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Computing technology for investigating failures of gas pipeline systems

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Gas pipelines of Fuel and Energy Facilities are related to high-energy systems. Failures of gas pipelines can entail very serious consequences for the population, service personal, and the surrounding environment.

Currently in the world there are methods of probability theory and mathematical statistics implemented for the risk assessment of pipeline systems. The attractiveness of stochastic methods for the risk assessment mostly is conditioned by their simple mathematical formalization and saving the required computational resources. The main drawbacks of these methods are: the absence of a reliable priority value for probabilistic characteristics of failure events; the necessity to use subjective expert estimations. As for complex objects and single events, the usage of these methods does not allow to obtain the accurate estimations while forecasting and analyzing failures. To avoid the above insufficiency, computing technology for integrated high accuracy modelling of failures, based on up-to-date numerical methods of continuum mechanics, qualitative theory of differential equations and mathematical optimization, are used. The computing technology for investigating failures of gas pipelines has been developed at the Computation Mechanics Technology Center of SPE VNIIEF-VOLGOGAZ Ltd.

The computing technology for high accuracy mathematical modelling of failures of gas pipelines consists of the following main modules: gathering and analysis of actual source information on failure; statement of problem and specifying the approaches for its formalization; fluid dynamic analysis of pipeline systems in nominal (during pre-failure period) and failure operation modes; non-linear structural analysis and modelling of pipeline fracture; modelling and forecasting harmful impact on the population and surrounding environment caused by failures of pipelines; analyzing the results of modelling and developing computation scenarios for failures; developing scientifically valid recommendations for preventing such failures.

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1. Introduction

Gas pipelines of Fuel and Energy Complex (FEC) are related to high-energy systems. Failures of gas pipelines can entail very serious consequences for the population, service personal, and surrounding environment.

As current world-wide methods used for the risk assessment of the pipeline systems there are methods of probability theory and mathematical statistics. Algorithms for practical use of these methods for assessing risk posed by failures at industrial objects are represented as techniques, management directives, and standards approved by supervisory state institutions.

The attractiveness of stochastic methods for the risk assessment mostly is conditioned by their simple mathematical formalization and saving computational resources required. The main drawbacks of these methods are the absence of reliable prior values for probabilistic characteristics of failure events and the necessity to use subjective expert estimations. As for complex objects and single event, the usage of these methods does not allow to obtain the accurate estimations while forecasting and analyzing failures.

To avoid the above-mentioned insufficiency, a computing technique for investigating failures developed at the Computation Technology Center (CMTC) of SPE VNIIEF-VOLGOGAZ Ltd., Russia, is used.

The technique is based on the principles of mathematical physics, up-to-date numerical methods of continuum mechanics, and mathematical optimization. It is grounded on the principles of simultaneous creating and numerical analyzing precise mathematical models describing failures at the pipelines, from failure initiation up to localizing its consequences. The mathematical models of pipeline objects used in this technique are the systems of differential equations (partial or ordinary differential equations) with relevant boundary conditions and/or appropriate mathematical optimization problems. Precise modelling is achieved by minimizing simplifications assumed in the mathematical models and implementing up-to-date grid methods for non-linear numerical analysis and hybrid methods for mathematical optimization.

The computing technique for precise mathematical modelling of the failures at the gas pipelines includes the following main stages:

- gathering and analysis of actual initial failure information,
- mathematical formalization of the problem of failure investigation,
- fluid dynamic analysis of pipeline systems during pre-failure and at failure,
- non-linear structural analysis and simulation of pipeline fracture during failures,
- simulation of harmful impact on the population and surrounding environment caused by failures,
- development of computation scenarios for failures and scientifically validated recommendations to prevent similar failures.

The computation technique can be implemented in order to investigate and forecast feasible failures, including failure preventive measures development.

2. Gathering and processing of initial failure information

As the initial information for investigating causes and mechanisms of failures of pipelines one uses design and construction, geodesic, geological and normative documentation, mapping materials, and technical inspection data on actual pipeline state. To analyze failure consequences it is also necessary to have the information on weather conditions during the failure. Determination of physical properties of pipe materials and surrounding soils requires laboratory tests.

3. Mathematical formalization of failure investigation problem

The failure investigation problem is mathematically formalized based on a method of mathematical simulation of FEC pipelines for enhancing their safety [1]. The accuracy and effectiveness of the method were proved by application of the method in Russia and abroad during ten years [1-3].

Mathematical simulation of complex high-pressure pipelines is based on a principle of simultaneous creation (or choice) and numerical analysis of mathematical models for specific structures and processes, those describing critical behaviour and failure of pipelines, from the failure initiation up to localizing its consequences. These mathematical models are generated by applying models of continuum mechanics. More precisely, the systems studied involve the Maxwell, Navier-Stokes, Reynolds, and Navier equations completed with appropriate boundary and initial conditions.

Mathematical formulation is also based on the experience gained by industrial personnel of FEC facility.

4. Computational fluid dynamics analysis of pipeline systems during a pre-failure period and at failure

Failures of pipelines are often caused by hydraulic mode violations during the transport of gas mixtures and multiphase media through pipeline systems. To simulate nominal and failure modes of the pipeline systems one can implement CorNet [7] and/or AMADEUS software (a joint development of the CTC of SPE VNIIEF-VOLGOGAZ Ltd., SPP-DSTG company (Slovakia), and Mathematical Institute of Slovak Academy of Sciences) [8, 9]. We would like to illustrate the software capabilities in the case of AMADEUS.

Mathematical models for multicomponent gas and multiphase media (gas-liquid) flows through the pipeline systems, those describing unsteady nonisothermal turbulent flow of viscous chemically inert compressible multicomponent heat-conductive gas mixture and unsteady nonisothermal circular flow of multiphase media have been realized in AMADEUS [9]. Along with the unsteady modes, AMADEUS is capable of simulating steady state modes of gaseous and liquid products transport through the pipeline systems. Also, AMADEUS allows to simulate multicomponent gas mixture compression at compressor stations in nominal and failure modes, including surge.

All the mathematical models for multiphase and multicomponent media transport through the pipelines are generated by complete system of the integral Navier-Stokes equations, assuming that there are no shock waves in a flow [8,9]. For example, while simulating dry and purified gas transport through linear parts of main pipelines (LPMP), as a basic model the complete system of the integral Navier-Stokes equations is implemented, written for homogenous multicomponent flows:

$$\frac{d}{dt}\int\limits_{V(t)} \vec{\mathbf{\Phi}}\, dV = \int\limits_{V(t)} \vec{\mathbf{\Pi}}\, dV - \int\limits_{S(t)} \vec{\mathbf{J}}\, dS, \tag{4.1}$$

where:

$\vec{\mathbf{\Phi}}$ – a vector-function of physical characteristics per unit of volume (for example, the components of the vector-function may be the following ones: the specific mass, specific linear momentum, specific energy);

$\vec{\mathbf{\Pi}}$ – a vector-function characterizing physical characteristics production $\vec{\mathbf{\Phi}}$ (including internal sources);

$\vec{\mathbf{J}}$ – a vector-function characterizing the flow of physical characteristics $\vec{\mathbf{\Phi}}$ through the surface $S(t)$;

$V(t)$ – the volume of continuum;

$S(t)$ – the surface bounding the volume $V(t)$;

t – time (march variable).

The vector functions in Eq. (4.1) for homogeneous multicomponent gas mixture are as follows:

$$\vec{\mathbf{\Phi}} = \begin{bmatrix} \varrho \\ \varrho Y_1 \\ \vdots \\ \varrho Y_{N_S} \\ \varrho \vec{v} \\ \varrho\left(\varepsilon + \frac{v^2}{2}\right) \end{bmatrix}, \qquad \vec{\mathbf{\Pi}} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \varrho \vec{\mathbf{F}} \\ \varrho \vec{\mathbf{F}} \cdot \vec{v} + Q \end{bmatrix},$$

$$\vec{\mathbf{J}} = \begin{bmatrix} 0 \\ \vec{\mathbf{\Psi}}_1 \cdot \vec{\mathbf{n}} \\ \vdots \\ \vec{\mathbf{\Psi}}_{N_S} \cdot \vec{\mathbf{n}} \\ p\,\vec{\mathbf{n}} - \vec{\tau}_{\mathbf{n}} \\ p\,v_{\mathbf{n}} - \vec{\tau}_{\mathbf{n}} \cdot \vec{v} + \vec{\mathbf{W}} \cdot \vec{\mathbf{n}} + \sum\limits_{m=1}^{N_S} \varepsilon_m \vec{\mathbf{\Psi}}_m \cdot \vec{\mathbf{n}} \end{bmatrix}, \tag{4.2}$$

where:

ϱ – the density;

$\vec{v}$ – the gas velocity;

$v_n = \vec{v} \cdot \vec{\mathbf{n}}$ – the projection of $\vec{v}$ onto the unit external normal $\vec{\mathbf{n}}$ to the surface element dS;

p – the pressure;

$\vec{\tau}_n = \boldsymbol{\tau} \cdot \vec{\mathbf{n}}$ – the stress conditioned by the viscous friction at the area element with the external normal $\vec{\mathbf{n}}$ ($\boldsymbol{\tau}$ – the viscous stress tensor);

$\vec{\mathbf{F}}$ – the specific body force;

ε – the specific (per unit of mass) internal gas energy;

Q – the specific (per unit of volume) heat generation rate;

$\vec{\mathbf{W}} = -k\,\vec{\nabla} T$ – the heat flux, where:

k – the heat conductivity,

T – the temperature;

$\vec{\mathbf{\Psi}}_m = -\varrho\, D_m\, \vec{\nabla} Y_m$, where:

D_m – the local (at a point) diffusion coefficient of the m-th component,

Y_m – the local relative mass fraction of the m-th component of the gas mixture;

N_S – the number of homogeneous gas mixture components.

To complete the system of Eqs. (4.1), (4.2), one specifies equations of state as well as boundary and initial conditions. The equations of state describe supplementary thermodynamic relations between unknown functions.

When making transformation from the basic model to the mathematical ones for the specific gas dynamic processes in the pipelines, one should obligatory implement the ***principle of minimizing supplementary simplifications and assumptions*** [9]. To illustrate the above-mentioned procedure we provide the final form of the gas dynamic model for unsteady non-isothermal turbulent flow (without shock waves) of viscous chemically inert compressible multicomponent heat-conductive gas mixture in a pipe with a circular variable cross-section and absolutely rigid rough heat-conductive walls derived by transformation from the spatial model (4.1), (4.2) to the appropriate one-dimensional model [9]:

$$\frac{\partial(\varrho f)}{\partial t} + \frac{\partial}{\partial x}(\varrho w f) = 0 ; \tag{4.3a}$$

$$\begin{gathered} \frac{\partial}{\partial t}(\varrho Y_m f) + \frac{\partial}{\partial x}(\varrho Y_m w f) - \frac{\partial}{\partial x}\left(\varrho f D_m \frac{\partial Y_m}{\partial x}\right) = 0 , \\ m = \overline{1, N_S - 1} , \quad Y_{N_S} = 1 - \sum_{m=1}^{N_S - 1} Y_m ; \end{gathered} \tag{4.3b}$$

$$\frac{\partial(\varrho w f)}{\partial t} + \frac{\partial(\varrho w^2 f)}{\partial x} = -f\left(\frac{\partial p}{\partial x} + g\varrho\frac{\partial z_1}{\partial x}\right) - \frac{\pi}{4}\lambda\varrho w |w| R ; \tag{4.3c}$$

$$\begin{aligned} &\frac{\partial}{\partial t}\left[\varrho f\left(\varepsilon + \frac{w^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[\varrho w f\left(\varepsilon + \frac{w^2}{2}\right)\right] \\ &\quad = -\frac{\partial}{\partial x}(p w f) - \varrho w f g \frac{\partial z_1}{\partial x} - - p \frac{\partial f}{\partial t} + Q f + \frac{\partial}{\partial x}\left(k f \frac{\partial T}{\partial x}\right) \\ &\qquad - \Phi(T, T_{oc}) + \frac{\partial}{\partial x}\left(\varrho f \sum_{m=1}^{N_S} \varepsilon_m D_m \frac{\partial Y_m}{\partial x}\right) ; \end{aligned} \tag{4.3d}$$

$$\varepsilon_m = \varepsilon_m(\{S_{mix}\}) , \quad m = \overline{1, N_S}, \quad T_1 = T_2 = \ldots = T_{N_S} ; \tag{4.3e}$$

$$p = p(\{S_{mix}\}) ; \tag{4.3f}$$

$$\varepsilon = \varepsilon(\{S_{mix}\}) ; \tag{4.3g}$$

$$k = k(\{S_{mix}\}) ; \tag{4.3h}$$

$$D_m = D_m(\{S_{mix}\}) , \quad m = \overline{1, N_S}, \tag{4.3i}$$

where:

f – the sectional area of the pipeline;

w – the projection of the mixture velocity vector (averaged in the cross section) onto a geometrical axis of symmetry of the pipeline (assuming full-developed turbulent flow in the pipeline);

g – the acceleration of gravity module;

z_1 – the pipeline altitude above sea level or the other reference plane suitable for users;

$\{S_{mix}\}$ – a set of prescribed parameters;

λ – the friction factor in the Darcy-Weisbach formula [10];

π – the Pythagorean number;

$R = \sqrt{f/\pi}$ – the internal radius of the pipeline;

ε_m – specific (per unit mass) internal energy of m-th component;

T_m – temperature of m-th component;

t – time;

x – spatial coordinate along the geometrical axis of the pipeline (the spatial variable).

The function $\Phi(T, T_s)$ is determined by the law of heat transfer from the pipe to the surrounding environment and represents the total heat flow through the pipe walls having the perimeter χ of the flow area f ($\Phi(T, T_s) > 0$ – the heat emission, T_s – the temperature of the surrounding environment). Equations (4.3) use the physical values averaged in the pipeline cross-section.

The system of equations (4.3) is completed with boundary, initial and conjugation conditions.

As the conjugation conditions one can preset the boundary conditions simulating complete pipe rupture and/or its shutdown (operation of a valve).

At present, one-dimensional problems of computational fluid dynamics (4.3) is well investigated and developed area of numerical methods of continuum mechanics The development of difference schemes for investigating initial systems of gas dynamic equations implemented in the CFD simulators in this case is the nigglining work. These are performed by the popular methods and techniques.

For example, the classes of difference analogues for initial partial differential equations in AMADEUS have been derived by an integral interpolation method [10]. AMADEUS uses a variety of the difference schemes: two-layer and three-layer; explicit and implicit, conservative and completely conservative ones. Figure 1 shows AMADEUS implementation under development of measures for localizing consequences of hypothetic failure at a multiline main gas pipeline of SPP-DSTG (Slovakia).

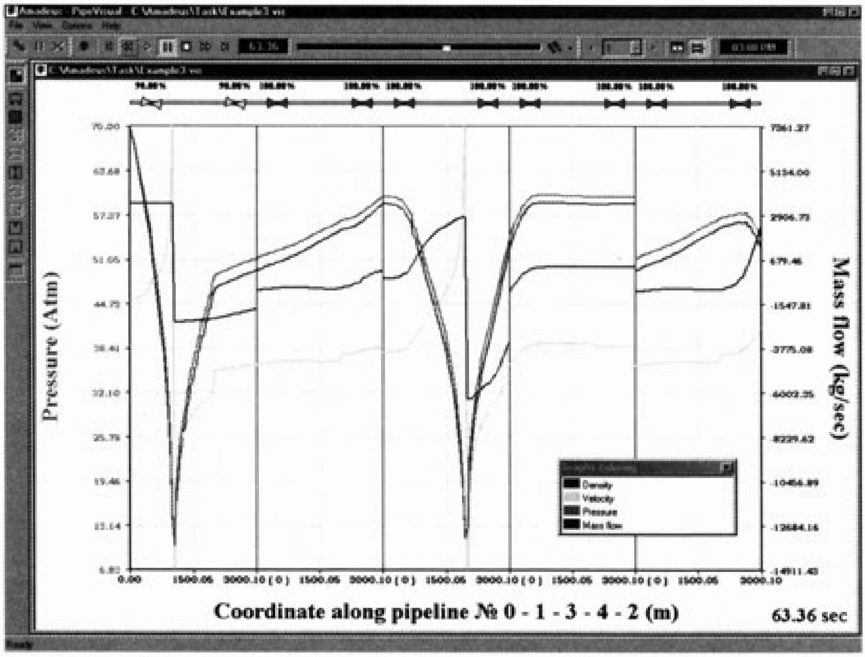

FIGURE 1. Simulation of the third line rupture of the multiline main gas pipeline.

5. Nonlinear structural analysis and simulation of pipeline rupture upon failure

FEC pipelines are topologically complex spatial structures with a lot of branches, intersections, tees, elbows etc. They are affected by a variety of loads (internal pressure, nonlinear temperature field, reaction of supports etc.). Interconnected aboveground as well as underground (horizontal, vertical, and sloping) pipeline sections are typical for these structures. Fracture of pipelines that have been in operation for a long time is often caused by the environmental impact, for example, displacement of the pipeline from the design position as a result of soil shearing or local thinning of the pipe walls (corrosion, erosion, mechanical damage etc.). A method for nonlinear strength analysis of the pipelines at failure has been developed by CTC [3, 11-13]. The proposed method for the nonlinear strength analysis of FEC pipelines allowing for their structure and operational conditions is based on applying numerical methods for solution of 3-D nonlinear problems of deformable solid mechanics. As is well-known, under static loads the problem of determining stress-strain state of a structure is reduced to solving differential equations of equilibrium (the Navier equations). These equations in an arbitrary curvilinear coordinate system are as follows [14]:

$$\nabla_j \sigma^{ij} + F^i = 0, \qquad i,j = 1,2,3, \tag{5.1}$$

where:
σ^{ij} – the contravariant components of a stress tensor;
F^i – the contravariant components a body (volumetric) force vector;
∇_j – the operator of covariant derivation;
under the prescribed boundary condition:

$$\sigma^{ij} n_j = T^i. \tag{5.2}$$

Here the following notation is assumed:
T^i – the contravariant components of the surface force vector;
n_j – the covariant components of the normal vector to the boundary surface.

For solving the problems of deformable solid mechanics it is necessary to express the Navier equations in terms of displacements using geometrical relations (the Cauchy equations establishing the relations between displacements and strains, and the Saint–Venant equations of strain continuity), and complete the system of equations by adding constitutive relations (equations establishing the relations between stresses and strains that depend on material model (linear-elastic, elastic-plastic etc.)).

The obtained systems of the differential equations of equilibrium for 3-D structures can be solved only by numerical methods. One of the most currently popular methods for the numerical solution of continuum mechanics is the finite element method (FEM) [15]. FEM is widely used for solving mainly the problems of deformable solid mechanics (this popularity is conditioned by proved convergence of FEM for the elliptical problems and feasibility to use nonregular meshes). Among the variety of commercial programs realizing FEM as a mean to simulate stress-strain state of the pipelines, ANSYS software has been chosen [16]. This software posses the quality certificate ISO9001 and a set of the required functional capabilities including both built-in extenders and adds-in of the capabilities required.

At the first stage strain-stress analysis of FEC pipelines is performed in a beam approximation. Thus, the entire pipeline structure is simulated by straight and curved beams of a circular section. While simulating and analyzing the structure within this stage all the loads influencing stress-strain state of the pipeline are taken into account: an excessive internal pressure, thermal deformations, stresses of elastically curved pipes, nonlinear interaction of soil and underground pipeline sections, weight of pipelines, valves and medium transported as well as other loads conditioned by the pipeline system functioning. These are loads from ground surface sources, the pipeline axis shift from the design position, contacts with supports etc.

The analysis by the beam models permits to determine the stress-strain state of the pipeline structure taken as a whole and exposing the most loaded sections, forces, and moments at the boundaries of these sections; hence, it is of approximate character. So the analysis is performed assuming linear-elastic behaviour of the pipe materials. The plastic strains of the pipelines could be also taken into consideration while analyzing the structure stability or failure.

At the second stage, more detailed analysis of the most loaded pipeline sections is performed by shell and solid finite element models. While applying the boundary conditions, the results of the previous stage are used. Interpolation of necessary data on the boundary conditions from the beam to shell and solid models based on the well-known Saint Venant principle [14] is carried out automatically.

Interpolation of the boundary conditions from the shell to solid models is performed using the submodelling procedure realized in ANSYS and from the beam to shell models by using the programs developed at CTC. These programs are subjoined to ANSYS as add-in macros. This analysis is performed in physically and geometrically nonlinear statement, i.e., allowing for elastic-plastic behaviour of the pipe steel and pipeline stiffness changing under deformations.

Thus the second stage analysis allows to obtain real stress-strains state of the pipeline section considering all the loads influencing the structure and detail pipeline geometry (Fig. 2a).

The analysis of the results obtained in the second stage enables to find the objective strength of each FEC pipeline section. The strength analysis is based on normative criteria: admissible loads and ultimate states as well as the simulation of the structure fracture implementing criteria of fracture mechanics (brittle, elastc-plastic, etc). Figure 2b presents the results of simulating the elastic-plastic fracture of the tee with defective welded joint under internal pressure.

As it has been mentioned before, a key condition to obtain the real stress-strain state and carry out objective strength estimation of FEC pipelines is an adequate simulation of nonlinear pipe/soil interaction. In this case for the first stage of the analysis using beam elements one implements linearized ideal elastic-plastic models of soils recommended for practical calculations and described in detail in [17]. Usage of these models with parameters obtained mainly experimentally allows already at the first stage to take into account such important characteristics substantially influencing on the pipeline/soil

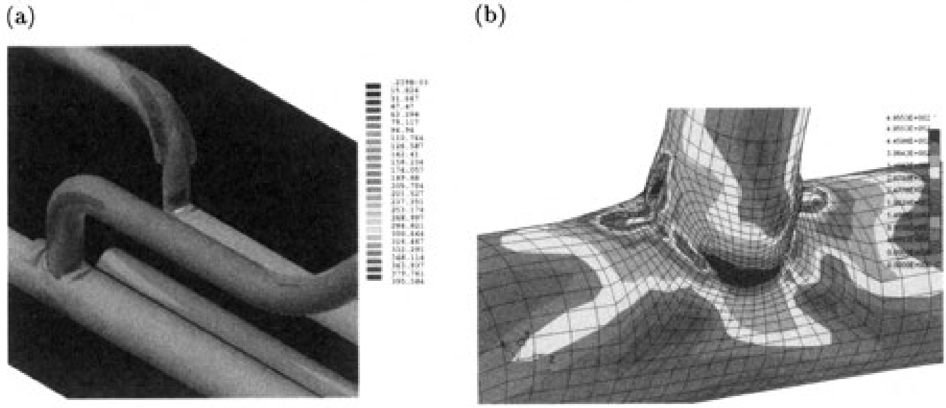

FIGURE 2. Examples of strength analysis for pipelines of the compressor station "Lyskovskaya" of "VOLGOTRANSGAZ" (Russia): (a) equivalent stresses [MPa] arising in tees of underground collectors under operational loads; (b) equivalent stresses [MPa] under fracture of a tee with defective welded joint.

interaction as weight of the pipeline, medium transported and soil, depth of the pipeline burying, various non-linear resistance of soil regarding vertical up and down displacement of the pipeline etc. At the second stage the soil surrounding the pipeline is considered as a continuum and simulated by solid finite elements. To set elastic-plastic properties of the medium equations of state of real soils are used. More detailed information on simulation of soils is provided in [18, 19].

6. Simulation of harmful environmental and societal impact caused by failures

Harmful environmental and societal impact is caused by main hazardous factors of failures of pipelines. These factors can be conditionally divided into two groups:

1. *debris affection* – an object is affected by the primary or secondary debris;
2. *gas hazard*:
    - toxic affection – caused by natural gas dispersion in the atmosphere,
    - heat affection – an object is affected by combusting methane-air mixture,
    - baric affection – an object is affected by shock and/or detonation waves.

6.1. Debris affection

Debris affection is typical for failures at high-pressure gas pipelines. At failure, gas expansion energy is spent for the pipes deformation and rupture, surrounding soil and/or atmosphere compression, acceleration of debris etc. To determine an amount of the gas energy expansion transformed into the kinetic energy and estimate initial velocities of the debris, this approach implements both the experimental data and results of numerical simulation of the pipelines rupture [20].

For this the problem the dynamic analysis of structures is reduced to solution of differential equations of deformable body motion in 3-D nonlinear statement under prescribed boundary and initial conditions. In Cartesian coordinate system, the acceleration of the structure points is the second time derivative of displacements $\ddot{u}_i$. Applying the d'Alembert principle we add the forces of inertia to the body forces influencing the structure and obtain the equation of motion:

$$\sigma_{ij,j} - \varrho\,\ddot{u}_i + \varrho\,F_i = 0, \tag{6.1}$$

where:

σ_{ij} – the components of a stress tensor,

ϱ – the density of material,

u_i – the components of the displacement vector,

F_i – the components of the body force vector.

Solution of the system (6.1) must satisfy all the prescribed boundary and initial conditions. In the general case there are three types of boundary conditions:

- the traction boundary condition

$$\sigma_{ij}\,n_j = T_i^*(\mathbf{x},t), \qquad \mathbf{x} \in S_1, \tag{6.2a}$$

- the displacement boundary condition

$$u_i = u_i^*(\mathbf{x},t), \qquad \mathbf{x} \in S_2, \tag{6.2b}$$

- the contact discontinuity

$$(\sigma_{ij}^+ - \sigma_{ij}^-)\,n_j = 0\,, \qquad \mathbf{x} \in S_3, \tag{6.2c}$$

where:

$S = S_1 \cup S_2 \cup S_3$ – the boundary surface of the structure,

n_j – components of a normal vector to the boundary surface,

$\mathbf{x} = (x_i)$ – the Cartesian coordinates of surface point $(i = 1, 2, 3)$,

$T_i^*(\mathbf{x}, t)$ – the prescribed surface force components,
$u_i^*(\mathbf{x}, t)$ – the prescribed boundary displacements.

The initial conditions have the following form:

$$u_i = u_i^0, \qquad \dot{u}_i = \dot{u}_i^0, \qquad t = 0. \tag{6.3}$$

Depending on the goal of the study, the initial-boundary value problem (6.1)–(6.3) can be solved by using an appropriate method. In our case the direct displacement method will be the most suitable.

The obtained systems of nonlinear partial differential equations is solved by the FEM that makes it possible to obtain a detailed behaviour in time for stress-strain state of the structure allowing for all active dynamic loads and elastic-plastic properties of material.

Within each time step it is checked whether continuum fracture criteria are met. In case the criteria are met, it is considered that a corresponding element of the structure looses its capability to bear load and its characteristics are excluded while forming the stiffness matrix at the next time step. Examples of simulation of high pressure gas pipelines of SPP-DSTG (Slovakia) and calculations of the debris parameters are represented in Fig. 3.

FIGURE 3. Numerical values of the parameters of a large piece of debris produced under rupture of underground main gas pipeline (a scale of the von Mises equivalent stresses [MPa], a plot of velocities [m/s]).

Areas that will be probably affected by the debris are determined by numerical simulation.

6.2. Gas hazard

Upon pipelines failure, compressed natural gas escapes into the surrounding environment and intensively mixes with the ambient air. The natural gas transmitted and stored contains more 98% of methane. This entails methane-air mixture formation.

The methane-air mixture is very flammable and toxic. The natural gas emission entailing formation of very flammable and toxic methane–air mixture is known as gas hazard. Thus numerical analysis of the gas hazard is focused on:

- the reduction of harmful environmental impact,
- the risk analysis for industrial facilities; preventing failures of gas industry facilities,
- minimization of damages to be inflicted by potential failures,
- the analysis of causes of failures that occurred.

The applied mathematical methods for the gas hazard simulation are based on numerical analysis of complete system of the Reynolds equations by grid methods. A problem is stated and solved as two-dimensional (axisymmetric) and three-dimensional. The methane-air mixture is considered as a two-component homogeneous gas mixture of two viscous heat conductive chemically inert ideal gases. The model for the two-component gas flow is considered in diffusion approximation. To allow for turbulence of the gas emissions and outflows, the well-known (k-ε)-turbulence model is implemented.

While analyzing numerically the gas hazard caused by the natural gas emissions a key problem is the determination of methane concentration fields. The methane concentration in the ambient air is considered as a main characteristics for qualitative and quantitative analysis of after-effects entailed by these emissions, for analysis of toxic affection and feasibility of the methane-air mixture ignition. Hence, the statement of the problem for the numerical analysis of the gas hazard can be formulated in the following way: to determine the methane concentration fields in the open atmosphere in the area of the natural gas outflow or emission as a result of numerical analysis of gas dynamic equations describing nonsteady, nonisothermal flow of two component gas mixture, where one component is the methane and the other one is the ambient air. To this end the boundary conditions should reflect a state of the atmosphere, terrain, structure of an emission source etc.

The following general simplifications and assumptions for simulation are advised: gas mixture is a mixture of two viscous heat-conductive chemically inert ideal gases, a model for the two-component gas flow is created in diffusion approximation, and the turbulence model (k-ε) is implemented.

The natural gas outflows into the atmosphere under supercritical pressure drop. So there are very severe demands concerning the accuracy of calculations preformed. Yet, in order to estimate the gas hazard areas one has to perform calculations for an area, which is sized kilometers, but flow velocities in this area are low enough.

To reduce time for calculations and save computational resources, the problem is solved by stages.

At the first stage the problem on a jet formation is solved. High gradients of unknown functions and high velocities of flow are typical for this particular problem. Thus it is reasonable to consider this flow as being compressible. In the second stage the interaction of the quasistationary jet and atmosphere is considered. The second stage is characterized by low velocities of gas flow and low gradients of unknown functions in the area considered. Thus, to estimate the gas hazard it suffices to use models of incompressible gas flows.

The results of each consecutive stage of the gas hazard assessment are used for the boundary and initial conditions at the following stages of the investigation. Hence the solution of the problem is based on the known principle of implementing different gas dynamic models in different domains of the flow with the subsequent seaming of the solution on separating surfaces.

To solve the stated problem different methods can be used, namely: the method of finite volumes, finite elements, finite difference, coarse particles, etc. Figure 4 shows the solution of realistic problem.

This approach for simulating emergency emissions of gas mixtures transported through the pipelines is described in detail in the papers [21, 22]. The approach allows high accuracy estimation of the concentration field parameters of the methane-air mixture taking into account the terrain and state of the atmosphere. The risk assessment of the toxic affection of population in this technology is reduced to an analysis of probability of lethal consequence for the population. The latter depends on the population locality in a specific field of concentrations that changes in space and time.

Heat affection intensity is assessed by numerical methods simulating ignition of the methane-air mixture based on the known concentration fields. Then, the methane-air mixture combustion is simulated as a diffusion plume or combusting ball. To this end the intensity of heat radiation from the combusting methane-air mixture is assessed with respect to the space and time by numerical methods of thermal dynamics. The risk analysis for objects to be probably affected by heat determines probable ignition and combustion

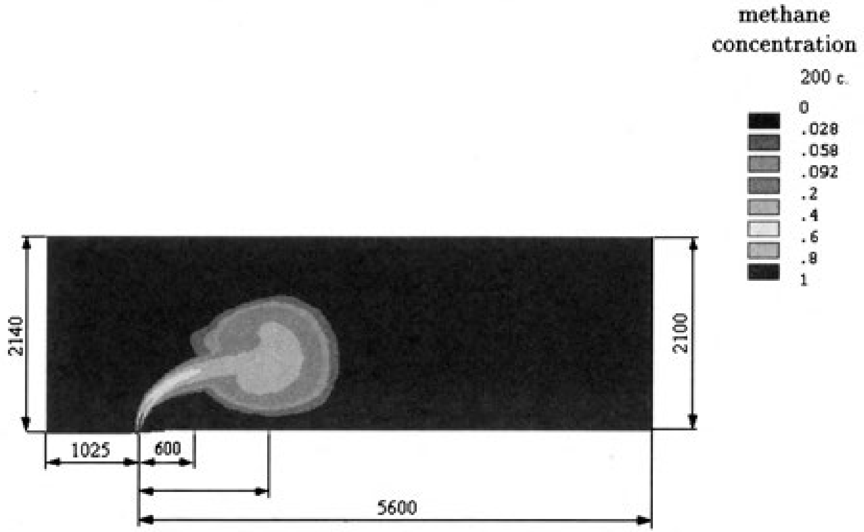

FIGURE 4. A field of relative mass fraction of methane carried by the wind during pipeline fracture.

of surface material of the object studied. These are analyzed by taking into account the preset distance from fire and radiation intensity. Heat influence on the object due to the heat conductivity and convection is not so intensive upon fire at the pipeline facilities. More detailed approach to the analysis of heat affection risk is represented in [23].

While simulating methane-air mixture ignition and combustion, one performs numerical analysis of possible transforming a normal combustion mode into convective one and then into low velocity detonation. Upon detonation the objects adjacent to the place of a failure are mainly affected by shock waves. These are analyzed taking into account the location of the object with respect to the place of the failure and the shock wave parameters obtained by mathematical simulation. The baric affection analysis allows for the detonation mode (high velocity or low velocity) and movement of the affected object.

7. Development of computation scenarios for failures and scientifically validated recommendations to prevent these failures

A computation scenario for a failure is based on the analysis of high accuracy mathematical simulation results of the failure and comparing them with the failure investigation materials. Each item of the scenario is validated by mathematical models and results of numerical analysis.

The relation between the mathematical models while developing the computation scenario is realized by the boundary conditions. For instance, dynamic loads influencing a pipeline due to internal pressure of transported media are determined as a result of gas dynamic analysis of flows in pipelines during pre-failure period and at failure. These are necessary for analyzing the causes and consequences of the pipeline rupture. The results of gas dynamic and strength analysis are used as the boundary conditions for debris affection and gas hazard assessment.

The recommendations regarding failure preventive measures are developed according to the computation scenario for a real or hypothetical failure at a specific pipeline transportation facility. To this end each recommendation is simulated by the above mathematical methods in terms of how it might be acting due to the need to analyze the effectiveness of the undertaken recommendation and to exclude harmful after-effects resulted from this recommendation realization. The detailed description of the computation scenario development for the realistic failure occurred at the compressor station "Arskaya" of "VOLGOTRANSGAZ" (Russia) and the recommendations to prevent similar failures can be found in [4].

8. Conclusion

The computation technology for investigating failures of gas pipeline systems enables specialists in gas, oil, petrochemical, and chemical industries to fulfill the following tasks:

- validated investigation of realistic failures,
- multi-objective risk analysis for operating pipelines including those being designed and constructed,
- reliable identification of feasible failure causes and development measures to prevent failures and/or localize their consequences.

The integral character of the obtained results should be especially emphasized. Such approaches have never been used before in the pipeline industry.

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As current world-wide methods used for the risk assessment of the pipeline systems there are methods of probability theory and mathematical statistics. Algorithms for practical use of these methods for assessing risk posed by failures at industrial objects are represented as techniques, management directives, and standards approved by supervisory state institutions.

The attractiveness of stochastic methods for the risk assessment mostly is conditioned by their simple mathematical formalization and saving computational resources required. The main drawbacks of these methods are the absence of reliable prior values for probabilistic characteristics of failure events and the necessity to use subjective expert estimations. As for complex objects and single event, the usage of these methods does not allow to obtain the accurate estimations while forecasting and analyzing failures.

To avoid the above-mentioned insufficiency, a computing technique for investigating failures developed at the Computation Technology Center (CMTC) of SPE VNIIEF-VOLGOGAZ Ltd., Russia, is used.

The technique is based on the principles of mathematical physics, up-to-date numerical methods of continuum mechanics, and mathematical optimization. It is grounded on the principles of simultaneous creating and numerical analyzing precise mathematical models describing failures at the pipelines, from failure initiation up to localizing its consequences. The mathematical models of pipeline objects used in this technique are the systems of differential equations (partial or ordinary differential equations) with relevant boundary conditions and/or appropriate mathematical optimization problems. Precise modelling is achieved by minimizing simplifications assumed in the mathematical models and implementing up-to-date grid methods for non-linear numerical analysis and hybrid methods for mathematical optimization.

The computing technique for precise mathematical modelling of the failures at the gas pipelines includes the following main stages:

- gathering and analysis of actual initial failure information,
- mathematical formalization of the problem of failure investigation,
- fluid dynamic analysis of pipeline systems during pre-failure and at failure,
- non-linear structural analysis and simulation of pipeline fracture during failures,
- simulation of harmful impact on the population and surrounding environment caused by failures,
- development of computation scenarios for failures and scientifically validated recommendations to prevent similar failures.

The computation technique can be implemented in order to investigate and forecast feasible failures, including failure preventive measures development.

2. Gathering and processing of initial failure information

As the initial information for investigating causes and mechanisms of failures of pipelines one uses design and construction, geodesic, geological and normative documentation, mapping materials, and technical inspection data on actual pipeline state. To analyze failure consequences it is also necessary to have the information on weather conditions during the failure. Determination of physical properties of pipe materials and surrounding soils requires laboratory tests.

3. Mathematical formalization of failure investigation problem

The failure investigation problem is mathematically formalized based on a method of mathematical simulation of FEC pipelines for enhancing their safety [1]. The accuracy and effectiveness of the method were proved by application of the method in Russia and abroad during ten years [1-3].

Mathematical simulation of complex high-pressure pipelines is based on a principle of simultaneous creation (or choice) and numerical analysis of mathematical models for specific structures and processes, those describing critical behaviour and failure of pipelines, from the failure initiation up to localizing its consequences. These mathematical models are generated by applying models of continuum mechanics. More precisely, the systems studied involve the Maxwell, Navier-Stokes, Reynolds, and Navier equations completed with appropriate boundary and initial conditions.

Mathematical formulation is also based on the experience gained by industrial personnel of FEC facility.

4. Computational fluid dynamics analysis of pipeline systems during a pre-failure period and at failure

Failures of pipelines are often caused by hydraulic mode violations during the transport of gas mixtures and multiphase media through pipeline systems. To simulate nominal and failure modes of the pipeline systems one can implement CorNet [7] and/or AMADEUS software (a joint development of the CTC of SPE VNIIEF-VOLGOGAZ Ltd., SPP-DSTG company (Slovakia), and Mathematical Institute of Slovak Academy of Sciences) [8, 9]. We would like to illustrate the software capabilities in the case of AMADEUS.

Mathematical models for multicomponent gas and multiphase media (gas-liquid) flows through the pipeline systems, those describing unsteady nonisothermal turbulent flow of viscous chemically inert compressible multicomponent heat-conductive gas mixture and unsteady nonisothermal circular flow of multiphase media have been realized in AMADEUS [9]. Along with the unsteady modes, AMADEUS is capable of simulating steady state modes of gaseous and liquid products transport through the pipeline systems. Also, AMADEUS allows to simulate multicomponent gas mixture compression at compressor stations in nominal and failure modes, including surge.

All the mathematical models for multiphase and multicomponent media transport through the pipelines are generated by complete system of the integral Navier-Stokes equations, assuming that there are no shock waves in a flow [8,9]. For example, while simulating dry and purified gas transport through linear parts of main pipelines (LPMP), as a basic model the complete system of the integral Navier-Stokes equations is implemented, written for homogenous multicomponent flows:

$$\frac{d}{dt}\int\limits_{V(t)} \vec{\mathbf{\Phi}}\, dV = \int\limits_{V(t)} \vec{\mathbf{\Pi}}\, dV - \int\limits_{S(t)} \vec{\mathbf{J}}\, dS, \tag{4.1}$$

where:

$\vec{\mathbf{\Phi}}$ – a vector-function of physical characteristics per unit of volume (for example, the components of the vector-function may be the following ones: the specific mass, specific linear momentum, specific energy);

$\vec{\mathbf{\Pi}}$ – a vector-function characterizing physical characteristics production $\vec{\mathbf{\Phi}}$ (including internal sources);

$\vec{\mathbf{J}}$ – a vector-function characterizing the flow of physical characteristics $\vec{\mathbf{\Phi}}$ through the surface $S(t)$;

$V(t)$ – the volume of continuum;

$S(t)$ – the surface bounding the volume $V(t)$;

t – time (march variable).

The vector functions in Eq. (4.1) for homogeneous multicomponent gas mixture are as follows:

$$\vec{\mathbf{\Phi}} = \begin{bmatrix} \varrho \\ \varrho Y_1 \\ \vdots \\ \varrho Y_{N_S} \\ \varrho \vec{v} \\ \varrho\left(\varepsilon + \frac{v^2}{2}\right) \end{bmatrix}, \qquad \vec{\mathbf{\Pi}} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \varrho \vec{\mathbf{F}} \\ \varrho \vec{\mathbf{F}} \cdot \vec{v} + Q \end{bmatrix},$$

$$\vec{\mathbf{J}} = \begin{bmatrix} 0 \\ \vec{\mathbf{\Psi}}_1 \cdot \vec{\mathbf{n}} \\ \vdots \\ \vec{\mathbf{\Psi}}_{N_S} \cdot \vec{\mathbf{n}} \\ p\,\vec{\mathbf{n}} - \vec{\boldsymbol{\tau}}_{\mathbf{n}} \\ p\,v_{\mathbf{n}} - \vec{\boldsymbol{\tau}}_{\mathbf{n}} \cdot \vec{v} + \vec{\mathbf{W}} \cdot \vec{\mathbf{n}} + \sum\limits_{m=1}^{N_S} \varepsilon_m \vec{\mathbf{\Psi}}_m \cdot \vec{\mathbf{n}} \end{bmatrix}, \tag{4.2}$$

where:

ϱ – the density;

$\vec{v}$ – the gas velocity;

$v_n = \vec{v} \cdot \vec{\mathbf{n}}$ – the projection of $\vec{v}$ onto the unit external normal $\vec{\mathbf{n}}$ to the surface element dS;

p – the pressure;

$\vec{\boldsymbol{\tau}}_n = \boldsymbol{\tau} \cdot \vec{\mathbf{n}}$ – the stress conditioned by the viscous friction at the area element with the external normal $\vec{\mathbf{n}}$ ($\boldsymbol{\tau}$ – the viscous stress tensor);

$\vec{\mathbf{F}}$ – the specific body force;

ε – the specific (per unit of mass) internal gas energy;

Q – the specific (per unit of volume) heat generation rate;

$\vec{\mathbf{W}} = -k\,\vec{\nabla} T$ – the heat flux, where:

k – the heat conductivity,

T – the temperature;

$\vec{\mathbf{\Psi}}_m = -\varrho\, D_m \vec{\nabla} Y_m$, where:

D_m – the local (at a point) diffusion coefficient of the m-th component,

Y_m – the local relative mass fraction of the m-th component of the gas mixture;

N_S – the number of homogeneous gas mixture components.

To complete the system of Eqs. (4.1), (4.2), one specifies equations of state as well as boundary and initial conditions. The equations of state describe supplementary thermodynamic relations between unknown functions.

When making transformation from the basic model to the mathematical ones for the specific gas dynamic processes in the pipelines, one should obligatory implement the ***principle of minimizing supplementary simplifications and assumptions*** [9]. To illustrate the above-mentioned procedure we provide the final form of the gas dynamic model for unsteady non-isothermal turbulent flow (without shock waves) of viscous chemically inert compressible multicomponent heat-conductive gas mixture in a pipe with a circular variable cross-section and absolutely rigid rough heat-conductive walls derived by transformation from the spatial model (4.1), (4.2) to the appropriate one-dimensional model [9]:

$$\frac{\partial(\varrho f)}{\partial t} + \frac{\partial}{\partial x}(\varrho w f) = 0\,; \tag{4.3a}$$

$$\begin{gathered}\frac{\partial}{\partial t}(\varrho Y_m f) + \frac{\partial}{\partial x}(\varrho Y_m w f) - \frac{\partial}{\partial x}\left(\varrho f D_m \frac{\partial Y_m}{\partial x}\right) = 0\,,\\ m = \overline{1,\, N_S - 1}\,, \quad Y_{N_S} = 1 - \sum_{m=1}^{N_S-1} Y_m\,;\end{gathered} \tag{4.3b}$$

$$\frac{\partial\,(\varrho w f)}{\partial\, t} + \frac{\partial\,(\varrho w^2 f)}{\partial\, x} = -f\left(\frac{\partial p}{\partial x} + g\,\varrho\,\frac{\partial z_1}{\partial x}\right) - \frac{\pi}{4}\,\lambda\,\varrho\, w\,|w|\,R\,; \tag{4.3c}$$

$$\begin{aligned}&\frac{\partial}{\partial t}\left[\varrho f\left(\varepsilon + \frac{w^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[\varrho w f\left(\varepsilon + \frac{w^2}{2}\right)\right]\\ &\quad = -\frac{\partial}{\partial x}(p\, w\, f) - \varrho\, w\, f\, g\,\frac{\partial z_1}{\partial x} - -p\,\frac{\partial f}{\partial t} + Q\, f + \frac{\partial}{\partial x}\left(k\, f\,\frac{\partial T}{\partial x}\right)\\ &\qquad - \Phi\,(T,\, T_{oc}) + \frac{\partial}{\partial x}\left(\varrho\, f \sum_{m=1}^{N_S} \varepsilon_m\, D_m\,\frac{\partial Y_m}{\partial x}\right);\end{aligned} \tag{4.3d}$$

$$\varepsilon_m = \varepsilon_m\,(\{S_{mix}\})\,, \quad m = \overline{1,\, N_S}, \quad T_1 = T_2 = \ldots = T_{N_S}; \tag{4.3e}$$

$$p = p\,(\{S_{mix}\})\,; \tag{4.3f}$$

$$\varepsilon = \varepsilon\,(\{S_{mix}\})\,; \tag{4.3g}$$

$$k = k\,(\{S_{mix}\})\,; \tag{4.3h}$$

$$D_m = D_m\,(\{S_{mix}\})\,, \quad m = \overline{1,\, N_S}, \tag{4.3i}$$

where:

f – the sectional area of the pipeline;

w – the projection of the mixture velocity vector (averaged in the cross section) onto a geometrical axis of symmetry of the pipeline (assuming full-developed turbulent flow in the pipeline);

g – the acceleration of gravity module;

z_1 – the pipeline altitude above sea level or the other reference plane suitable for users;

$\{S_{mix}\}$ – a set of prescribed parameters;

λ – the friction factor in the Darcy-Weisbach formula [10];

π – the Pythagorean number;

$R = \sqrt{f/\pi}$ – the internal radius of the pipeline;

ε_m – specific (per unit mass) internal energy of m-th component;

T_m – temperature of m-th component;

t – time;

x – spatial coordinate along the geometrical axis of the pipeline (the spatial variable).

The function $\Phi(T, T_s)$ is determined by the law of heat transfer from the pipe to the surrounding environment and represents the total heat flow through the pipe walls having the perimeter χ of the flow area f ($\Phi(T, T_s) > 0$ – the heat emission, T_s – the temperature of the surrounding environment). Equations (4.3) use the physical values averaged in the pipeline cross-section.

The system of equations (4.3) is completed with boundary, initial and conjugation conditions.

As the conjugation conditions one can preset the boundary conditions simulating complete pipe rupture and/or its shutdown (operation of a valve).

At present, one-dimensional problems of computational fluid dynamics (4.3) is well investigated and developed area of numerical methods of continuum mechanics The development of difference schemes for investigating initial systems of gas dynamic equations implemented in the CFD simulators in this case is the nigglining work. These are performed by the popular methods and techniques.

For example, the classes of difference analogues for initial partial differential equations in AMADEUS have been derived by an integral interpolation method [10]. AMADEUS uses a variety of the difference schemes: two-layer and three-layer; explicit and implicit, conservative and completely conservative ones. Figure 1 shows AMADEUS implementation under development of measures for localizing consequences of hypothetic failure at a multiline main gas pipeline of SPP-DSTG (Slovakia).

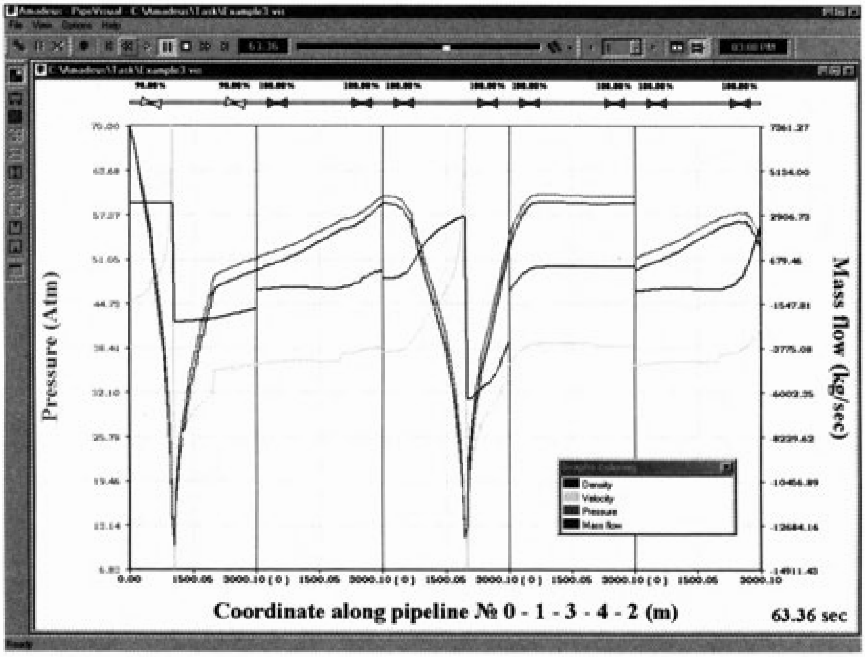

FIGURE 1. Simulation of the third line rupture of the multiline main gas pipeline.

5. Nonlinear structural analysis and simulation of pipeline rupture upon failure

FEC pipelines are topologically complex spatial structures with a lot of branches, intersections, tees, elbows etc. They are affected by a variety of loads (internal pressure, nonlinear temperature field, reaction of supports etc.). Interconnected aboveground as well as underground (horizontal, vertical, and sloping) pipeline sections are typical for these structures. Fracture of pipelines that have been in operation for a long time is often caused by the environmental impact, for example, displacement of the pipeline from the design position as a result of soil shearing or local thinning of the pipe walls (corrosion, erosion, mechanical damage etc.). A method for nonlinear strength analysis of the pipelines at failure has been developed by CTC [3, 11-13]. The proposed method for the nonlinear strength analysis of FEC pipelines allowing for their structure and operational conditions is based on applying numerical methods for solution of 3-D nonlinear problems of deformable solid mechanics. As is well-known, under static loads the problem of determining stress-strain state of a structure is reduced to solving differential equations of equilibrium (the Navier equations). These equations in an arbitrary curvilinear coordinate system are as follows [14]:

$$\nabla_j \sigma^{ij} + F^i = 0, \qquad i, j = 1, 2, 3, \tag{5.1}$$

where:
σ^{ij} – the contravariant components of a stress tensor;
F^i – the contravariant components a body (volumetric) force vector;
∇_j – the operator of covariant derivation;
under the prescribed boundary condition:

$$\sigma^{ij} n_j = T^i. \tag{5.2}$$

Here the following notation is assumed:
T^i – the contravariant components of the surface force vector;
n_j – the covariant components of the normal vector to the boundary surface.

For solving the problems of deformable solid mechanics it is necessary to express the Navier equations in terms of displacements using geometrical relations (the Cauchy equations establishing the relations between displacements and strains, and the Saint–Venant equations of strain continuity), and complete the system of equations by adding constitutive relations (equations establishing the relations between stresses and strains that depend on material model (linear-elastic, elastic-plastic etc.)).

The obtained systems of the differential equations of equilibrium for 3-D structures can be solved only by numerical methods. One of the most currently popular methods for the numerical solution of continuum mechanics is the finite element method (FEM) [15]. FEM is widely used for solving mainly the problems of deformable solid mechanics (this popularity is conditioned by proved convergence of FEM for the elliptical problems and feasibility to use nonregular meshes). Among the variety of commercial programs realizing FEM as a mean to simulate stress-strain state of the pipelines, ANSYS software has been chosen [16]. This software posses the quality certificate ISO9001 and a set of the required functional capabilities including both built-in extenders and adds-in of the capabilities required.

At the first stage strain-stress analysis of FEC pipelines is performed in a beam approximation. Thus, the entire pipeline structure is simulated by straight and curved beams of a circular section. While simulating and analyzing the structure within this stage all the loads influencing stress-strain state of the pipeline are taken into account: an excessive internal pressure, thermal deformations, stresses of elastically curved pipes, nonlinear interaction of soil and underground pipeline sections, weight of pipelines, valves and medium transported as well as other loads conditioned by the pipeline system functioning. These are loads from ground surface sources, the pipeline axis shift from the design position, contacts with supports etc.

The analysis by the beam models permits to determine the stress-strain state of the pipeline structure taken as a whole and exposing the most loaded sections, forces, and moments at the boundaries of these sections; hence, it is of approximate character. So the analysis is performed assuming linear-elastic behaviour of the pipe materials. The plastic strains of the pipelines could be also taken into consideration while analyzing the structure stability or failure.

At the second stage, more detailed analysis of the most loaded pipeline sections is performed by shell and solid finite element models. While applying the boundary conditions, the results of the previous stage are used. Interpolation of necessary data on the boundary conditions from the beam to shell and solid models based on the well-known Saint Venant principle [14] is carried out automatically.

Interpolation of the boundary conditions from the shell to solid models is performed using the submodelling procedure realized in ANSYS and from the beam to shell models by using the programs developed at CTC. These programs are subjoined to ANSYS as add-in macros. This analysis is performed in physically and geometrically nonlinear statement, i.e., allowing for elastic-plastic behaviour of the pipe steel and pipeline stiffness changing under deformations.

Thus the second stage analysis allows to obtain real stress-strains state of the pipeline section considering all the loads influencing the structure and detail pipeline geometry (Fig. 2a).

The analysis of the results obtained in the second stage enables to find the objective strength of each FEC pipeline section. The strength analysis is based on normative criteria: admissible loads and ultimate states as well as the simulation of the structure fracture implementing criteria of fracture mechanics (brittle, elastc-plastic, etc). Figure 2b presents the results of simulating the elastic-plastic fracture of the tee with defective welded joint under internal pressure.

As it has been mentioned before, a key condition to obtain the real stress-strain state and carry out objective strength estimation of FEC pipelines is an adequate simulation of nonlinear pipe/soil interaction. In this case for the first stage of the analysis using beam elements one implements linearized ideal elastic-plastic models of soils recommended for practical calculations and described in detail in [17]. Usage of these models with parameters obtained mainly experimentally allows already at the first stage to take into account such important characteristics substantially influencing on the pipeline/soil

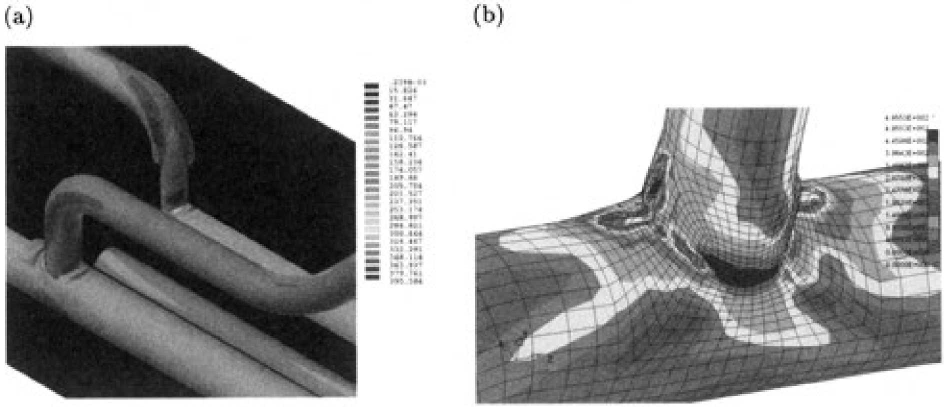

FIGURE 2. Examples of strength analysis for pipelines of the compressor station "Lyskovskaya" of "VOLGOTRANSGAZ" (Russia): (a) equivalent stresses [MPa] arising in tees of underground collectors under operational loads; (b) equivalent stresses [MPa] under fracture of a tee with defective welded joint.

interaction as weight of the pipeline, medium transported and soil, depth of the pipeline burying, various non-linear resistance of soil regarding vertical up and down displacement of the pipeline etc. At the second stage the soil surrounding the pipeline is considered as a continuum and simulated by solid finite elements. To set elastic-plastic properties of the medium equations of state of real soils are used. More detailed information on simulation of soils is provided in [18, 19].

6. Simulation of harmful environmental and societal impact caused by failures

Harmful environmental and societal impact is caused by main hazardous factors of failures of pipelines. These factors can be conditionally divided into two groups:

1. *debris affection* – an object is affected by the primary or secondary debris;
2. *gas hazard*:
    - toxic affection – caused by natural gas dispersion in the atmosphere,
    - heat affection – an object is affected by combusting methane-air mixture,
    - baric affection – an object is affected by shock and/or detonation waves.

6.1. Debris affection

Debris affection is typical for failures at high-pressure gas pipelines. At failure, gas expansion energy is spent for the pipes deformation and rupture, surrounding soil and/or atmosphere compression, acceleration of debris etc. To determine an amount of the gas energy expansion transformed into the kinetic energy and estimate initial velocities of the debris, this approach implements both the experimental data and results of numerical simulation of the pipelines rupture [20].

For this the problem the dynamic analysis of structures is reduced to solution of differential equations of deformable body motion in 3-D nonlinear statement under prescribed boundary and initial conditions. In Cartesian coordinate system, the acceleration of the structure points is the second time derivative of displacements $\ddot{u}_i$. Applying the d'Alembert principle we add the forces of inertia to the body forces influencing the structure and obtain the equation of motion:

$$\sigma_{ij,j} - \varrho\,\ddot{u}_i + \varrho\,F_i = 0, \tag{6.1}$$

where:

σ_{ij} – the components of a stress tensor,

ϱ – the density of material,

u_i – the components of the displacement vector,

F_i – the components of the body force vector.

Solution of the system (6.1) must satisfy all the prescribed boundary and initial conditions. In the general case there are three types of boundary conditions:

- the traction boundary condition

$$\sigma_{ij}\,n_j = T_i^*(\mathbf{x},t), \qquad \mathbf{x} \in S_1, \tag{6.2a}$$

- the displacement boundary condition

$$u_i = u_i^*(\mathbf{x},t), \qquad \mathbf{x} \in S_2, \tag{6.2b}$$

- the contact discontinuity

$$(\sigma_{ij}^+ - \sigma_{ij}^-)\,n_j = 0\,, \qquad \mathbf{x} \in S_3, \tag{6.2c}$$

where:

$S = S_1 \cup S_2 \cup S_3$ – the boundary surface of the structure,

n_j – components of a normal vector to the boundary surface,

$\mathbf{x} = (x_i)$ – the Cartesian coordinates of surface point $(i = 1,2,3)$,

$T_i^*(\mathbf{x},t)$ – the prescribed surface force components,
$u_i^*(\mathbf{x},t)$ – the prescribed boundary displacements.

The initial conditions have the following form:

$$u_i = u_i^0, \qquad \dot{u}_i = \dot{u}_i^0, \qquad t = 0. \tag{6.3}$$

Depending on the goal of the study, the initial-boundary value problem (6.1)–(6.3) can be solved by using an appropriate method. In our case the direct displacement method will be the most suitable.

The obtained systems of nonlinear partial differential equations is solved by the FEM that makes it possible to obtain a detailed behaviour in time for stress-strain state of the structure allowing for all active dynamic loads and elastic-plastic properties of material.

Within each time step it is checked whether continuum fracture criteria are met. In case the criteria are met, it is considered that a corresponding element of the structure looses its capability to bear load and its characteristics are excluded while forming the stiffness matrix at the next time step. Examples of simulation of high pressure gas pipelines of SPP-DSTG (Slovakia) and calculations of the debris parameters are represented in Fig. 3.

FIGURE 3. Numerical values of the parameters of a large piece of debris produced under rupture of underground main gas pipeline (a scale of the von Mises equivalent stresses [MPa], a plot of velocities [m/s]).

Areas that will be probably affected by the debris are determined by numerical simulation.

6.2. Gas hazard

Upon pipelines failure, compressed natural gas escapes into the surrounding environment and intensively mixes with the ambient air. The natural gas transmitted and stored contains more 98% of methane. This entails methane-air mixture formation.

The methane-air mixture is very flammable and toxic. The natural gas emission entailing formation of very flammable and toxic methane–air mixture is known as gas hazard. Thus numerical analysis of the gas hazard is focused on:

- the reduction of harmful environmental impact,
- the risk analysis for industrial facilities; preventing failures of gas industry facilities,
- minimization of damages to be inflicted by potential failures,
- the analysis of causes of failures that occurred.

The applied mathematical methods for the gas hazard simulation are based on numerical analysis of complete system of the Reynolds equations by grid methods. A problem is stated and solved as two-dimensional (axisymmetric) and three-dimensional. The methane-air mixture is considered as a two-component homogeneous gas mixture of two viscous heat conductive chemically inert ideal gases. The model for the two-component gas flow is considered in diffusion approximation. To allow for turbulence of the gas emissions and outflows, the well-known (k-ε)-turbulence model is implemented.

While analyzing numerically the gas hazard caused by the natural gas emissions a key problem is the determination of methane concentration fields. The methane concentration in the ambient air is considered as a main characteristics for qualitative and quantitative analysis of after-effects entailed by these emissions, for analysis of toxic affection and feasibility of the methane-air mixture ignition. Hence, the statement of the problem for the numerical analysis of the gas hazard can be formulated in the following way: to determine the methane concentration fields in the open atmosphere in the area of the natural gas outflow or emission as a result of numerical analysis of gas dynamic equations describing nonsteady, nonisothermal flow of two component gas mixture, where one component is the methane and the other one is the ambient air. To this end the boundary conditions should reflect a state of the atmosphere, terrain, structure of an emission source etc.

The following general simplifications and assumptions for simulation are advised: gas mixture is a mixture of two viscous heat-conductive chemically inert ideal gases, a model for the two-component gas flow is created in diffusion approximation, and the turbulence model (k-ε) is implemented.

The natural gas outflows into the atmosphere under supercritical pressure drop. So there are very severe demands concerning the accuracy of calculations preformed. Yet, in order to estimate the gas hazard areas one has to perform calculations for an area, which is sized kilometers, but flow velocities in this area are low enough.

To reduce time for calculations and save computational resources, the problem is solved by stages.

At the first stage the problem on a jet formation is solved. High gradients of unknown functions and high velocities of flow are typical for this particular problem. Thus it is reasonable to consider this flow as being compressible. In the second stage the interaction of the quasistationary jet and atmosphere is considered. The second stage is characterized by low velocities of gas flow and low gradients of unknown functions in the area considered. Thus, to estimate the gas hazard it suffices to use models of incompressible gas flows.

The results of each consecutive stage of the gas hazard assessment are used for the boundary and initial conditions at the following stages of the investigation. Hence the solution of the problem is based on the known principle of implementing different gas dynamic models in different domains of the flow with the subsequent seaming of the solution on separating surfaces.

To solve the stated problem different methods can be used, namely: the method of finite volumes, finite elements, finite difference, coarse particles, etc. Figure 4 shows the solution of realistic problem.

This approach for simulating emergency emissions of gas mixtures transported through the pipelines is described in detail in the papers [21, 22]. The approach allows high accuracy estimation of the concentration field parameters of the methane-air mixture taking into account the terrain and state of the atmosphere. The risk assessment of the toxic affection of population in this technology is reduced to an analysis of probability of lethal consequence for the population. The latter depends on the population locality in a specific field of concentrations that changes in space and time.

Heat affection intensity is assessed by numerical methods simulating ignition of the methane-air mixture based on the known concentration fields. Then, the methane-air mixture combustion is simulated as a diffusion plume or combusting ball. To this end the intensity of heat radiation from the combusting methane-air mixture is assessed with respect to the space and time by numerical methods of thermal dynamics. The risk analysis for objects to be probably affected by heat determines probable ignition and combustion

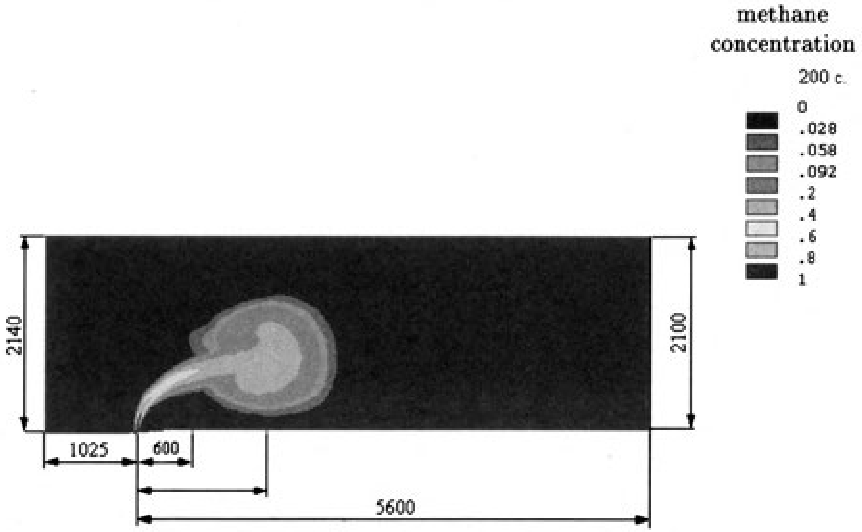

FIGURE 4. A field of relative mass fraction of methane carried by the wind during pipeline fracture.

of surface material of the object studied. These are analyzed by taking into account the preset distance from fire and radiation intensity. Heat influence on the object due to the heat conductivity and convection is not so intensive upon fire at the pipeline facilities. More detailed approach to the analysis of heat affection risk is represented in [23].

While simulating methane-air mixture ignition and combustion, one performs numerical analysis of possible transforming a normal combustion mode into convective one and then into low velocity detonation. Upon detonation the objects adjacent to the place of a failure are mainly affected by shock waves. These are analyzed taking into account the location of the object with respect to the place of the failure and the shock wave parameters obtained by mathematical simulation. The baric affection analysis allows for the detonation mode (high velocity or low velocity) and movement of the affected object.

7. Development of computation scenarios for failures and scientifically validated recommendations to prevent these failures

A computation scenario for a failure is based on the analysis of high accuracy mathematical simulation results of the failure and comparing them with the failure investigation materials. Each item of the scenario is validated by mathematical models and results of numerical analysis.

The relation between the mathematical models while developing the computation scenario is realized by the boundary conditions. For instance, dynamic loads influencing a pipeline due to internal pressure of transported media are determined as a result of gas dynamic analysis of flows in pipelines during pre-failure period and at failure. These are necessary for analyzing the causes and consequences of the pipeline rupture. The results of gas dynamic and strength analysis are used as the boundary conditions for debris affection and gas hazard assessment.

The recommendations regarding failure preventive measures are developed according to the computation scenario for a real or hypothetical failure at a specific pipeline transportation facility. To this end each recommendation is simulated by the above mathematical methods in terms of how it might be acting due to the need to analyze the effectiveness of the undertaken recommendation and to exclude harmful after-effects resulted from this recommendation realization. The detailed description of the computation scenario development for the realistic failure occurred at the compressor station "Arskaya" of "VOLGOTRANSGAZ" (Russia) and the recommendations to prevent similar failures can be found in [4].

8. Conclusion

The computation technology for investigating failures of gas pipeline systems enables specialists in gas, oil, petrochemical, and chemical industries to fulfill the following tasks:

- validated investigation of realistic failures,
- multi-objective risk analysis for operating pipelines including those being designed and constructed,
- reliable identification of feasible failure causes and development measures to prevent failures and/or localize their consequences.

The integral character of the obtained results should be especially emphasized. Such approaches have never been used before in the pipeline industry.

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