Method for Creation of Cell Models as a Universal Tool for the Development of Mathematical Models of Dynamics Used to Perform Smart Control of Oil Production Facilities

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Abstract. The author suggests using a method based on cell models to develop dynamic mathematical models intended for the smart control of oil production facilities. The method is applicable both to the facilities with lumped parameters and for those with distributed parameters (being more suitable for the latter as they are more complex in terms of computations). The paper provides the examples of mathematical description of the processes performed using the cellular model for some vessels most widely used in oil production, and the examples of simulation of controlled facilities by MATLAB Simulink, as well as the simulation results in the form of statistic and dynamic characteristics of the facilities by various channels, which are consistent with the experimental data. The general simulation methodology is formulated. The models obtained can be implemented in industrial automation for oil production industry.

1. Introduction
The topic discussed in this paper is related to the class of problems that occur in the course of development of mathematical software – models and algorithms – for modern smart controllers designed to control oil production and treatment facilities. Using expensive tools such as aspenOne by Aspen Tech or HYSYS by Honeywell to create advanced control systems for oil production processes is not effective due to the relatively low yield of oil production facilities (as compared with large oil refining complexes) and their geographical distribution across the territory of the fields with dozens of kilometers between the facilities. At the same time, the developers of MathWorks’ MATLAB software have enhanced the latest versions of their product with the possibility to directly upload the program code of simulation and control programs developed using such applications as Simulink, Fuzzy Logic Toolbox, Neural Networks Toolbox in the memory of logical controllers thus turning general-purpose PLCs into smart control tools, which gave rise to new researches devoted to the creation of smart control systems using MATLAB Simulink [1] including the systems for oil production facilities [2,3]. All this turns the task of developing mathematical models and control algorithms by MATLAB Simulink tools into a leading-edge topic.

The method of chemical facilities simulation based on cell models. The method of chemical facilities simulation based on cell models as a equal-size mixed flow reactors in series, which is suggested in this paper, is relatively well known [4,5]. However, in former years, this method was hindered to a large extent by the insufficient power of electronic computing machines required to solve differential equation systems in real time mode. Today, as the potential of computational equipment has increased...
manifold, this simulation method is rather actively used for the mathematical description of the applications of nanoparticles/nanofluids in the Enhanced Oil Recovery process [6], thermal [7,8] and chemical [9] processes, in construction industry [10] and computer engineering [11]. The paper offers alternate solutions both for static and dynamic problems. Dynamic models of facilities are required for the purpose of real time control.

The goal of this paper is to provide the examples demonstrating the general principles of creation of cell dynamic models both with lumped parameters and distributed parameters intended for the control of oil production processes.

2. Peculiarities of Cell Dynamics Models for Process Vessels of Different Types

It is reasonable to examine the physics of a cell model by the example of the cell hydrodynamics model that serves as the basis for such models of any nature. The essence of the cell model is that the control facility is represented by several cells connected in series through which the flow of fluid or gas passes. At the same time, it is assumed that the flow in each cell has the structure of ideal mixing and there is no missing between the cells [4]. Figure 1 explains the cell model structure by the example of serially connected objects of ideal mixing.

![Figure 1](image1.png)

**Figure 1.** Example of hydrodynamic cell model of a system consisting of \( n \) serially connected objects of ideal mixing.

The mathematical description of the cell model considered is represented by a system of \( n \) standard differential balance equations of the following type:

\[
\frac{dC_i(t)}{dt} = \frac{1}{\tau_i} [C_{i-1}(t) - C_i(t)], \quad i = 1, n
\]

where \( C_i(t) \), \( C_{i-1}(t) \) is the substance concentration in the flow at the inlet of cell \( i \) and at its outlet, mol/m\(^3\); \( V_i \) is the volume of ideal mixing cell, m\(^3\); \( v \) is the volumetric flow rate (volume flow) through the cell system, m\(^3\)/s; \( t \) is time, s; \( n \) is the number of cells. Variable \( \tau_i \) designates the mean time of fluid particles residence in a cell, which is an important parameter of the cell model. If \( n = 1 \), the cell model transforms into an ideal mixing model, if \( n \to \infty \), it turn into an ideal displacement model [3] characterized by the piston flow of the fluid without the longitudinal mixing, which can be seen from the charts in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Reaction of cell model to a unit signal \( l(t) \) (on the left) and a pulse signal \( \delta(t) \) (on the right) at different number of cells \( n=1, 3, 5, 10 \).

Real chemical facilities may have the properties of both ideal mixing objects and ideal displacement object, as well as a combination of both. By changing \( n \) we can use the cell model to create different types of hydrodynamic or thermal regime, which is the reason for using the cell approach as a universal simulation tool.

In case of heat exchange or mass exchange processes, there occur the phenomena of either heat exchange or substance exchange, and the balance equations (1) are composed considering these phenomena. In this case, the individual cells relating to different flows start interacting. The region of such interaction also involves the sections of isolation medium between the flows, i.e. the heat exchanger walls or the interface.
Let us define the general features and peculiarities of cell models creation for various types of processes and vessels used in chemical and oil production industries. Figure 3 illustrates the overall view of a parallel-flow shell and tube exchanger, while Figures 4, 5 demonstrate the method for the creation of cell model of this vessel.

The differential equation of an individual heat carrier flow corresponding to the ideal displacement model considering the heat transfer can be written as:

\[ S \cdot \rho \cdot C_p \frac{dT}{dt} = -V \cdot \rho \cdot C_p \frac{dT}{dt} + \frac{F}{L} K_T \cdot F \cdot \Delta T, \tag{2} \]

where \( S \) is the area of the flow cross section, \( m^2 \); \( L \) is the length of the ideal displacement zone, \( m \); \( l \) is a space coordinate varying from 0 to \( L \); \( T = T(l, t) \) is the function of heat carrier flow temperature distribution along the space coordinate in time; \( \rho \) is the heat carrier density, \( \text{kg/m}^3 \); \( C_p \) is the heat carrier specific heat capacity, \( \text{J/(kg \cdot K)} \); \( v \) is the volumetric flow rate, \( \text{m}^3/s \); \( F \) is the heat exchange area, \( m^2 \); \( K_T \) is the heat-transfer factor, \( \text{W/(m}^2\text{-K)} \); \( \Delta T \) is the mean temperature difference between the heat carriers, \( K \); \( t \) is time, \( s \).

Figure 4 shows the following: \( D_1 \) is the outer (first) pipe diameter, \( m \); \( S_1 \) is the area of the outer pipe cross section, \( m^2 \); \( D_2 \) is the inner (second) pipe diameter, \( m \); \( S_2 \) is the area of the inner pipe cross section, \( m^2 \); \( L \) is the cell length, \( m \); \( S_w \) is the inner pipe wall cross section, \( m^2 \); \( h_w \) is the inner pipe wall thickness, \( m \).

The standard method for model creation of a heat exchanger of the type “displacement-displacement” where the heat carrier flow is based on the pipe-in-pipe principle includes the composition of a partial differential equation system of the form (2) for each heat carrier and an additional heat balance equation of the wall separating the heat carrier, and the subsequent solving of the system by special numerical techniques (for example, by the finite-difference method). Nevertheless, this method is rather labor-intensive. The cell method suggests a simpler, more illustrative and at the same time more efficient alternative. The scheme shown in Figure 6 explains the structure of a similar cell model composed for a counter-flow heat exchanger. The difference between the counter-flow heat exchanger model and that of a parallel-flow heat exchanger (Figure 4) is that the flow direction of the second heat carrier changes as the heat carrier with temperature \( T_{20} \) comes to cell \( n \), i.e. to the far right cell, and goes out with temperature \( T_3 \) from the first (far left) cell. Consequently, the flows direction of the second heat carrier also changes for all intermediate cells. The equation system for pair \( i \) of the cells separated by a wall section can be written in the form of the system of standard differential equations (3)-(5) that can be solved by Simulink tools without any significant computational problems.

\[
\frac{dT_i}{dt} = \frac{v_i \cdot n \cdot (T_{i(i-1)} - T_i) - \alpha_1 F_1 (T_{i(i-1)} - T_{i2})}{V_i \cdot \rho_i \cdot C_p} \cdot \frac{1}{V_i \cdot \rho_i \cdot C_p}, \quad i = 1 \ldots n \tag{3}
\]

\[
\frac{dT_2}{dt} = \frac{v_2 \cdot n \cdot (T_{2(i-1)} - T_{2i}) + \alpha_2 F_2 (T_{i2} - T_{2(i-1)})}{V_2 \cdot \rho_2 \cdot C_p} \cdot \frac{1}{V_2 \cdot \rho_2 \cdot C_p}, \quad i = 1 \ldots n \tag{4}
\]
\[
\frac{dT_i}{dt} = \left[ F_1 \alpha_1 (T_{1i} - T_3) - F_2 \alpha_2 (T_{3i} - T_2) \right] \frac{1}{C_i G_i}, \quad i = \overline{1,n}
\]

where \( V_1, V_2 \) are the total volumes of the first and second pipes, correspondingly, \( m^1; \rho_1 \) and \( \rho_2 \) are densities of the first and second heat carriers, correspondingly, \( kg/m^3; C_{\rho_1} \) and \( C_{\rho_2} \) define the heat capacity of the first and second heat carrier, correspondingly, \( J/(kg\cdot K) \); \( T_{1i}, T_{2i}, T_{3i} \) are the temperatures of the first and second heat carrier and the wall, correspondingly, \( K; \alpha_1, \alpha_2 \) are heat-transfer factors, \( W/(m^2\cdot K) \); \( v_1 \) and \( v_2 \) are the volumetric flow rates of the first and second heat carrier, correspondingly, \( m^3/s; G_3 \) is the wall material mass, \( kg; C_s \) is the wall material specific heat capacity, \( J/(kg\cdot K) \); \( t \) is time, \( s \).

It should be noted that the mathematical description of the state of \( i \) pair of cells in the form of the equation system (3)-(5) will not change in any way if the model is replaced with a counter-flow heat exchanger model. Considering that each of the cells is an ideal mixing cell, figuratively speaking, it makes no difference for the cell from where – from the left or from the right – the input flow of the adjacent heat carrier comes. Besides, the direction of the output flow of the second heat carrier in the block scheme of this cell has no influence on the form of the mathematical description of the cell.

As a consequence of this extremely important circumstance, in order to replace the model of a counter-flow heat exchanger with the model of a parallel-flow heat exchanger and vice versa, it is sufficient to switch the input and output signals of the cells in the existing block model as is shown below without producing any corrective actions either in the cell subprograms or at the upper level of the model.

It should be also noted that at the number of cells \( n=1 \) the equation system (3)-(5) will serve as the basis for simulating dynamic objects with lumped parameters of the type “mixing-mixing” also widely spread in the chemical technology, which determines the universal nature of the suggested approach.

Figure 6. Cell model of a counter-flow heat exchanger.

Figure 7. The scheme of process flows in a modular tube heater PTB-10.
While the combustion gases flow around the coiled tubes, the convective heat exchange of the gases with the oil emulsion pipe walls is performed. The total heat exchange is considered to be the sum of its convective and radiative portions. Upon completion of the heat exchange the exhaust gases are sent to the flues and are removed from the heater with the temperature of up to 400 °C.

In the case under consideration it is suggested that the cell model of the type “mixing-displacement” (Figure 8) should be used according to which one of the heat carrier flows (combustion gases) is simulated using one ideal mixing cell (a heat exchange chamber). The second flow of oil emulsion has the features of the ideal displacement model and will be described as a sequence of $n$ cells similarly to the example described above.

The equation system of the cell model of this type is represented in the following form. The heat balance equation will be written as

$$
\frac{dT_{\text{gas}}}{dt} = \frac{v_{\text{gas}}}{V_{\text{gas}}} \cdot (T_{\text{gas, b}} - T_{\text{gas}}) - \frac{(1 - \beta) \cdot \rho_{\text{gas}} \cdot F_{\text{gas}}}{V_{\text{gas}} \cdot C_{p,\text{gas}}} \cdot (T_{\text{gas}} - \frac{1}{n} \sum_{i=1}^{n} T_{w,i}) - \frac{\beta \cdot \varepsilon \cdot \rho_{\text{gas}} \cdot 10^4}{V_{\text{gas}} \cdot C_{p,\text{gas}}} \left( T_{\text{gas}} - \left( \frac{1}{n} \sum_{i=1}^{n} T_{w,i} \right) \right) - \frac{\Delta E_{\text{gas,loss}}}{V_{\text{gas}} \cdot C_{p,\text{gas}}},
$$

(6)

where $T_{\text{gas}}$ is the temperature of gases in all points and at the outlet of the heat exchange chamber (exhaust gas temperature), $K$; $v_{\text{gas}} = v_{\text{gas}}(T_{\text{gas}})$ is the volumetric flow rate of combustion gases at temperature $T_{\text{gas}}$ $m^3/s$; $V_{\text{gas}}$ is the volume of the heat exchange chamber, $m^3$; $T_{\text{gas, b}} = T_{\text{gas, b}}(\alpha_{\text{air}}, T_{\text{air}})$ is the gas temperature in the combustion chamber (at the heat exchange chamber inlet) at air excess factor $\alpha_{\text{air}}$ and air temperature $T_{\text{air}}$, $K$; $\beta$ is the proportion of radiation and convection heat exchange in the heat exchange chamber; $\alpha_{\text{gas}}$ is the factor of heat transfer from gas to the pipe wall, $W/(m^2 \cdot K)$; $C_{p,\text{gas}} = C_{p,\text{gas}}(T_{\text{gas}})$ is the combustion gases heat capacity at temperature $T_{\text{gas}}$, $J/(kg \cdot K)$; $T_{w,i}$ is the wall temperature in cell $i$, $K$; $\Delta E_{\text{gas,loss}}$ is the heat lost into the ambient environment (5%); $J/s$.

The system of heat balance equations for $n$ cells simulating the heat balance between the pipe wall and the oil emulsion has the following form:

$$
\frac{dT_{\text{em}(i)}}{dt} = \frac{v_{\text{em}}}{V_{\text{em}(i)}} \cdot (T_{\text{em}(i-1)} - T_{\text{em}(i)}) + \frac{\alpha_{\text{em}} \cdot F_{\text{em}(i)}}{V_{\text{em}(i)} \cdot C_{\text{em}(i)} \cdot \rho_{\text{em}(i)}} \cdot (T_{\text{w}(i)} - T_{\text{em}(i)}), \ i = \overline{1,n}
$$

(7)

where $V_{\text{em}(i)}$ is the inner volume of the pipe part relating to cell $i$, $m^3$; $\rho_{\text{em}(i)} = \rho_{\text{em}(i)}(T_{\text{em}(i)})$ is the emulsion density as the function of the temperature in cell $i$, $kg/m^3$; $C_{\text{em}(i)} = C_{\text{em}(i)}(T_{\text{em}(i)})$ is the emulsion heat capacity as the function of the temperature in cell $i$, $J/(kg \cdot K)$; $T_{\text{w}(i)}$ is the wall temperature in cell $i$, $K$; $\alpha_{\text{em}}$ is the factor of heat transfer from the wall to the oil emulsion, $W/(m^2 \cdot K)$; $v_{\text{em}}$ is the volumetric flow rate of the emulsion in the pipe, $m^3/c$; $F_{\text{em}(i)}$ is the area of the inner surface of the pipe relating to cell $i$, $m^2$.

The system of heat balance equations for $n$ cells simulating the heat balance of the pipe wall has the following form:

$$
\frac{dT_{\text{w}(i)}}{dt} = \frac{F_{\text{gas}(i)}}{M_{\text{w}(i)} \cdot C_{\text{w}(i)}} \cdot (T_{\text{gas}} - T_{\text{w}(i)}) - \frac{F_{\text{em}(i)} \cdot \alpha_{\text{em}}}{M_{\text{w}(i)} \cdot C_{\text{w}(i)}} \cdot (T_{\text{w}(i)} - T_{\text{em}(i)}), \ i = \overline{1,n}.
$$

(8)

where $M_{\text{w}(i)}$ is the mass of pipe wall relating to cell $i$; $C_{\text{w}(i)} = C_{\text{w}}(T_{\text{w}(i)})$ is the heat capacity of pipe wall material at temperature $T_{\text{w}(i)}$, $J/(kg \cdot K)$; $F_{\text{gas}(i)}$ is the part of the pipe outer surface relating to cell
$i, m^2; T_{em(i)}$ is the emulsion temperature in cell $i$, $K$; $T_{w(i)}$ is the temperature of the pipe wall in cell $i$, $K$.

The dependencies of values of individual parameters from the temperature found in various published reference documents are illustrated by Figures 9-12 and equations (8)-(9).

![Figure 9](image.png) **Figure 9.** Dependence of isobar heat capacity of combustion products and air mixture on the temperature.

![Figure 10](image.png) **Figure 10.** Dependence of steel (St20) heat capacity on the temperature.

![Figure 11](image.png) **Figure 11.** Dependence of water heat capacity on the temperature.

![Figure 12](image.png) **Figure 12.** Dependence of oil heat capacity on the temperature.

The density of emulsion $\rho_{em(i)}$ is calculated according to the equation

$$\rho_{em(i)} = \frac{100}{\frac{W_{em}}{\rho_{wat(i)}} + \frac{100-W_{em}}{\rho_{oil(i)}}},$$

where $\rho_{wat(i)}$ and $\rho_{oil(i)}$ are the values of water and oil density at the emulsion temperature $T_{em(i)}$, kg/m$^3$; $W_{em}$ is the oil emulsion wetness, wt.%.

The heat capacity of emulsion $C_{em(i)}$ is calculated as the weighted average between the heat capacity values of oil $C_{oil}$ and water $C_{wat}$ where the oil emulsion wetness value $W_{em}$ is used as the weighting factor:

$$C_{em(i)} = 0.01\cdot[C_{oil}(1-W_{em}) + C_{wat}W_{em}].$$

### 3. Configuration of Cell Models

The scheme of the parallel-flow heat exchanger cell model that realizes the solution of equations (3)-(5) is based on the multiple-layer principle using embedded systems to provide even greater clearness and usability of the model (refer to Figure 13 – 17).

In order to compose the model of a counter-flow shell and tube exchanger, the initial data can be used from the example given for a parallel-flow heat exchanger. As was mentioned above, if the model of a parallel-flow heat exchanger is available, the model of a counter-flow heat exchanger can be configured just by switching the input and output signals of the cell block schemes without making any corrections in the lower and upper levels of the model.
Figure 13. Scheme of upper level.

Figure 14. Scheme of the third level.

Figure 15. Scheme of the second level of the cell model of a parallel-flow heat exchanger.

Figure 16. Scheme of cell model of T1 calculation

Figure 17. Scheme of cell model of T3 calculation

Figure 18 illustrates the scheme of the second level of the counter-flow heat exchanger model after switching the input and output channels of the cells. The difference from Figure 15 is that the input block for the second heat carrier was transferred to the lower right corner of the scheme while the output block is placed in the lower left corner.

Figure 19 shows subsystem Subs_PTB-10 of the middle nest level including the individual cells of the model. For the sake of greater clearness, the figure includes gaps and shows only a half of the cells. The upper row of the scheme includes the single cell – ideal mixing subsystem Subs_T_gas of the heat exchange chamber. The middle row of the scheme is composed of 16 cells – subsystems Subs_T_PW - Subs_T_PW15 –
simulating the heat exchange that goes on in the pipe wall. The lower level of the scheme is represented by 16 cells – subsystems Subs_T_em - Subs_T_em15 PW15 – used to simulate heat exchange processes inside the oil emulsion pipe. The schemes of other subsystems that perform the calculations in compliance with equations (6)-(10) are omitted as they are too cumbersome.

4. Discussion of Simulation Results
The initial data used for calculations based on the cell dynamics model of heat exchangers are given in Table 1.

| Parameters Name                      | Pipe $T_1$ | Pipe $T_2$ |
|-------------------------------------|------------|------------|
| 1 Pipe diameter, $m$                | 0.1        | 0.05       |
| 2 Wall thickness, $m$               | -          | 0.003      |
| 3 Pipe length, $m$                  | 10         | 10         |
| 4 Input temperature, $C$            | 95         | 5          |
| 5 Heat carrier consumption, $m^3/h$ | 1.0        | 2.0        |
| 6 Heat carrier density, $kg/m^3$    | 980        | 880        |
| 7 Heat carrier heat capacity, $J/(kg*K)$ | 4220    | 880        |
| 8 Heat transfer factor, $W/(m^2*K)$ | 200        | 400        |
| 9 Heat exchange area, $m^2$         | 1.57       | 1.38       |
| 10 Specific heat capacity of the wall material, $J/(kg*K)$ | -          | 500        |
| 11 Density of wall material, $kg/m^3$ | -          | 7700       |
| 12 Volume occupied by heat carrier, $m^3$ | 0.0589 | 0.0173     |
| 13 Wall weight, $kg$                | -          | 34.1       |

Figure 20-24 illustrate the results of simulation of parallel-flow and counter-flow heat exchangers in the form of diagrams of static and dynamic process characteristics.

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Figure 20-24 illustrate the results of simulation of parallel-flow and counter-flow heat exchangers in the form of diagrams of static and dynamic process characteristics.
Figure 21. Temperature curves of hot heat carrier ($T_1$ on the left) and cold heat carrier ($T_2$ on the right) at the outlet of the 1st, 3rd, 6th, 9th and 12th cells of the counter-flow heat exchanger model.

Figure 22. Temperature curves of hot heat carrier ($T_1$) and cold heat carrier ($T_2$) along the pipe of the parallel-flow heat exchanger model (on the left) and counter-flow heat exchanger model (on the right).

Figure 23. C-curves of $T_2$ reaction to pulse disturbance in flow passage $v_1$ (on the left) and in flow passage $v_2$ (on the right) of the parallel-flow heat exchanger
Figure 24. C-curves of $T_2$ reaction to pulse disturbance in flow passage $v_1$ (on the left) and in flow passage $v_2$ (on the right) of the counter-flow heat exchanger.

The initial data used to calculate the heating mode based on the cell model of PTB-10 heater are as follows: the heater power rating is $10$ MW; fuel gas consumption $v_{\text{gas}} = 1000$ m$^3$/h; oil emulsion consumption $G_{\text{em}} = 375000$ kg/h; emulsion temperature at the heater inlet $T_{\text{em,in}} = 12^\circ$C; the temperature of combustion air $T_{\text{air}} = 7^\circ$C; the temperature of emulsion at the heater outlet $T_{\text{em,out}} = 47^\circ$C; wetness (moisture content) of emulsion $W_{\text{em}} = 55\%$ weight; formation water density is $1048$ kg/m$^3$; formation water heat capacity is $3971$ J/(kg·K); oil heat capacity is $1923$ J/(kg·K); oil density at $293$ K is $864$ kg/m$^3$; the outer diameter of heat exchange pipes is $0.159$ m; the inner diameter of heat exchange pipes is $0.143$ m; the inner surface of the pipes $F_c = 137.4$ m$^2$; the outer surface of smooth pipes is $148.6$ m$^2$; the outer surface of extended surface pipes $F_{\text{gas}} = 1366$ m$^2$; the volume of the heat exchange chamber $V_{\text{gas}} = 29.4$ m$^3$; the length of heat exchange pipe without the bend is $9$ m; the number of pipe rows in one bundle is $2$; the air excess factor is $1.3$; the heat losses into the ambient environment is $0.05$; the coiled pipe weight $M_c = 7780$ kg.

The initial data were also used to calculate and accept the following parameters of the model: the factor of heat transfer from gas to the pipe wall, $\alpha_{\text{gas}} = 42.5$ W/(m$^2$·K); the factor of heat transfer from the pipe wall to oil emulsion, $\alpha_{\text{em}} = 800$ W/(m$^2$·K); correction factor of radiation heat transfer equation, $e_{\text{rad}} = 770$ J/(s·K$^4$); the proportion of radiation and convection heat exchange in the heat exchange chamber, $\beta = 0.56$; the total volume of the internal space of the oil emulsion, $V_{\text{em}} = 4.8$ m$^3$; the value of proportion of consumption gas and fuel gas consumption in the heater considering the air excess factor equal to $0.3 - 15.15$; the number of model cells of the pipe wall and emulsion $n = 16$. The information about the fuel gas composition is given in Table 2.

Table 2. Data on fuel gas composition

| Fuel Gas Components, mole fraction | N$_2$ | CO$_2$ | CH$_4$ | C$_3$H$_6$ | C$_4$H$_8$ | iC$_4$H$_{10}$ | nC$_4$H$_{10}$ | iC$_5$H$_{12}$ | NC$_5$H$_{12}$ | C$_6$H$_{14}$ |
|----------------------------------|-------|--------|--------|------------|------------|--------------|--------------|--------------|---------------|-------------|
|                                  | 0.023 | 0.013  | 0.864  | 0.028      | 0.046      | 0.008        | 0.014        | 0.002        | 0.002         | 0.001       |

The values of output parameters characterizing the static properties of PTB-10 model can be traced using the diagrams of Figure 25 showing the temperature curve of the wall and the temperature curve of the emulsion along the pipe. The diagrams were created using the following values of the input parameters: fuel gas consumption $v_{\text{gas}} = 1000$ m$^3$/h under normal conditions; oil emulsion flow $G_{\text{em}} = 375000$ kg/h; emulsion temperature at the heater inlet $T_{\text{em,in}} = 12^\circ$C; wetness (moisture content) of emulsion $W_{\text{em}} = 55\%$ weight;
Figure 25. Temperature curves of the wall (on the left) and temperature curves of emulsion (on the right) in PTB-10 heater along the pipe in the stable mode. The pipe length $L$ is defined in relative units corresponding to the consecutive number of the cell from 0 to 15.

Figure 26. Curves of temperatures of the heater exhaust gases $T_{\text{gas}}$, temperature of pipe wall at the heater output $T_{\text{PW}, n}$ and emulsion temperature $T_{\text{em}, \text{out}}$ at the heater output during the initial start of the model.

The characteristic curves shown in Figure 25 demonstrate that the emulsion temperature changes along the pipe in a slightly nonlinear manner – the deviation from the linear dependence graph is shown (dashed straight lines). Figures 26-30 below demonstrate the dynamic properties of the model by individual channels used to introduce the pulse and step disturbance and record $C$- and $F$-curves by the emulsion temperature at the heater output. The pulse width used to obtain $C$-curve made up 8 s, the moment of $\delta(t)$-pulse introduction is 496 s, the moment of step signal $l(t)$ is 500 s.

Figure 27. View of $C$-curve (on the left) and $F$-curve (on the right) for the channel “gas consumption – emulsion temperature at the heater output”.

Figure 28. View of $C$-curve (on the left) and $F$-curve (on the right) for the channel “emulsion temperature at the heater inlet – emulsion temperature at the heater outlet”.
Figure 29. View of $C$-curve (on the left) and $F$-curve (on the right) for the channel “emulsion consumption – emulsion temperature at the heater outlet”.

Figure 30. View of $C$-curve (on the left) and $F$-curve (on the right) for the channel “emulsion wetness – emulsion temperature at the heater outlet”.

The reduced dynamic characteristics of PTB-10 by the channels “gas consumption – emulsion temperature at the heater output” (Figure 27) and “emulsion consumption – emulsion temperature at the heater outlet” (Figure 29) correspond to the known experimental data while the models and/or principle of the composition can be recommended for practical application.

5. Conclusion and Summary

The completed researches allowed determining some general peculiarities and the sequence of creation of dynamic cell models for several types of vessels used for oil emulsion treatment at oil and gas fields, namely:

1. Examination of the facility, acquisition of static and dynamic characteristics by different channels, elaboration of the general control concept and model type – “mixing-mixing”, “mixing-displacement”, “displacement-displacement”.
2. Model configuration in accordance with the model type.
3. Identification of the model factors in compliance with experimental data and reference sources.
4. Refinement of the model and correction of the model factors, if required.
5. Selection of the controller type and upload of the developed model code in the controller.
6. Check of the model correctness using the existing equipment.
7. Making decision on the method of smart control, development of the control code using MATLAB Simulink tools, upload of the code in the controller.

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