, \alpha_h, \alpha_g\), the total absorption coefficient \(\alpha\) is determined mainly by the water absorption coefficient \(\alpha_w\) and water saturation reservoir \(s_w\)
\[\alpha \approx m \cdot s_w \cdot \alpha_w (f, T)\]

The water absorption coefficient \(\alpha_w\) increases with the frequency of radiation and decreases with increasing water temperature. Thus, the total absorption coefficient \(\alpha\) varies in a nonlinear manner as in the space of the reservoir, as well as in the course of time. The water absorption coefficient \(\alpha_w\) was determined from the data presented in work [23].

In the calculation of permeability the following dependences were used
\[k_w(s_w) = \begin{cases} ((s_w-0.2)/0.8)^{3.5}, & 0.2 < s_w \leq 1 \\ 0, & 0 \leq s_w \leq 0.2 \end{cases}\]
\[k_0(s_w) = \begin{cases} (1-s_w/0.9)^{3.5}(1+3s_w), & 0 < s_w \leq 0.9 \\ 0, & s_w \geq 0.9 \end{cases}\]

The equation of the gas state can be written as
\[\rho_g(T, P) = \frac{P}{\zeta RT}\]

where \(\zeta = \zeta(P, T)\) is coefficient, taking account of the difference between the properties of real and perfect gas, which in Berthelot form is as follows:
\[\zeta = 1 + 0.07 \frac{P T}{P_0 T_0^2} \left(1 - \frac{T^2}{T_0^2}\right)\]

The gas viscosity is a function of pressure and temperature, density and viscosity of water are functions of temperature.

The system of equations (1) - (23) reduces to a system of four equations for the unknown quantities \(T, P, s_h\) and \(s_w\).

Initial conditions are as follows:
\[T(r, z, 0) = T_0, \ P(r, z, 0) = P_0, \ s_h(r, z, 0) = s_{h0}, \ s_w(r, z, 0) = s_{w0}\]

On the upper and lower boundaries of the reservoir boundary conditions for equations (1-2) are recorded in the form
\[\bar{v}_{w.g} = 0\]
and for equation (13) as follows
\[T = const\]
The side boundary is open for heat and mass fluxes

\[ T = \text{const}, \quad P = \text{const} \quad (27) \]

Downhole pressure is given by

\[ P(r,z,t)|_{r=b} = P_b \quad (28) \]

Simulation of heating reservoir was carried out by finite element commercial software package COMSOL Multiphysics. A numerical algorithm for the finite element method is based on the procedure of minimizing the functional corresponding to the continuous problem solved. The result of this procedure is the substitution of the system of partial differential equations system of algebraic equations with the coefficients approximating functions, which are actually the values of the unknown function at the vertices of the subdivision. In the present research computational domain task was divided approximately into 40000 finite elements having the form of triangles. Finite element mesh was nonuniform. Concentration of elements was carried out in areas of expected strongest changes in temperature and electromagnetic field, i.e. near the radiation source and at the interfaces of the reservoir-surrounding rock. As the basis functions piecewise-continuous quadratic Lagrange polynomials were used. The number of degrees of freedom of the problem was still approximately 170000. The numerical integration required to find the elements of the Jacobian, was carried out using the Gauss quadrature formula. To solve systems of linear algebraic equations Gaussian method was used, adapted to the use of very sparse matrices. The relative accuracy of calculations at each step of the iterative process was 0.01. Calculations were performed on a computer that has a processor with a clock speed of 3.33 GHz and 4 GB of RAM. Typical calculation time was approximately 60 hours.

Calculations were performed for the parameters listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_s )</td>
<td>2000 kg/m³</td>
</tr>
<tr>
<td>( \rho_h )</td>
<td>910 kg/m³</td>
</tr>
<tr>
<td>( \lambda_w )</td>
<td>0.58 W/(m·K)</td>
</tr>
<tr>
<td>( \lambda_g )</td>
<td>0.0072 W/(m·K)</td>
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<tr>
<td>( \lambda_h )</td>
<td>2 W/(m·K)</td>
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<tr>
<td>( \lambda_s )</td>
<td>1.9 W/(m·K)</td>
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<tr>
<td>( C_W )</td>
<td>4200 J/(kg·K)</td>
</tr>
<tr>
<td>( C_G )</td>
<td>2093 J/(kg·K)</td>
</tr>
<tr>
<td>( C_H )</td>
<td>2700 J/(kg·K)</td>
</tr>
<tr>
<td>( C_S )</td>
<td>920 J/(kg·K)</td>
</tr>
<tr>
<td>( Q )</td>
<td>510 kJ/kg</td>
</tr>
<tr>
<td>( R )</td>
<td>8,3143 J/(mol·K)</td>
</tr>
<tr>
<td>( M_{CH_4} )</td>
<td>0,016043 kg/mol</td>
</tr>
<tr>
<td>( M_{H_2O} )</td>
<td>0,018 kg/mol</td>
</tr>
<tr>
<td>( M_h )</td>
<td>0,119543 kg/mol</td>
</tr>
<tr>
<td>( A_{HS} )</td>
<td>0,375 mm³</td>
</tr>
<tr>
<td>( \Delta E )</td>
<td>9,4 kJ/mol</td>
</tr>
<tr>
<td>( k_d^0 )</td>
<td>1,24·10⁶ mol/(m²·MPa·s)</td>
</tr>
<tr>
<td>( N )</td>
<td>2</td>
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<tr>
<td>( n )</td>
<td>5.75</td>
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<tr>
<td>( m )</td>
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</tr>
<tr>
<td>( a_1 )</td>
<td>10 K</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>128,1 K</td>
</tr>
<tr>
<td>( T_c )</td>
<td>190,5 K</td>
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<tr>
<td>( P_c )</td>
<td>45,8·10⁷ Pa</td>
</tr>
</tbody>
</table>

Table 1. Parameters used in simulation runs.

RESULTS AND DISCUSSION
In this work, we studied numerically the model of dissociation of gas hydrate in porous medium reservoir of Class 3 under the action of microwave radiation. Calculations were performed for the three microwave radiation frequencies 460 MHz, 915 MHz and 2.45 GHz allowed for industrial use. The research of the model was conducted for three variants of bed stimulation. In the first option, the wellbore pressure was lower than the reservoir pressure (depressurization). In the second variant, the wellbore pressure was equal to the reservoir...
pressure. In the third variant, the wellbore pressure was higher than the pressure in the reservoir (injection of fluid into the reservoir). In the first variant, fluids flow to the well because of the pressure gradient. In local regions where the pressure is below the equilibrium pressure, gas hydrate is decomposed into water and gas. This reaction is endothermic, taking place due to the sensible heat of the reservoir and surrounding rocks. As a result, the temperature decreases in these regions of the reservoir. Under such conditions, the rate of heat transfer is small and the dissociation of gas hydrate is slow. The acceleration of the process of dissociation of gas hydrate can be obtained due to the supply of heat released by the absorption of electromagnetic radiation. The disadvantage of this approach is that due to the flow of water and gas to the well part of the extracted heat is carried away by this flow and is not involved in the dissociation of gas hydrate. In the second variant all the heat released by the absorption of radiation is expended on heating the formation and dissociation of gas hydrate. However, in this case, the convective heat transfer is small. It leads to overheating of the area near the well where the gas hydrate is completely decomposed. The energy efficiency of such an action is reduced. In the third variant because of the pressure gradient between the well and reservoir water and gas are flowing along the radial direction from the borehole. The most intense absorption of microwave radiation by water occurs in the borehole area. The flow of the heated water into the formation creates a significant convective heat transfer, which contributes to the effective dissociation of gas hydrate. The comparison of results of three variants of stimulation studies allowed us to conclude that the best results on the rate of dissociation of gas hydrate, as well as the energy efficiency of the method were obtained for the third option.

In this paper, the research of the model of gas hydrate decomposition was conducted for different values of absolute permeability $K_0$ (from 0.1 to 100 mD), the initial hydrate saturation $s_{h0}$ (from 0.2 to 0.8), as well as for various conditions of bed stimulation: the power (from 5 to 30 kW) and frequency of microwave radiation (460 MHz, 915 MHz and 2.45 GHz), the pressure difference in the well and reservoir (from 0 to 8 MPa), the heating time (from 0 to 30 days). In conducting the numerical study of the model by the spatial and temporal distributions of temperature, pressure, hydrate saturation, water saturation, gas saturation in the reservoir, and the dependence of the masses of dissociated hydrates and precipitated water and gas on the heating time were obtained. Figures 1-2 show the calculated temperature and pressure in the reservoir dependent on radial distance from a radiation source for three heating times ($K_0 = 3 \cdot 10^{-15} m^2$, $f = 400 MHz$, $W = 10 kW$).

Figure 1 shows a characteristic kink of temperature graph indicating the boundary separating the reservoir into two regions: in the first the temperature remains constant and equal to the initial temperature of the reservoir. The rapid growth in the other is observed. The constancy of temperature in the first region is due to the fact that all the piped heat is expended on the dissociation of gas hydrate available there, and in the second region, located close to the source of radiation the heating of water and gas occurs in the absence of gas hydrate. It is evident that the region of elevated temperature and pressure in the reservoir expands in the course of time. As can be seen from Figure 3 in this region the reservoir pressure is less than the equilibrium pressure of the existence of gas hydrate at the local temperature. Therefore, in this region the gas hydrate dissociated in water and gas.

Figure 4 shows the hydrate saturation isolines in the reservoir. Figure 5 shows the hydrate saturation in the reservoir for three times of heating. It is evident that the phase transition (gas hydrate dissociation) occurs in an extended zone of about 3-10 m in the radial direction if the frequency of microwave radiation is 460 MHz. Fig.6 shows the hydrate saturation in the reservoir in the case of heating the layer of microwave radiation frequency $f = 2.45 GHz$. In this case a narrow region of gas hydrate decomposition is observed.

In this paper, we calculated the masses of the dissociated gas hydrate, gas hydrate dissociation rate and the volume of gas evolved at the same time. Figures 7-8 show the dependence of the masses of the dissociated gas hydrate and the volume of evolved gas on the heating time. The study of the model showed the possibility of determining the optimal conditions of bed stimulation. For reservoirs with given values of absolute permeability and the initial hydrate
Figure 1: The temperature distribution in a reservoir for three heating times:
--- 24 hours; --- 120 hours; --- 240 hours

Figure 2: The pressure distribution in a reservoir for three heating times:
--- 24 hours; --- 120 hours; --- 240 hours

Figure 3: The pressure distribution in a reservoir:
--- Pressure in a reservoir; --- equilibrium pressure

Figure 4: Hydrate saturation isolines in the reservoir:
\( s_h = 0.01; 0.1; 0.2; 0.3; 0.39 \)

Figure 5: The hydrate saturation in the reservoir for three times of heating:
--- 24 hours; --- 120 hours; --- 240 hours

Figure 6: The hydrate saturation in the reservoir
Figure 7  The dependence of the masses of the
dissociated gas hydrate on the heating time.
\( K_0 = 3 \cdot 10^{-15} \ m^2, f = 400 \ MHz, W = 10kW \)

Figure 8  The dependence of the volume of
evolved gas on the heating time.
\( K_0 = 3 \cdot 10^{-15} \ m^2, f = 400 \ MHz, W = 10kW \)

Figure 9  The dependence of the masses of the
dissociated gas hydrate on the heating time.
\( K_0 = 3 \cdot 10^{-13} \ m^2, f = 915 \ MHz, W = 10kW \)

Figure 10  The dependence of the masses of the
dissociated gas hydrate on the heating time.
\( K_0 = 3 \cdot 10^{-15} \ m^2, f = 915 \ MHz, W = 10kW \)

Figure 11  The dependence of the masses of the
dissociated gas hydrate on the heating time.
\( K_0 = 3 \cdot 10^{-14} \ m^2, f = 2.45 \ GHz, W = 10kW \)

Figure 12  The dependence of the masses of the
dissociated gas hydrate on the heating time.
\( K_0 = 3 \cdot 10^{-14} \ m^2, f = 915 \ MHz, W = 5kW \)
saturation the optimal values of power and frequency of microwave radiation and the pressure difference in the well and reservoir have been determined. The overheating of the area around the well, which has already completely decomposed gas hydrate is not significant at the optimum values of these parameters. The energy efficiency of thermal bed stimulation increases. Figures 9-12 show the dependence of the mass of the dissociated gas hydrate on heating time for the layers with different values of absolute permeability and the initial hydrate saturation at the optimal conditions of bed stimulation.

It was found that the application of microwave radiation with frequencies 915 MHz and 2.45 GHz results in a higher rate of dissociation of gas hydrate for reservoirs with high absolute permeability (10-100 mD) and the initial hydrate saturation is less than 0.5. For reservoirs with low absolute permeability (<10 mD), the best results are obtained using microwave radiation with a frequency of 460 MHz.

Let’s calculate the efficiency of the method of gas extraction from gas hydrate using electromagnetic heating. The calculation is performed for the heating time $t=240$ hours ($f=2.45$ GHz, $W=5$ kW). Electromagnetic energy released in the reservoir is 

$$E_{em} = 5 \cdot 10^3 [W] \cdot 240 [hour] \cdot 3600 [s] = 4,32 \cdot 10^9 J$$

Energy given off by burning of methane hydrate, during the dissociation is equal to

$$Q_{CH_4} = 1186.9 [kJ] \cdot 4 \cdot 10^7 [J/kg] = 4,75 \cdot 10^{10} J$$

where $q = 4 \cdot 10^7 J/kg$ - the heat released during the combustion of 1 kg of methane.

Then the ratio of the received and expended energy is equal to

$$\frac{Q_{CH_4}}{E_{em}} = \frac{4,75 \cdot 10^{10}}{4,32 \cdot 10^9} \approx 11$$

Thus, the method can be considered as acceptable in terms of energy efficiency.

It has been shown that the efficiency of heating depends significantly on proper choice of radiator frequency and power. These results are quite usable from a practical standpoint, and the electromagnetic heating method is technically achievable and competitive, for example, with the inhibitor injection method. It is shown that high frequency microwave heating may be used for stimulating gas production from gas hydrate reservoirs.

ACKNOWLEDGMENT

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REFERENCES


