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ТЕПЛО-ГІДРАВЛІЧНИЙ РОЗРАХУНОК МЕРЕЖІ НАФТОВИХ ТРУБОПРОВОДІВ НА ОСНОВІ ДВОШАРОВОГО БОНД-ГРАФУ

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THERMAL-HYDRAULIC CALCULATION OF OIL PIPELINES NETWORK BASED ON A TWO LAYERS BOND-GRAPH

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ABSTRACT

Purpose. Parallel synchronized calculation of networks with certain hydraulic and thermal properties of separate oil pipelines, which is possible with the use of a two-layer bond graph and a complex methods of potentials in nodes and methods loop currents in circuits. The authors propose to link two layers of graphs of the scheme using the equation of state of oil as a gas-liquid mixture, which will simplify and increase the speed of calculations.

Findings. The principles of operation of the ball valve of the shut-off valve and its main differences from the flopper shutter are considered in detail. Also, the geometric parameters of the ball itself are demonstrated in detail. Examples of design are given, and the operating principle of the most common models of shut-off valves is described.

Originality. The connection of the hydraulic and thermal layer of the bond-graph is realized by taking into account the average temperatures and the total heat transfer coefficient on the branches of the graph.

Practical implications. The developed system of equations of the two-layer bond graph is applied to an estimation of work of networks of oil pipelines at designing and change of operational modes.

Keywords: pipelines network, bond-graph, method of potentials, loop current method, mathematical model, oilpipe operational modes, oil.

Introduction Engineering network systems are well modeled using multilayer bond graphs [1-2]. Thermal and hydraulic circuits, systems with distributed parameters are represented by a set of elements of individual layers, which are further synchronized by iterative calculations or search and connect branches and nodes [3-4].

The system of equations of the mathematical model of the hydraulic network of connected oil pipelines according to [5-6] and electro-hydraulic analogy in matrix form

$$\boldsymbol{A}_* \cdot \boldsymbol{Z}^{-1} \cdot \boldsymbol{A}_*^{\boldsymbol{T}} \cdot (\boldsymbol{F} - \boldsymbol{F_o}) = \boldsymbol{A}_* \cdot \boldsymbol{J} - \boldsymbol{A}_* \cdot \boldsymbol{Z}^{-1} \cdot \boldsymbol{E}$$

– flow balance in the circuits (1)

$\boldsymbol{I} + \boldsymbol{J} = \boldsymbol{Z}^{-1} \cdot (\boldsymbol{E} + \boldsymbol{U})$ - Ohm's general law

$\boldsymbol{U} = \boldsymbol{A}^{\boldsymbol{T}} \cdot (\boldsymbol{F} - \boldsymbol{F_o})$ – balance of potential differences,

where current – *I*;
potential – *F*;
voltage – *U*; A_* -

We make the following substitutions of parameters according to the principles of analogy [2]:

-current *I* per square mass flow (*Mq*) Mq^2 = I;

- potential *F* per square pressure *P* at the node P^2 = *F*;

- the resistance between the nodes *Z* is left Z = Z;

- voltage *U* per square pressure drop $P^2_2 - P^2_1$ on the branch (from point 1 to point 2) $P^2_2 - P^2_1 = U$;

- voltage source *E* per potential pressure energy between nodes *Ep = E*;

- current sources *J* per square mass flow on the branch $S^2 = J$.

The specified transition to hydraulic parameters taking into account the above-mentioned substitutions of quantities (units of measurement) transforms (1) into the following system of equations of the mathematical model of the first (hydraulic) layer:

$$\boldsymbol{A_* \cdot Z^{-1} \cdot A_*^T \cdot (P^2 - P_0^2) = A_* \cdot S^2 - A_* \cdot Z^{-1} \cdot E_p - Mq^2 + S^2 = Z^{-1} \cdot (E_p + P_2^2 - P_1^2)} \quad (2)$$
$$\boldsymbol{P_2^2 - P_1^2 = A^T \cdot (P^2 - P_0^2)}$$

To the system (2), where the balance and hydraulic losses from friction are restrained, it is traditionally necessary to add the equations of state, energy and heat exchange [7]

$P = \rho \cdot z \cdot R \cdot T$ - state equation of the gas-liquid mixture (oil), (3)

$Q_t = M_q C_p (T_2 - T_1) = K S (T_{av} - T_o)$ - heat exchange (4)

$w(T2 - T1) = \lambda T(d2T/dx2)/Cp\rho + qv(Tav\text{-}To)/Cp\rho Mf$ (5)

where λ is the coefficient of pneumatic resistance of the pipeline; *z* is the gas compressibility; *R* is the gas constant; *P* is the pressure; *T* is the temperature; *Re* is the Reynolds number, *L* is the gas pipeline length; *D* is the gas pipeline diameter; ρ is the gas density; *S* is the area of cross section of the gas pipeline; *v* is the gas velocity.

Traditionally, it is proposed to do calculations in parallel, but both layers of the network system exist as if separately [7-8].

This leads to an increase in the difficulty of synchronization on the branches and nodes of the scheme, increasing the time of the overall coordination of material and heat balances.

Thermohydraulic calculations of oil pipeline networks are performed by engineers using modern software, which simplifies preliminary technological forecasting.

To do this, in particular, use complete systems of equations for each individual section of the pipe, which are similar to the [6] like

$$\begin{cases} \frac{1}{z(P,T)RT}\cdot\frac{\partial P}{\partial t}+\frac{w}{z(P,T)RT}\cdot\frac{\partial P}{\partial x}+\rho(P,T)\cdot\frac{\partial w}{\partial x}- \\ -\frac{K_1\rho(P,T)}{T}\cdot\frac{\partial T}{\partial t}+\frac{1}{S}\cdot dG_x(x_в,t_в)=0, \\ \frac{1}{\rho(P,T)}\cdot\frac{\partial P}{\partial x}+\frac{\partial w}{\partial t}+2\cdot\alpha\cdot w\cdot\frac{\partial w}{\partial x}+(1+\alpha)\cdot\frac{w^2}{P}\cdot\frac{\partial P}{\partial x}+\frac{\lambda(P,T,w,k_e)\cdot w^2}{2\cdot D}=0, \\ c_p(P,T)\cdot\left(w\frac{\partial T}{\partial x}+\frac{\partial T}{\partial t}-K_2\cdot D_j\cdot(P,T)\frac{\partial P}{\partial x}\right)+\frac{4\cdot K\cdot\ln(T-T_0)}{\rho(P,T)\cdot D}+K_3\frac{k-1}{k}\frac{w}{R}\frac{\partial w}{\partial t}=0, \\ P=\rho\cdot z(P,T)\cdot R\cdot T, \\ c_p(P,T)=1695+1{,}838\cdot T+\frac{1960\cdot(P-10^5)}{T^3}, \\ D_j=9{,}26\cdot10^{-3}\frac{\Delta^{1,3}\cdot R\cdot T^{0,7}}{(P_1-P_2)}[\ln(1695+1{,}838T+1960\cdot T^{-3}\cdot P_1), \\ -\ln(1695+1{,}838T+1960\cdot T^{-3}\cdot P_2)\Big], \\ z(P,T)=1-5{,}5\cdot\frac{\Delta^{1,3}}{T^{3,3}}\cdot P, \\ \lambda(P,T,w,k_e)=0{,}067\left(\frac{158}{\mathrm{Re}(P,T,w)}+\frac{2\cdot k_e}{D}\right)^{0,2}, \\ \mu(P,T,M)=\frac{(9.41+0.02\cdot M)\cdot(1.8\cdot T)^{1.5}}{(209+19\cdot M+1.8\cdot T)\cdot10^7}\cdot EXP\left[\left(3.5+\frac{547.8}{1.8\cdot T}+0.01\cdot M\right)\times\right. \\ \left.\times\left(\frac{P\cdot10^3}{Zskv(P,T)\cdot\frac{8314.3}{M}\cdot T}\right)^{\left[2.4-0.2\left(3.5+\frac{547.8}{1.8T}+0.01M\right)\right]}\right], \end{cases}$$

(6)

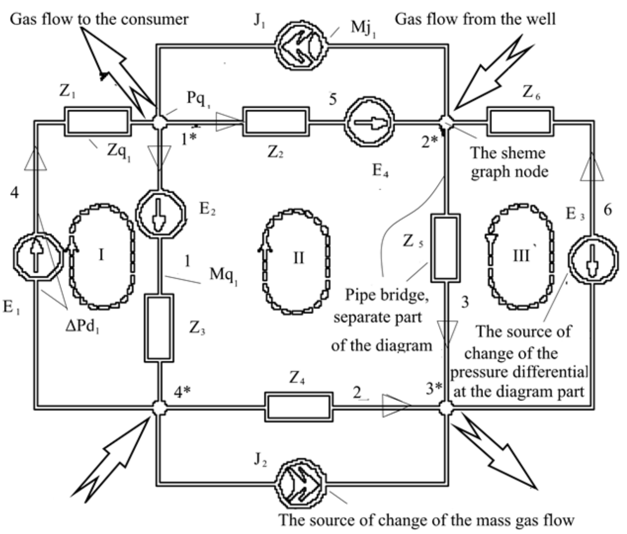
where *μ (P, T, M)* is dynamic viscosity; *P* is pressure; *T* is temperature; *M* is molar mass; k_e is equivalent internal roughness of the pipeline wall; *w* is the averaged in the cross section flow rate of the gas; *D* is diameter; Re is the Reynolds number; x_B is longitudinal coordinate; t_B is time; *To* is temperature of ground and rocks near the pipeline; G_x (x_B, t_B) is mass flow rate in the branch; K_1, K_2, K_3 are coefficients that take into account dimension and analytical simplifications.

It can be seen that system (6) takes into account the nonstationarity and throttle effect, which in many cases is insignificant for liquid oil pipelines.

In some cases, it is possible to use a simplified mathematical apparatus based on an adequate model with averaged parameters, which speeds up the work and provides sufficient accuracy. This is the approach proposed in this paper. The construction of a simplified mathematical model for fast engineering calculation operations is chosen as the research task.

Despite the large number of precedents for the application of graph theory in oil and gas [3-8], methodologies for analysis of engineering and technological elements of oil and gas fields with the involvement of bond graphs [3, 4, 7-10], compilation and analysis of bond graphs of oil pipelines with heat transfer in modern research separately and is not presented in detail.

Main Part. Taking the model from our work [6] and the principles of initial approximations of calculations from work [11]



$$B=\begin{pmatrix} 1\,0\,0\,1\,0\,0 \\ -1\,-1\,1\,0\,1\,0 \\ 0\,0\,1\,0\,0\,1 \end{pmatrix} \qquad A=\begin{pmatrix} 1\,0\,0\,-1\,1\,0 \\ 0\,0\,1\,0\,-1\,-1 \\ 0\,-1\,-1\,0\,0\,1 \end{pmatrix} \qquad Z=\begin{pmatrix} Z_3\,0\,0\,0\,0\,0 \\ 0\,Z_4\,0\,0\,0\,0 \\ 0\,0\,Z_5\,0\,0\,0 \\ 0\,0\,0\,Z_1\,0\,0 \\ 0\,0\,0\,0\,Z_2\,0 \\ 0\,0\,0\,0\,0\,Z_6 \end{pmatrix}$$

$$E=(E_2\;0\;0\;E_1\;E_4\;-E_3)^T \qquad J=(0\;-J_2\;0\;0\;J_1\;0)^T$$

Fig.1 - The network of oil and gas pipelines as a bond-graph of the hydraulic layer.

From the results of work [11] it is possible to accept both a hydraulic and a thermal model, since the flows of gas and liquid mixtures were considered. This is applicable for solving the problem posed in our work:

To develop the problem of the research into the system of equations, we will take into consideration the pipe heat transfer in the system of equations (5-6). After transformations, we will obtain the general system of equations of the mathematical model of non-isothermal non-stationary one-dimensional motion of the gas-liquid mixture in the pipeline during heat transfer through a cylindrical wall in the form:

$$\begin{gathered}
\frac{\partial P}{\partial x}+\frac{\partial(\rho w)}{\partial t}+(1+\beta)\frac{\partial(\rho w^2)}{\partial x}+\frac{\rho g \partial h}{\partial x}+\frac{\lambda \rho w^2}{2D}=0; \\
\frac{\partial \rho}{\partial t}+w\frac{\partial \rho}{\partial x}+\rho\frac{\partial w}{\partial x}=0; \\
P=\rho z R T; \\
w\frac{\partial T}{\partial x}+\frac{\partial T}{\partial t}-D_j\frac{w\partial P}{\partial x}+\frac{4K_t(T-T_0)}{\rho D C_p}-K_\lambda\frac{\lambda}{D}\frac{w^3}{C_p}=0; \\
w=\frac{\partial x}{\partial t}; \\
M_q=wS\,\rho,
\end{gathered} \tag{7}$$

where P is the pressure of the mixture; T is the temperature of the mixture; w is the flow velocity averaged in cross-section; ρ is the density of the mixture; D is the diameter of a pipeline; x is the longitudinal coordinate of a pipeline; t is the time; T_o is the temperature of soil and rocks near a pipeline (environment); K_t is the coefficient of thermal conductivity from the mixture to the environment of the system "mixture – pipeline – environment"; D_j is the Joule-Thomson coefficient; K_λ is the coefficient of convective heat transfer in the mixture flow; C_p is the isobaric thermal capacity of the mixture; z is the coefficient of compressibility of the mixture; λ is the coefficient of hydraulic resistance of a pipeline; g is the gravity acceleration; β is the Coriolis coefficient; M_q is the mass flow rate of the mixture, L is the pipeline length.

If we consider the system of equations (2) and the system of equations (7) together, then it is possible to make some simplifications in accordance with the specifics of oil pipelines. At constant M_q, the equation of balance of energies (fourth in system (7)) for the quasi-stationary process, taking into consideration the throttle effect is converted into the form (4):

$$\begin{gathered}
M_q\cdot C_p\cdot((T_2-T_1)-D_j\cdot(P_2-P_1))= \\
=K_t\cdot\pi\cdot D\cdot\int_0^L(T_0-T_x(x))\,dx,
\end{gathered} \tag{8}$$

where $T_x(x)$ is the dependence of temperature on longitudinal coordinate in the pipeline; T_1, T_2 are the temperatures at the beginning and at the end of the considered pipeline section.

Thus, for a network of oil pipelines, it is sufficient to take a set of equations (2), (3), and (8), which will be sufficient to connect the thermal and hydraulic layer of the bond graph using the equation of state (3) and mathematical results from [12].

The latter facts will make it possible to quickly assess the technological modes and productivity of oil pipelines without using more complex programs and analytical models. As a result of modeling the circuit (Fig. 1), it was found that in this case it is possible to apply average temperatures T_{av} and generalized heat transfer coefficients K on separate branches of the bond-graph layers. And this averaging can be done according to the temperature and pressure data at the nodes of the circuit.

The obtained results correlate well with theoretical hypotheses from the works [13,14], as well as with guidelines for further research in modern theoretical research.

Conclusions. The use of bonding the layers of the bond-graph in terms of hydraulic and thermal characteristics is possible with the use of averaged heat engineering parameters. In this case, the hydraulic section can be taken such that there is an average temperature and an average heat transfer rate, which allows you to synchronize the layers and bring them to a single and unified numbering of branches and nodes. Reception is efficient for modeling and preliminary assessment of technological modes of operation of the oil pipeline network.

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ABSTRACT (IN UKRAINIAN)

Мета. Паралельний синхронізований розрахунок трубопровідних мереж з індивідуальними гідравлічними і тепловими властивостями окремих нафтопроводів, який можливий з використанням двошарового бонд-графа (зв'язкового графа) і комплексного поєднання методу потенціалів у вузлах з методом струмів у ланцюгах. Автори пропонують пов'язати два шари зв'язкового графа схеми за допомогою рівняння стану нафти як газорідинної суміші, що спростить і збільшить швидкість попередніх технологічних розрахунків.

Висновки. Застосування зв'язування шарів бонд-графу щодо гідравлічних і теплових характеристик можливе із застосуванням ряду усереднених термобаричних параметрів. В цьому випадку гідравлічна ділянка може вважатися такою, на якій є середня температура і середній показник теплообміну, що дозволяє синхронізувати шари і привести їх до єдиної і уніфікованої нумерації гілок і вузлів. Прийом виявився програмно-працездатним і перевірений на практиці для моделювання та попередньої оцінки технологічних режимів роботи мережі нафтопроводів.

Оригінальність. Зв'язок гідравлічного і теплового шарів бонд-графу реалізована з урахуванням середніх температур і сумарного коефіцієнта теплопередачі на гілках графа.

Практичне значення. Розроблена система рівнянь двошарового графа зв'язків (бонд-графа) застосовується для інженерної оцінки роботи мереж нафтопроводів при технологічному проектуванні і зміні режимів роботи ділянок мережі нафтопроводів.

Ключові слова: *трубопровідна мережа, бонд-граф, метод потенціалів, метод контурних струмів, математична модель, режими роботи трубопроводів, нафта.*

ABSTRAST (IN RUSSIAN)

Цель. Параллельный синхронизированный расчет трубопроводных сетей с индивидуальными гидравлическими и тепловыми свойствами отдельных нефтепроводов, который возможен с использованием двухслойного бонд-графа (связного графа) и комплексного соединения метода потенциалов в узлах с методом токов в цепях. Авторы предлагают связать два слоя связного графа схемы с помощью уравнения состояния нефти как газожидкостной смеси, что упростит и увеличит скорость предварительных технологических расчетов.

Выводы. Применение связывания слоев бонд-графа по гидравлическим и тепловым характеристикам возможно с применением ряда усредненных теплотехнических параметров. В этом случае гидравлический участок может приниматься таким, на котором есть средняя температура и средний показатель теплообмена, что позволяет синхронизировать слои и привести их к единой и унифицированной нумерации ветвей и узлов. Прием оказался программно-работоспособен и проверен на практике для моделирования и предварительной оценки технологических режимов работы сети нефтепроводов.

Оригинальность. Связь гидравлического и теплового слоев бонд-графа реализована с учетом средних температур и суммарного коэффициента теплопередачи на ветвях графа.

Практическое значение. Разработанная система уравнений двухслойного графа связей (бонд-графа) применяется для инженерной оценки работы сетей нефтепроводов при технологическом проектировании и изменении режимов работы участков сети нефтепроводов.

Ключевые слова: *трубопроводная сеть, бонд-граф, метод потенциалов, метод контурных токов, математическая модель, режимы работы трубопроводов, нефть.*

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