Journal of KONBiN 3(23)2012
ISSN 1895-8281

NUMERICAL RECOVERY OF GAS FLOWS AT PIPELINE ACCIDENTS

NUMERYCZNE ODTWORZENIE WARTOŚCI PRZEPŁYWÓW GAZU W PRZYPADKU AWARII RUROCIĄGÓW

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***Abstract**: The article describes numerical method of physical gas flow parameters recovery at accidents investigation, which are conditioned by guillotine rupture of a pipe in gas trunkline and distribution pipeline systems. The information about full-scale measurements of time dependences of gas flow parameters at defined points inside pipelines system and at its boundaries is the base for recovery implementation at numerical investigation of accidents. Numerical recovery is carried out by defining and solving a special identification problem.*

***Keywords:** gas trunkline rupture, identification problem, numerical gas flow recovery.*

***Streszczenie**: W artykule opisano numeryczną metodę odtworzenia parametrów rzeczywistego przepływu gazu podczas badania wypadków, w których nastąpiło przerwanie rury na całym obwodzie. Metoda może być stosowana zarówno dla rurociągów magistralowych, jak i dla rur w sieciach dystrybucyjnych. Informacje o pełnej skali pomiarów zależności parametrów przepływu gazu w określonych punktach wewnątrz systemu rurociągów jako funkcji czasu stanowią podstawę do numerycznego odtworzenia tych przebiegów w przypadku badania i analizy wypadków. Odtworzenie numeryczne jest wykonywane poprzez zdefiniowane i rozwiązanie specyficznego zadania identyfikacyjnego.*

***Słowa kluczowe:** pęknięcie gazowego rurociągu magistralowego, zadanie identyfikacji, numeryczne odtworzenie wartości przepływu gazu*

1. Problem statement

At numerical analysis of accidents we face the necessity of physical parameters recovery of comersial gas flow along gaspipeline systems [1–3]. Limited field measurement data is the characterstic feature of such problem statement. In this case it is reasonable to formalize the problemin the form of generalized mathematical identification problem of adequate space-time distribution of actual flow parameters of transported gases based on full-scale measurements in a substantially limited number of locations.

It is initially assumed in this paper that the length and location of analysable system allows for using the one-dimensional setup for the gas network gas flow recovery problem [4].

In the modeling commercial gas is treated as homogeneous multi-component viscous gas mixture of known composition with specified heat transfer, physical and mechanical properties. Equations of state for this mixture are assumed to be known.

Basic modes of gas transportation at accident are assumed to be transient and non-isothermal. However, for the purpose of requrment lowering of the used computational resourses and increasing of the efficiency of calculation results obtaining, we here adopt the assumption that actual dynamics of simulated gas flow permits spreading of basic assumptions of well known quasi-steady-state flow change method to computational algorithms of transport flow recovery at discretization of the analyzable time interval [4].

In the frame of described above problem statement it is reasonably to use methods from [4–9] in order to obtain numerical estimates of space-time distribution of pressure, density, temperature and gas flow rate transmitted along pipeline system. The listed above works contain practical algorithms description of numerical analysis of gas flow along branched and circular graded pipelines that characterized by sufficient wide range of properties in the accuracy and adequacy of obtained results with respect to actual gas-dynamic processes. This gives an opportunity to optimize the choice of the method of flow parameters calculation on the basis of actual requrments producible to the efficiency of accident investigation and realiability of obtained results. However, the problem statement of such choice realization goes beyond the scope of this paper and do not considered here.

For the 1D problem statement, one can assume that field measurements of gas flow parameters are taken at fixed points located both at the boundaries of the pipeline system (boundary points) and along the length of the pipelines (internal points). Boundary points are generally used to take measurements of pressure, temperature and mass flow rate of gases (considering their composition), and internal points are used to measure gas pressure. Ambient temperature is measured at points spaced apart from each other at considerable distances. Results of such measurements may contain random and systematic errors.

Thus, using the above background information, we should formulate and describe special identification problem statement, allowing us to recover the space-time distribution of actual gas flow estimates at accident for the given time interval $\Delta\tau$

at known methods of numerical analysis of transient and non-isothermal gas flow parameters and deficiency of full-scale measurements. It is also necessary to propose the approaches to numerical solution of formulated identification problem.

2. Formalization of the transport flow recovery problem

We introduce the notion of Identification Point (IP). In our case, the IP is an inner or boundary point in the computational model of the pipeline network of interest, in which full-scale measurements of pressure of the transported gas mixture are taken over a given time interval $\Delta\tau$. The choice of gas mixture pressure as an identification parameter is explained by the fact that pressure histories in real pipeline systems are determined today more accurately than temperature or flow rate parameters. The example of actual and potential IPs distribution in the Moscow Gas Ring (MGR) model is presented in Fig. 1. In this picture the IPs location are denoted by a yellow circle. The IPs numbering corresponds to its conventional identifier, which are used at modeling.

In the course of mathematical identification, calculated and measured estimates of gas mixture pressure histories for the entire set of IPs distributed across the computational model of the pipeline network should be fitted as closely as possible. The preferable location of each IP is determined subject to the following requirement: any considerable change in gas dynamic parameters of pipeline system operation should be accompanied by considerable changes in gas mixture flow parameters actually measured at this point. The distribution of IPs in the computational model of the pipeline system should be as uniform as possible.

Under mathematical identification theory the close fit between corresponding calculated and measured pressure histories in the general case should be provided in three senses [10]: close fit between two functional relations (in essence, between the first derivatives of the functions being compared); close fit between two functional relations in metric $\mathrm{L}_2 = \|\mathbf{Y}\|_2 = \sqrt{\sum_{i=1}^{n} y_i^2}$, $\mathbf{Y} \in R^n$; close fit between two functional relations within their uniform deviation, i.e. in the metric $\mathrm{L}_0 = \|\mathbf{Y}\|_0 = \max_{1 \le i \le n} |y_i|$, $\mathbf{Y} \in R^n$.

Real pipeline systems contain a number of branches, through which transmitted fluids enter or leave the system. Inlet branches that supply the gas mixture into the simulated pipeline system will be designated conventionally as “supplier branches”, and outlet branches, as “consumer branches”. In the first approximation, it is assumed that each network branch cannot change its purpose over a given time interval $\Delta\tau$, i.e. a gas supplier cannot become a consumer and vice versa.

At accident investigation the pipeline ruptured zone can be conventionally trated as new nonauthorized concumer branch.

In practice, there is generally a shortage of instruments at outlet boundaries of the gas pipeline system of interest. In this case, a number of consumers having no flow rate meters joint declare their gas consumption based on regulatory documents. All the foregoing (together with real instrument errors and encountered cases of artificial under-/overdeclaration of gas mixture volumes transported through the pipeline system) results in arithmetic discrepancies between estimated volumes of gas supply made by consumers and suppliers. This situation should be taken into account in gas flows recovery.

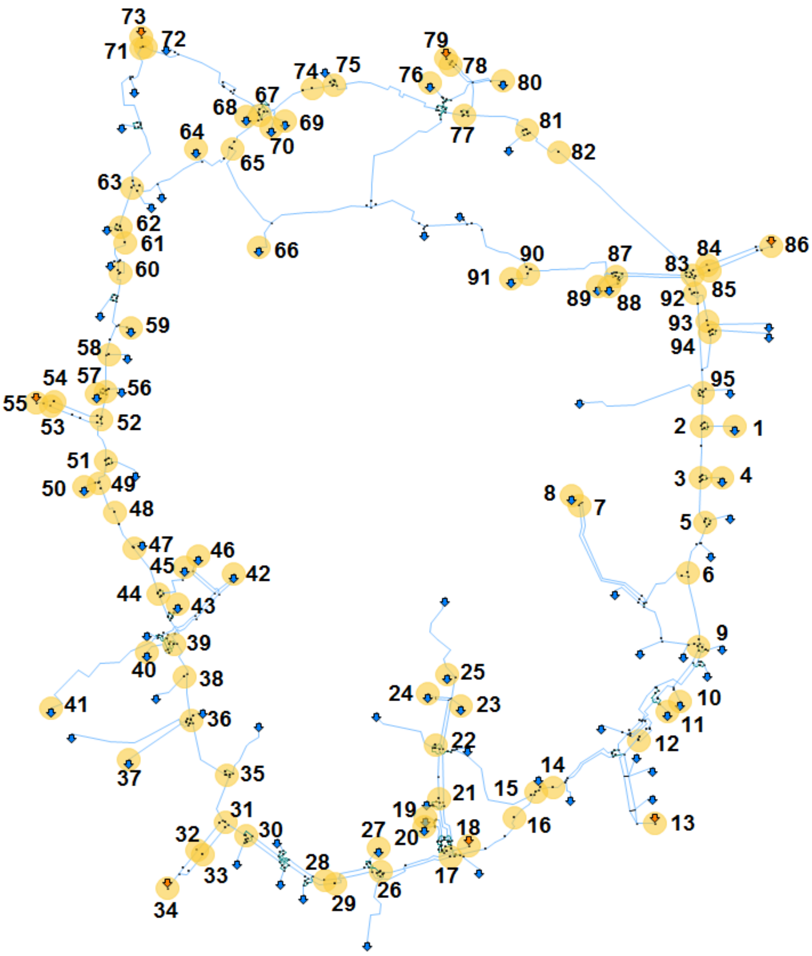


Fig.1. Basic diagram of actual and potential IPs distribution in the MGR pipelines

Given all the reasoning above, the special problem of mathematical identification can be stated using conditional optimization:

$$\mathrm{P}\left[t,\, F_{\text{scenario}},\, \mathbf{Z}(t)\right] \to \min_{\mathbf{Z}(t)\in\mathbf{\Pi}(t)\subset R^{n}}, \tag{1}$$

where $\mathrm{P}\left[t,\, F_{\text{scenario}},\, \mathbf{Z}(t)\right]$ is a formal representation of the target function; t is time; F_{scenario} is the flag of involved computational scenarios of the identification problem; $\mathbf{Z}(t)$ is a vector function of controlled boundary conditions (BC). In our case, components of the vector function $\mathbf{Z}(t)$ are time functions of pressure and mass flow rates of the gas mixture at outlet boundaries of the gas pipeline system, i.e. components of boundary conditions. They are distributed in the following way: gas mixture pressures at $u\ (u \le l)$ outlets of supplier branches and at $s\ (s \le k)$ outlets of consumer branches, where l is a given number of supplier branches, through which the gas mixture flows into the gas pipeline system over the time $\Delta\tau$; k is a given number of consumer branches through which the gas mixture leaves the gas pipeline system over the time $\Delta\tau$; mass flow rates of the gas mixture at $(l-u)$ outlets of supplier branches and at $(k-s)$ outlets of consumer branches. Hence, the total number of variable components in the boundary conditions is $n = l + k$. In production simulations, the search for boundary conditions at outlet boundaries of a number of branches during identification can be replaced with rigidly set Dirichlet boundary conditions in the form of combinations of known time functions of measured mass flow rates and pressures of the gas mixture. This reduces the number of variable components in the boundary conditions, $n < l + k$. Note also that as Dirichlet boundary conditions for temperature and relative mass fraction one can use predefined time laws for respective measured values.

At accident investigation specialists fase the necessity of gas flow recovery under three basic assumptions [4]: estimated volumes of gas mixture supply declared by suppliers and consumers contain errors (the Full Distrust computational scenario); only supplier-declared estimated volumes of gas mixture supply are credible (the Trust-in-Supplier computational scenario); only consumer-declared estimated volumes of gas mixture supply are credible (the Trust-in-Consumer computational scenario). The flag of the computational scenario assigned to the identification problem F_{scenario} takes the values of 11, 12, 13, 21, 22, 23, 31, 32 and 33 in series, allowing us to choose various modifications of the problem statement (1). The way of using the set of values assigned to the flag F_{scenario} will be demonstrated below (see (2) and (4)).

The kernel $\mathrm{P}\left[t,\, F_{\text{scenario}},\, \mathbf{Z}(t)\right]$ of the target function of the problem (1) subject to the requirement that calculated and measured values should fit together in the three above senses can be formalized as follows:

$$\mathrm{P}\left[t, F_{\text{scenario}}, \mathbf{Z}(t)\right] = \\ = \begin{cases} \left\| \mathbf{p}_{\text{calc}}^{\text{IP}}\left[t, \mathbf{Z}(t)\right] - \mathbf{p}_{\text{meas}}^{\text{IP}}(t) \right\|_2, \text{if } F_{\text{scenario}} < 21; \\ \left\| \left\{ \mathbf{p}_{\text{calc}}^{\text{IP}}\left[t, \mathbf{Z}(t)\right] - \mathbf{p}_{\text{meas}}^{\text{IP}}(t) \right\}_{\text{I}} + \left\{ \mathbf{p}_{\text{meas}}^{\text{IP}}(t) - \mathbf{p}_{\text{calc}}^{\text{IP}}\left[t, \mathbf{Z}(t)\right] \right\}_{\text{II}} \right\|_2, \text{if } F_{\text{scenario}} < 31; \\ \left\| \frac{\partial}{\partial t} \mathbf{p}_{\text{calc}}^{\text{IP}}\left[t, \mathbf{Z}(t)\right] - \frac{\partial}{\partial t} \mathbf{p}_{\text{meas}}^{\text{IP}}(t) \right\|_2 - \text{otherwise}, \end{cases} \tag{2}$$

where $\mathbf{p}_{\text{calc}}^{\text{IP}}\left[t, \mathbf{Z}(t)\right] \in R^{M_{\text{IP}}}$ is a vector function simulation the time variation of calculated estimates of gas mixture pressure at the IP; M_{IP} is the number of IPs; $\mathbf{p}_{\text{meas}}^{\text{IP}}(t) \in R^{M_{\text{IP}}}$ is a given vector function describing the time variation of measured estimates of gas mixture pressure at the IP; $(\text{I}, \text{II})_\nu$, $\nu = \overline{1, M_{\text{difference}}}$, is symbolic representation of IPs pairs that determine the controlled natural and virtual pressure drops in the gas mixture, $M_{\text{difference}}$ is the number of given pairs of IPs. The values of components of the vector function $\mathbf{p}_{\text{calc}}^{\text{IP}}\left[t, \mathbf{Z}(t)\right]$ is defied by numerical analysis of gas flow parameters along pipeline network under consideration for the known initial conditions and defined Dirichlet boundary conditions, containing all the components of the vector function $\mathbf{Z}(t)$. In this case, for carrying out stated above analysis, we strongly recommend giving preference to high-accuracy methods of flow modeling along pipelines, suggested in [4].

The first form of the kernel of the target function (i.e. for $F_{\text{scenario}} < 21$ in (2)) in the problem statement (1) expresses the requirement that calculated and measured estimates of gas mixture pressure should be close in the second and third senses (see above). In practice, striving for the fulfillment of this requirement makes it possible to obtain a correct solution in the presence of random errors in flow pressure measurements aggravated by single instrument failures. The idea of second form of the target function constructing (as $F_{\text{scenario}} < 31$ in (2)) belongs to Vladimir V. Kiselev [11]. First of all it is oriented on the compensaton of IPs shortage, which is frequently experienced in practice. Meanwhile in order to define natural and virtual gas mixture pressure differences controlled during minimization of (1), a generalized set of IP pairs is established in advance. The third form of the target function was proposed to enable a closer fit between calculated and measured estimates of gas mixture pressure in the first and third senses (see above). It is used for obtaining a correct solution in the presence of systematic errors in gas mixture pressure measurements and single instrument failures.

Now, let us proceed to discussing numerous constraints in (14):

$$\begin{aligned}\mathbf{Z}(t)\in\Pi(t)=\Big\{&\mathbf{Z}(t)\in R^n:\mathbf{g}(t)\le\mathbf{Z}(t)\le\mathbf{f}(t);\\&\left[g_q(t)\right]_s\le\left[q_{\text{calc}}^{\text{supplier}}\left[t,\mathbf{Z}(t)\right]\right]_s\le\left[f_q(t)\right]_s,\ s=\overline{1,l};\\&\left[g_q(t)\right]_s\le\left[q_{\text{calc}}^{\text{consumer}}\left[t,\mathbf{Z}(t)\right]\right]_{s-l}\le\left[f_q(t)\right]_s,\ s=\overline{l+1,\,l+k};\\&\left\langle unequality\left(\Delta\tau,F_{\text{scenario}},\mathbf{Z}(t)\right)\right\rangle\Big\},\end{aligned}\qquad(3)$$

where $\mathbf{g}(t)\in R^n$ and $\mathbf{f}(t)\in R^n$ are given vector functions that establish limits in simple constraints on the vector function of controlled boundary conditions based on structural and operational features of the simulated pipeline system, $\mathbf{g}(t)<\mathbf{f}(t)$; $\mathbf{g}_q(t)\in R^{l+k}$ and $\mathbf{f}_q(t)\in R^{l+k}$ are given vector functions that establish limits in constraints providing a-priory preservation of the defined purpose of the branch over the time interval $\Delta\tau$ (i.e. a gas supplier cannot become a gas consumer and vice versa, see above), $\mathbf{g}_q(t)<\mathbf{f}_q(t)$; $\mathbf{q}_{\text{calc}}^{\text{supplier}}\left[t,\mathbf{Z}(t)\right]\in R^l$ is a vector function, simulation the time variation of calculated estimates of gas mixture mass flow rate at outlets of supplier branches; $\mathbf{q}_{\text{calc}}^{\text{consumer}}\left[t,\mathbf{Z}(t)\right]\in R^k$ is a vector function that describes the time variation of calculated estimates of gas mixture mass flow rate at outlets of consumer branches; $\left\langle unequality\left(\Delta\tau,F_{\text{scenario}},\mathbf{Z}(t)\right)\right\rangle$ is is a formal representation of an additional limiting inequality. The values of vector function conponents $\mathbf{q}_{\text{calc}}^{\text{supplier}}\left[t,\mathbf{Z}(t)\right]\in R^l$ and $\mathbf{q}_{\text{calc}}^{\text{consumer}}\left[t,\mathbf{Z}(t)\right]$ are defied by numerical analysis of gas flow parameters along pipeline network under consideration for the known initial conditions and defined Dirichlet boundary conditions, containing all the components of the vector function $\mathbf{Z}(t)$. As in the above stated case we advise to use high-accuracy methods [4]. For the components of above stated vector function of gas flow rate that suppliers have the following law of signs is true: $\left[q_{\text{calc}}^{\text{supplier}}\left[t,\mathbf{Z}(t)\right]\right]_i>0$, the gas mixture flows into the modeled pipeline system, $i=\overline{1,l}$. The law of signs for components of the vector function $\mathbf{q}_{\text{calc}}^{\text{consumer}}\left[t,\mathbf{Z}(t)\right]$

has the form: if $\left[q_{\text{calc}}^{\text{consumer}}\left[t,\mathbf{Z}(t)\right]\right]_i < 0$, then the gas mixture moves from the gas pipeline system to the consumer, $i=\overline{1,k}$. The second and third inequalities in the list of constraints (3) make it possible to reliably control the variations in gas mass flow rates at outlets of all system branches irrespective of whether these functions are components of the vector function of controlled boundary conditions, or they are purely computational parameters needed for simulations of gas mixture flow through the pipeline system. The formal representation of the inequality $\left\langle unequality\left(\Delta\tau, F_{\text{scenario}}, \mathbf{Z}(t)\right)\right\rangle$ in (3) can be expanded in the following way:

$$\left\langle unequality\left(\Delta\tau, F_{\text{scenario}}, \mathbf{Z}(t)\right)\right\rangle =$$

$$= \begin{cases} -\int\limits_{\Delta\tau}\sum\limits_{j=1}^{k}\left[q_{\text{meas}}^{\text{consumer}}(t)\right]_j dt - \Delta \le \int\limits_{\Delta\tau}\sum\limits_{i=1}^{l}\left[q_{\text{calc}}^{\text{supplier}}\left[t,\mathbf{Z}(t)\right]\right]_i dt \le \int\limits_{\Delta\tau}\sum\limits_{i=1}^{l}\left[q_{\text{meas}}^{\text{supplier}}(t)\right]_i dt + \Delta, \\ \quad \text{if } \int\limits_{\Delta\tau}\sum\limits_{i=1}^{l}\left[q_{\text{meas}}^{\text{supplier}}(t)\right]_i dt \ge -\int\limits_{\Delta\tau}\sum\limits_{j=1}^{k}\left[q_{\text{meas}}^{\text{consumer}}(t)\right]_j dt \text{ and } \left(F_{\text{scenario}} = 11 \text{ или } 21 \text{ или } 31\right); \\ \int\limits_{\Delta\tau}\sum\limits_{i=1}^{l}\left[q_{\text{meas}}^{\text{supplier}}(t)\right]_i dt - \Delta \le \int\limits_{\Delta\tau}\sum\limits_{i=1}^{l}\left[q_{\text{calc}}^{\text{supplier}}\left[t,\mathbf{Z}(t)\right]\right]_i dt \le -\int\limits_{\Delta\tau}\sum\limits_{j=1}^{k}\left[q_{\text{meas}}^{\text{consumer}}(t)\right]_j dt + \Delta, \\ \quad \text{if } \int\limits_{\Delta\tau}\sum\limits_{i=1}^{l}\left[q_{\text{meas}}^{\text{supplier}}(t)\right]_i dt < -\int\limits_{\Delta\tau}\sum\limits_{j=1}^{k}\left[q_{\text{meas}}^{\text{consumer}}(t)\right]_j dt \text{ and } \left(F_{\text{scenario}} = 11 \text{ или } 21 \text{ или } 31\right); \\ \left\|\mathbf{q}_{\text{calc}}^{\text{consumer}}\left[t,\mathbf{Z}(t)\right] - \mathbf{q}_{\text{meas}}^{\text{consumer}}(t)\right\|_2 - \varepsilon \le 0, \text{ if } F_{\text{scenario}} = 13 \text{ or } 23 \text{ or } 33; \\ \left\|\mathbf{q}_{\text{calc}}^{\text{supplier}}\left[t,\mathbf{Z}(t)\right] - \mathbf{q}_{\text{meas}}^{\text{supplier}}(t)\right\|_2 - \varepsilon \le 0 - \text{otherwise,} \end{cases} \tag{4}$$

where $\mathbf{q}_{\text{meas}}^{\text{consumer}}(t) \in R^k$ is a given vector function that describes the time variation of measured or declared estimates of gas mass flow rates at outlets of consumer branches; $\mathbf{q}_{\text{meas}}^{\text{supplier}}(t) \in R^l$ is a given vector function that describes the time variation of measured or declared estimates of gas mass flow rates at outlets of supplier branches; $\varepsilon > 0$ is a predefined small quantity that establishes the minimum difference between calculated and measured mass flow rates in the second sense of close fit (see above); $\Delta = Q_{\text{discrep}}/2$, Q_{discrep} is a predefined empirical constant that corresponds to minimum value of module of accumulated discrepacy in gas supply estimates, which has significant practical importance at analysis of gaspipeline network under modeling. The following law of signs is true for components of the vector function $\mathbf{q}_{\text{meas}}^{\text{consumer}}(t)$: if $\left[q_{\text{meas}}^{\text{consumer}}(t)\right]_i < 0$, the gas mixture moves from the gas pipeline system to the consumer, $i=\overline{1,k}$. The law of signs for the components of above stated vector functions of gas flow rate (that suppliers have) has the form: $\left[q_{\text{meas}}^{\text{supplier}}(t)\right]_i > 0$, the gas mixture flows into the modeled pipeline system, $i = \overline{1,l}$.

3. On the special identification problem solution

Today, it does not seem possible to solve the problem (1–4) in such a statement using computing facilities available to a wide range of pipeline industry specialists. However, as mentioned in Sec.1, actual operation dynamics of most commercial gas trunklines renders it possible to use basic allowances and assumptions of the quasi-steady-state flow change method. In this connection, it is suggested that the time interval of interest $\Delta\tau$ be conventionally divided into $(N_t + 1)$ time layers separated from each other by a given uniform step Δt. The $m = 0$ layer will correspond to the lower boundary of the time interval Δt, and the $m = N_t$ layer, to its upper boundary. In order to improve the credibility of estimated gas mixture supply to consumers, when using the quasi-steady-state (for one time layer) problem statement, one should give consideration to the effect of product buildup in the pipes of the simulated pipeline system. For each time layer, the gas mixture buildup varies over the preceding time interval $\Delta\tau$. A practical way of accounting for this buildup was proposed by V. Kiselev [11].

For numerical solution of the problem (1–4) at the m-th time step the well-known method of modified Lagrange functions is suitable [12]. The successive solution of the problem (1–4) at the $(N_t + 1)$ time steps makes it possible to recover the agreed Dirichlet boundary conditions for all the pipeline system boundaries within the chosen computational scenarios. Upon their recovery based on the discrete values obtained, it is reasonable to interpolate the boundary conditions. Cubic spline interpolation performs well in this case.

4. On the criterion in the comparative analysis of finding solutions

The above approach to the numerical recovery of gas dynamic parameters of gas mixture flows through pipeline systems based on full-scale measurements gives a number of alternative solutions. This is associated, first of all, with a set of computational scenarios involved and ambiguity of building the vector function of controlled boundary conditions. In order to choose the best approximation of space-time distributions of real flow parameters, one should propose a criterion to compare the calculated gas dynamic parameters. Such a criterion can be developed by quantitative assessment of the fit between calculated and measured parameters of gas mixture pressure vs. time at each IP. For this purpose, let us introduce the so-called identification factor in the first sense for the j-th IP:

$$\text{Ident\_Level\_1}_j = \Delta\tau^{-1} \int_{\Delta\tau} \left| \frac{\partial}{\partial t} p_{\text{calc}}^{\text{IP}}(t) - \frac{\partial}{\partial t} p_{\text{meas}}^{\text{IP}}(t) \right|_j dt, \;\; j = \overline{1, M_{\text{IP}}}. \qquad (5)$$

The identification factor in the second sense in our case is written as:

$$\text{Ident\_Level\_2}_j = \Delta\tau^{-1} \int_{\Delta\tau} \left| p_{\text{calc}}^{\text{IP}}(t) - p_{\text{meas}}^{\text{IP}}(t) \right|_j dt, \;\; j = \overline{1, M_{\text{IP}}}. \qquad (6)$$

For simultaneous assessment of identification level in the first and second senses, the law of conventional coloring of IPs is used subject to achieved in its neighborhood identification level. One will take the small neighborhood of j-th IP for the time interval $\Delta\tau$ be at high identification level in the first and second senses, if at least one of the following conditions is satisfied [4]: 1) $\text{Ident\_Level\_1}_j < C_{\text{Blue IP}}^{\text{min\_1}}$; 2) $\text{Ident\_Level\_2}_j \le C_{\text{Green IP}}^{\text{min\_2}}$; 3) $\text{Ident\_Level\_1}_j \le C_{\text{Blue IP}}^{\text{max\_1}}$ and $C_{\text{Green IP}}^{\text{min\_2}} < \text{Ident\_Level\_2}_j < C_{\text{Blue IP}}^{\text{min\_2}}$, where $C_{\text{Green IP}}^{\text{min\_2}}$, $C_{\text{Blue IP}}^{\text{min\_1}}$, $C_{\text{Blue IP}}^{\text{max\_1}}$, $C_{\text{Blue IP}}^{\text{min\_2}}$ are given empirical constants. In order to make the practical results more demonstrative, the IP of interest will be denoted by a green circle because of the law of coloring usage in the IP layout diagram and the identification level in its neighborhood will be called green identification level. In a similar situation, the identification level is considered satisfactory in the first and second senses, if at least one of the following two conditions is satisfied [4]: 1) $C_{\text{Blue IP}}^{\text{max\_1}} < \text{Ident\_Level\_1}_j$ and $C_{\text{Green IP}}^{\text{min\_2}} < \text{Ident\_Level\_2}_j < C_{\text{Blue IP}}^{\text{min\_2}}$; 2) $C_{\text{Blue IP}}^{\text{min\_1}} \le \text{Ident\_Level\_1}_j \le C_{\text{Blue IP}}^{\text{max\_1}}$ and $C_{\text{Blue IP}}^{\text{min\_2}} \le \text{Ident\_Level\_2}_j \le C_{\text{Blue IP}}^{\text{max\_2}}$, where $C_{\text{Blue IP}}^{\text{max\_2}}$ is given empirical constant. In this case, the IP of interest in the IP layout diagram will be denoted by a blue circle (blue identification level). Achievement of the identification level disputable in the first and second sense (orange identification level) is characterized by satisfying simultaneously the following two conditions [4]: $C_{\text{Blue IP}}^{\text{min\_1}} \le \text{Ident\_Level\_1}_j \le C_{\text{Blue IP}}^{\text{max\_1}}$ and $C_{\text{Blue IP}}^{\text{max\_2}} < \text{Ident\_Level\_2}_j$. As a rule, such IPs display a systematic error in gas mixture flow pressure measurements. Such IPs need to be carefully analyzed by specialists operating the simulated pipeline system. If the above combinations of conditions are not satisfied, a conclusion is drawn that there is no identification in the first and second sense in the small neighborhood of this IP for the time interval $\Delta\tau$. In this case, the IP will be denoted by a red circle in the IP layout diagram, and the lack of identification in its neighborhood corresponds to the red level.

Analysis of the fit between time histories in the first and second sense does not allow us to account for the influence of individual discrepancy spikes in measurement results on the assessment of the achieved identification level to the full extent. Therefore, additional analysis of the fit between calculated and measured functions in the third sense is required in the neighborhood of the j-th IP:

$$\mathrm{Ident\_Level\_3}_j =$$

$$= \begin{cases} 0, \text{ if } \mathrm{Ident\_Level\_1}_j \leq C_{\mathrm{Blue\,IP}}^{\max\_1}; \\ \left\| p_{\mathrm{calc}}^{\mathrm{IP}}(t) - p_{\mathrm{meas}}^{\mathrm{IP}}(t) \right\|_0 = \sup\limits_{\Delta\tau} \left| p_{\mathrm{calc}}^{\mathrm{IP}}(t) - p_{\mathrm{meas}}^{\mathrm{IP}}(t) \right|_j - \text{otherwise}. \end{cases} \quad (7)$$

According to the method of comparison of calculated gas dynamic parameters described here, the identification level established in the first and second senses should be lowered [4]: from green to blue, if $C_{\mathrm{Green\,IP}}^{\min\_3} < \mathrm{Ident\_Level\_3}_j \leq C_{\mathrm{IP}}^{\sup\_3}$; from blue to orange, if $C_{\mathrm{Blue\,IP}}^{\min\_3} < \mathrm{Ident\_Level\_3}_j \leq C_{\mathrm{IP}}^{\sup\_3}$; from orange to red, when $C_{\mathrm{Orange\,IP}}^{\min\_3} < \mathrm{Ident\_Level\_3}_j \leq C_{\mathrm{IP}}^{\sup\_3}$; from any color to red, if $C_{\mathrm{IP}}^{\sup\_3} < \mathrm{Ident\_Level\_3}_j$, where $C_{\mathrm{Green\,IP}}^{\min\_3}$, $C_{\mathrm{Blue\,IP}}^{\min\_3}$, $C_{\mathrm{Orange\,IP}}^{\min\_3}$, $C_{\mathrm{IP}}^{\sup\_3}$ are given empirical constants. The procedure of lowering the identification level for each IP can be done only once, i.e. successive lowering of the green level to the blue one, the blue one, to the orange, and the orange, to the red is not permitted.

The overall assessment of the actual identification level achieved by the r-th computational gas dynamic mode of actual gas mixture flow through the pipeline system of interest over the given time interval is done using the formula:

$$\mathrm{P\_Id}_r =$$

$$= \left\{ S_{\mathrm{green}} \mathrm{P\_Id}_{\mathrm{green}}^r + S_{\mathrm{blue}} \mathrm{P\_Id}_{\mathrm{blue}}^r + S_{\mathrm{orange}} \mathrm{P\_Id}_{\mathrm{orange}}^r \right\} \frac{C_{\mathrm{Green\,IP}}^{\min\_2}}{S_{\mathrm{green}} M_{\mathrm{IP}}}, \quad r = \overline{1, V_{\mathrm{CFD}}}, \quad (8)$$

where

$$\mathrm{P\_Id}_{\mathrm{green}}^r = \sum_{j=1}^{L_{\mathrm{Green\,IP}}^r} \max{}^{-1} \left\{ C_{\mathrm{Green\,IP}}^{\min\_2}; \mathrm{Ident\_Level\_2}_j^r \right\};$$

$$\mathrm{P\_Id}_{\mathrm{orange}}^r = \sum_{j=1}^{N_{\mathrm{Orange\,IP}}^r} \left[\mathrm{Ident\_Level\_2}_j^r \right]^{-1};$$

$\mathrm{P\_Ident}_{\mathrm{blue}}^r = \sum_{j=1}^{K_{\mathrm{Blue\,IP}}^r} \max{}^{-1} \left\{ C_{\mathrm{Blue\,IP}}^{\min\_2}; \mathrm{Ident\_Level\_2}_j^r \right\}$; S_{green}, S_{blue}, S_{orange} are scalar weight factors used when establishing quantitative indices of the identification level achieved, $\left(S_{\mathrm{green}} > S_{\mathrm{blue}} > S_{\mathrm{orange}} > 0 \right)$; V_{CFD} is the number of obtained computational gas dynamic modes; $L_{\mathrm{Green\,IP}}^r$ is the number of green IPs for each r-th computational gas dynamic mode (if $L_{\mathrm{Green\,IP}}^r = 0$, then $\mathrm{P\_Id}_{\mathrm{green}}^r = 0$); $K_{\mathrm{Blue\,IP}}^r$ is the number of blue IPs for each r-th computational gas dynamic mode (if $K^r_{\text{Blue IP}} = 0$, then $\text{P\_Id}^r_{\text{blue}} = 0$); $N^r_{\text{Orange IP}}$ is the number of orange IPs for each r-th computational gas dynamic mode (if $N^r_{\text{Orange IP}} = 0$, then $\text{P\_Id}^r_{\text{orange}} = 0$).

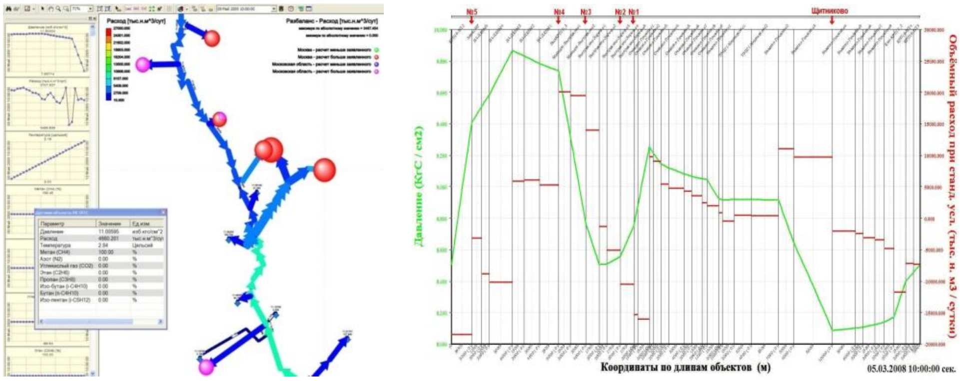
The solution to the problem of numerical recovery of gas flows in the simulated pipeline system will be a unique identified gas flow (IGF) that a-priory satisfies the defined requirements (constraints) and is compliant with the pipeline system's real physics of accident-free operation and characterized by the highest value of the quantitative index of identification level (8). Thus, the relation $\text{P\_Id}_{\text{CFD\_ID}} = \max\limits_{1 \le r \le V_{\text{CFD}}} \{\text{P\_Id}_r\}$, where $\text{CFD\_ID} \in [1, r]$ is the index, will be true for the IGF. It should be emphasized that the IGF status is assigned to the gas dynamic flow developed only if the following inequality is true for the corresponding prevalence factor of green, blue and orange IPs $F_{\text{CFD\_ID}}$:

$$F_{\text{CFD\_ID}} = M^{-1}_{\text{IP}} \left(L^{\text{CFD\_ID}}_{\text{Green IP}} + K^{\text{CFD\_ID}}_{\text{Blue IP}} + N^{\text{CFD\_ID}}_{\text{Orange IP}} \right) \ge C_{\text{CFD\_ID}},$$

where $C_{\text{CFD\_ID}} > 0$ is an empirical constant, the value of which is chosen based on the experience of doing simulations with the recovery method described here. Otherwise, a conclusion is drawn that the required identification level was not achieved and the IGF was not found, i.e. the recovery problem for the gas flows in the gas pipeline system was not solved.

5. Results of practical application

Efficiency of the method of numerical recovery of gas flows in trunkline systems proposed in the paper was demonstrated in 2008–2011 in production simulations at OOO "GAZPROM Mezhregiongaz Moscow" within the "Alfargus/Mosregiongaz" computer knowledgeware. The Moscow Gas Ring (MGR) has a total length of over 200 km and more than 80 consumer branches. The flow was recovered at 95 IPs, which were relatively uniformly distributed over the gas pipeline ring (see Fig. 1). Computer knowledgeware «Alfargus/Mosregiongaz» was used for numerical investigation of accident development mechanism, stipulated by pipeline rupture in Moscow (Ozernaya Street) in May, 2009. Examples of the pipeline system's gas flow parameters and directions of recovered gas flow in MGR are presented in Fig. 2.



a) b)

Fig.2. Example of transport flow recovery in southwest part of MGR at accident (temporal section) a) schematic representation of transported flows with its actual intensity; b) pressure and volumetric gas flow rate distribution along the pipeline length of analysable MGR segment

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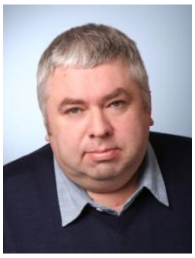

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