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- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.
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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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WIESŁAW PRÓCHNICKI and MAREK DZIDA*

Influence of gas parameters alteration on the form of gas-flow-impact appearing in long transportation pipelines

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Abstract

In the case of the gate-valve cut-off, in a very long transmission pipelines, considerable pressure overshoots are observed accompanying the gas flow impacts, caused as well by *shock* wave as by *reflected* one. The main factor, influencing the shock wave amplitude, is the velocity of gate-valve closing, determined by the servomotor-time-constant T_i. Because of possible variations of chemical constitution of gas transported through the pipeline – which renders physical, chemical and thermodynamic properties changes, it is necessary to examine theirs degree of influence on the processes of dynamic impact.

Keywords: Gas flow dynamics; Automatic control

1 Model of long line (continuum)

Pipeline schematic is shown in Fig. 1.

The model of distributed parameters is applied for the long-line dynamics description. Taking into account the equations of flow continuity, forces equilibrium and the equation of state, we have

$$\left.\begin{aligned} &\frac{\partial m}{\partial x}dx + \frac{\partial \rho}{\partial t}A \cdot dx = 0, \\ &dF_P = dF_T + dF_B, \\ &\frac{\partial p}{\partial \rho} \approx \kappa \frac{p}{\rho} = a^2, \end{aligned}\right\} \qquad (1)$$

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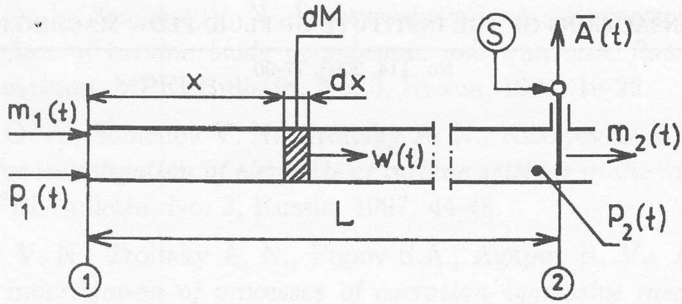

Figure 1. Uniform pipeline of A cross section. S – servomotor of gate-valve.

where: dF_B, dF_P, dF_T [N] – elementary forces of inertia, pressure and friction. All the parameters are the functions of time t and of length coordinate x.

The equations of forces are as follow:

$$\left.\begin{aligned} dF_B &= dM\frac{\partial w}{\partial t} = A\rho\frac{\partial w}{\partial t}dx \approx \frac{\partial m}{\partial t}dx, \\ dF_P &= -A\frac{\partial p}{\partial x}dx, \\ dF_T &= \lambda_f\frac{w^2}{2}\frac{A}{D}\,\rho\,dx = \lambda_f\frac{w}{2}\frac{m}{D}dx \approx \lambda_f\frac{w_0}{2}\frac{m}{D}dx, \end{aligned}\right\} \tag{2}$$

where: λ_f – friction coefficient, dependent on Reynolds number Re and roughness number r/k – see Fig. 2. Putting the expressions (2) in the system of equations (1), introducing the relative coordinate

$$\overline{x} = \frac{x}{L}, \tag{3}$$

and applying the linearization around the arbitrary selected mean point $x = x_0$, we have

$$\left.\begin{aligned} K_1\frac{\partial p}{\partial t} + \frac{\partial m}{\partial \overline{x}} = 0 \\ \frac{\partial p}{\partial \overline{x}} + \frac{L}{A}\cdot\frac{\partial m}{\partial t} + K_2\cdot m = 0 \end{aligned}\right\}, \tag{4}$$

where:

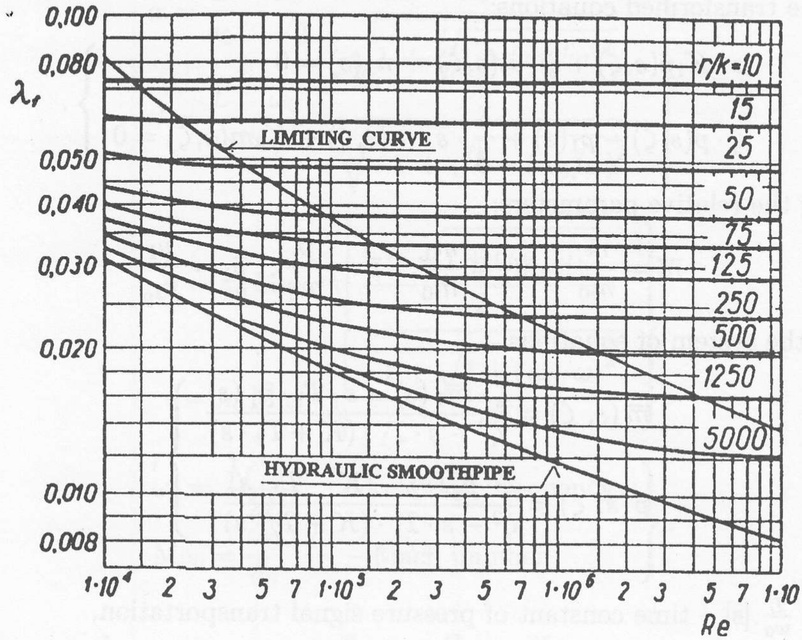

Figure 2. Number of friction λ_f (Re, r/k).

$$\left.\begin{aligned} K_1 &= L\cdot\frac{A}{\kappa_0}\cdot\frac{\rho_0}{p_0} \qquad \left[\mathrm{m}\cdot\mathrm{s}^2\right] \\ K_2 &= \frac{L}{2A}\cdot\frac{\lambda_f}{D}\cdot w_0 \qquad \left[\frac{1}{\mathrm{m}\cdot\mathrm{s}}\right] \\ \rho_0 &= \rho(x=x_0);\; p_0 = p(x=x_0) \\ \kappa_0 &= \kappa(x=x_0) \end{aligned}\right\}. \tag{5}$$

Denoting "s" as the complex variable of time t and "ζ" as the complex variable of linear coordinate $\overline{x}=\frac{x}{L}$, taking into consideration boundary conditions – (6a) and initial conditions – (6b)

$$\left.\begin{aligned} &\left.\begin{aligned} m(\overline{x}=0;\, t) &= m_1(t) \\ p(\overline{x}=0;\, t) &= p_1(t) \end{aligned}\right] \quad (a) \\ &\left.\begin{aligned} dm(\overline{x};\, t=0) &= 0 \\ dp(\overline{x};\, t=0) &= 0 \end{aligned}\right] \quad (b) \end{aligned}\right\} \tag{6}$$

we get the transformed equations:

$$\left.\begin{aligned} s\cdot K_1 p(s,\zeta)+\zeta\cdot m(s,\zeta)-m_1(s)=0\\ \zeta\cdot p(s,\zeta)-p_1(s)+\frac{L}{A}\cdot s\cdot m(s,\zeta)+K_2 m(s,\zeta)=0 \end{aligned}\right\}. \tag{7}$$

Applying the relative parameters:

$$\overline{m}=\frac{m}{m_0};\quad \overline{m}_1=\frac{m_1}{m_0};\quad \overline{p}=\frac{p}{m_0};\quad \overline{p}_1=\frac{p_1}{p_{1_0}} \tag{8}$$

we have the system of equations:

$$\left.\begin{aligned} \overline{m}\,(s,\,\zeta)=\frac{\zeta\cdot\overline{m}_1\,(s)-s\cdot T_1\cdot\overline{p}_1\,(s)}{\zeta^2-s\cdot T_1\cdot(K+T_2\cdot s)}\\ \overline{p}\,(s,\,\zeta)=\frac{\zeta\cdot\overline{p}_1\,(s)-(K-T_2\cdot s)}{\zeta^2-s\cdot T_1\cdot(K+T_2\cdot s)} \end{aligned}\right\}, \tag{9}$$

where:
$T_1=\frac{1}{\kappa_0}\cdot\frac{L}{w_0}$ [s] – time constant of pressure signal transportation,
$T_2=\frac{L\,m_0}{A\,p_0}$ [s] – time constant of mass accumulation,
$K=K_2\frac{m_0}{p_0}=\frac{Lm_0}{Ap_0}\,\frac{\lambda_f}{2D}w_0$ [-] – non-dimensional coefficient of hydraulic friction forces.

Regarding the complex variable "s", as a parameter, we get the inverse Laplace transformed function $\overline{m}$ and $\overline{p}$ in relation to linear coordinate $\overline{x}$:

$$\left.\begin{aligned} \overline{m}(s)=\overline{m}_1(s)Ch\left[\phi(s)\cdot\overline{x}\right]-\overline{p}_1(s)\frac{Sh\left[\phi(s)\cdot\overline{x}\right]}{\psi(s)}\\ \overline{p}(s)=\overline{p}_1(s)Ch\left[\phi(s)\cdot\overline{x}\right]-\overline{m}_1(s)\cdot\psi(s)\cdot Sh\left[\phi(s)\cdot\overline{x}\right] \end{aligned}\right\}. \tag{10}$$

For $\overline{x}=1$ $(x=L)$, satisfied are the equations:

$$\overline{m}(\overline{x}=1)=\overline{m}_2(s)\text{ and }\overline{m}(\overline{x}=1)=\overline{m}_2(s) \tag{10.1}$$

hence we have

$$\left.\begin{aligned} \overline{m}_2(s)=\overline{m}_1(s)Ch\left[\phi(s)\right]-\overline{p}_1(s)\frac{Sh\left[\phi(s)\right]}{\psi(s)}\\ \overline{p}_2(s)=\overline{p}_1(s)Ch\left[\phi(s)\right]-\overline{m}_1(s)\cdot\psi(s)\cdot Sh\left[\phi(s)\right] \end{aligned}\right\}, \tag{11}$$

where:

$$\left.\begin{aligned} \phi(s)=\sqrt{s\cdot T_1(K+s\cdot T_2)}=\alpha+\beta\cdot j\\ \psi(s)=\sqrt{\frac{K+s\cdot T_2}{s\cdot T_1}}=\gamma+\delta\cdot j \end{aligned}\right\} \tag{12}$$

$$\left.\begin{aligned} \alpha &= \frac{L}{a_0}\cdot\frac{\omega_0}{\sqrt{2}}\cdot\frac{1}{\sqrt{1+\sqrt{1+(\omega_0/\omega)^2}}} \\ \beta &= \frac{L}{a_0}\cdot\frac{\omega_0}{\sqrt{2}}\cdot\frac{1}{\sqrt{-1+\sqrt{1+(\omega_0/\omega)^2}}} \end{aligned}\right\} \tag{12.1}$$

$$\left.\begin{aligned} \gamma &= \kappa_0\,\mathrm{Ma}_0\cdot\sqrt{\frac{1+\sqrt{1+(\omega_0/\omega)^2}}{2}} \\ \delta &= \kappa_0\,\mathrm{Ma}_0\cdot\sqrt{\frac{-1+\sqrt{1+(\omega_0/\omega)^2}}{2}} \end{aligned}\right\} \tag{12.2}$$

$$\left.\begin{aligned} \omega_0 &= \frac{\lambda_f\cdot w_0}{2D} && \text{– reference frequency} \\ \mathrm{Ma}_0 &= \frac{w_0}{a_0} && \text{– Mach number} \end{aligned}\right\}. \tag{12.3}$$

2 Dynamic response of gas flow line

The main disturbance signal, is the velocity of the outflow-area closing. The design element (gate-valve) situated at the end of pipeline, closes the related flow area $\overline{A}(s)$, by the use of servomotor S of transfer function

$$G_s(s) = \frac{1}{1+s\cdot T_i}. \tag{13}$$

Assuming that the related area $\overline{A}(s)$ is approximately proportional to the G_s function, we have

$$\overline{A}(s) = \frac{1}{1+s\cdot T_i}. \tag{14}$$

Varying the time constant T_i, we can influence the value of amplitude of impact wave (over-pressure), as well as the negative pressure (vacuum) of reflected wave. For this purpose $\overline{p}_2(s)$ as the response on closing signal must be calculated. From Eq. (11), eliminating $\overline{m}_1(s)$ and making a simplifying assumption, that the related outflow $\overline{m}(s)$ is proportional to the related outflow area, i.e.

$$\overline{m}_2(s) \cong \overline{A}(s) = \frac{1}{1+s\cdot T_i}, \tag{15}$$

we have

$$\overline{p}_2(s) = \overline{p}_1(s)\frac{1}{Ch\left[\phi\left(s\right)\right]} - \frac{\psi(s)\cdot Th\left[\phi\left(s\right)\right]}{1+s\cdot T_i} \tag{16}$$

and taking into account expressions (12), we get the transfer function (spectral)

$$\overline{p}_2(\omega j) = \frac{\overline{p}_1(\omega j)}{Ch\,(\alpha+\beta j)} - \frac{(\gamma+\delta j)\,Th\,(\alpha+\beta j)}{1+\omega j\cdot T_i}, \tag{17}$$

where:

$$\left.\begin{aligned} Sh(\alpha+\beta j) &= A + Bj \\ Ch(\alpha+\beta j) &= C + Dj \\ A &= Sh\alpha\cdot\cos\beta \\ B &= Ch\alpha\cdot\sin\beta \\ C &= Ch\alpha\cdot\cos\beta \\ D &= Sh\alpha\cdot\sin\beta \\ Th(\alpha+\beta j) &= \frac{A+Bj}{C+Dj} \\ j &= \sqrt{-1} \end{aligned}\right\}. \tag{18}$$

The parameters α, β, γ, δ – are defined in Eqs. (12), (12.1) and (12.2).

For the complete (non related) parameters, the equation (17) will yield:

$$p_2(\omega j) = p_{10}\frac{\overline{p}\,(\omega j)}{Ch\,(\alpha+\beta j)} - m_0\frac{(\gamma+\delta j)\,Th\,(\alpha\beta j)}{1+\omega j\cdot T_i}. \tag{19}$$

3 Numerical example

The nominal (mean) values of the parameters: gas pressure $p_{10} = 13$ MPa, density under pressure p_{10}: $\rho_{13.0} = 180$ kg/m^3 ($\rho_{00} = 1.2787$ kg/m^3), velocity $w_0 = 1.2739$ m/s, flow rate $m_0 = 1.80$ kg/s, length of pipeline $L = 80$ km= 80000 m, diameter $D = 0.1$ m, index of adiabate $\kappa_0 = 1.24$, friction coefficient ($\lambda_f \cong 0.03$)[1], Reynolds number ($\mathrm{Re} \cong 1\cdot 10^5$)[2]. Time constant of gate-valve servomotor $T_i =$ var.

In the further part of the work, the influence of individual parameters variation will be considered on the dynamic properties of the gas flow impact.

[1]From the diagram Fig. 2 for $\mathrm{Re} = 5.7\cdot 10^5$ and $r/k \cong 125$, the $\lambda_f \cong 0.03$.

[2]For the natural gas under $p = 13$ MPa $\mathrm{Re} = \dfrac{w_0 D}{\nu_{13}} = \dfrac{w_0 D}{\frac{\mu_{13}}{\rho_{13}}} = \dfrac{1.274\cdot 0.1}{\frac{20}{180}\cdot 10^{-6}} \cong 5.7\cdot 10^5$

3.1 The influence of time-constant T_i variation

Time-constant T_i determined the velocity of outflow-area variation. The transient function of pressure $p_2(t)$, for different values of time-constant T_i, has been shown in Figs. 3 and 4. Remaining parameters are corresponding to steady nominal values – see point 3.

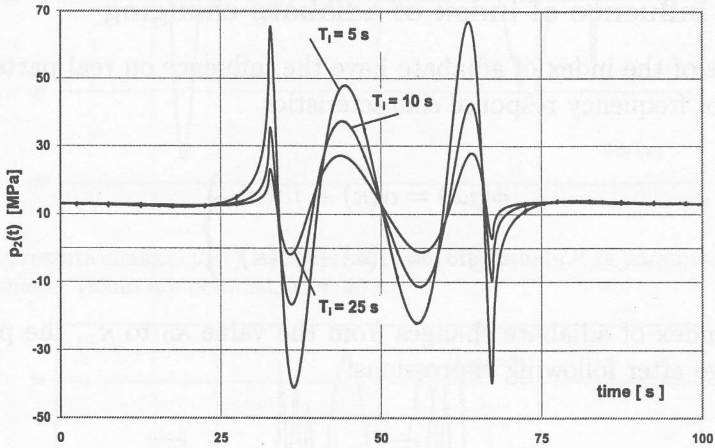

Figure 3. Gas pressure changes $p_2(t)$, at different time constant T_i as parameter. Remaining parameter values are nominal.

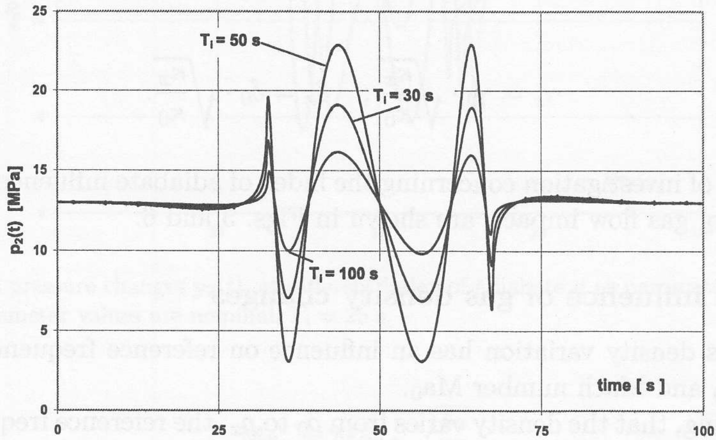

Figure 4. Gas pressure changes $p_2(t)$, at different time constant T_i as parameter. Remaining parameter values are nominal.

From the transients shown in Figs. 3 and 4, we can draw following conclusions:

- parameter T_i has considerable influence on overshoot amplitude of gas impact process;

- time of appearing and disappearing of the hydraulic impact is independent of the value of time constant T_i;
- for the range of time-constant $T_i >\sim 25$ s, the pulsations remain in the zone above atmospheric pressure (vacuum not present).

3.2 The influence of index of adiabate changing

Changes of the index of adiabate have the influence on real parts and imaginary parts of frequency response characteristics

$$\left.\begin{aligned}\phi(j\omega) &= \alpha(\kappa) + j\beta(\kappa)\\ \psi(j\omega) &= \gamma(\kappa) + j\delta(\kappa)\end{aligned}\right\}. \tag{20}$$

When the index of adiabate changes from the value κ_0 to κ_x, the parts α, β, γ and δ change after following expressions:

$$\alpha_x = \alpha_0 \cdot \sqrt{\frac{\kappa_0}{\kappa_x}}; \quad \beta_x = \beta_0 \cdot \sqrt{\frac{\kappa_0}{\kappa_x}}, \tag{21}$$

and

$$\gamma_x = \gamma_0 \cdot \sqrt{\frac{\kappa_x}{\kappa_0}}; \quad \delta_x = \delta_0 \cdot \sqrt{\frac{\kappa_x}{\kappa_0}}. \tag{22}$$

The results of investigation concerning the index of adiabate influence on dynamic properties of gas flow impact, are shown in Figs. 5 and 6.

3.3 The influence of gas density changes

The gas density variation has an influence on reference frequency ω_0, speed of sound a_0 and Mach number Ma_0.

Assuming, that the density varies from ρ_0 to ρ_x, the reference frequency, speed of sound and the Mach number vary according to the following expressions:

$$\omega_x = \omega_0 \cdot \frac{\rho_0}{\rho_x}, \tag{23}$$

$$a_x = a_0 \cdot \sqrt{\frac{\rho_0}{\rho_x}}, \tag{24}$$

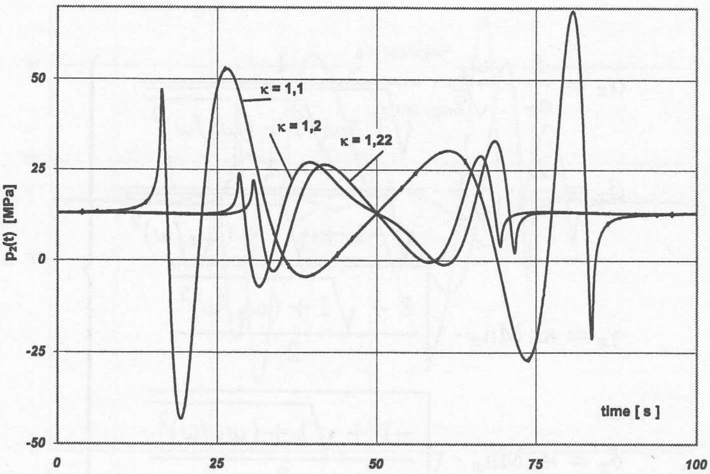

Figure 5. Gas pressure changes $p_2(t)$, at different index of adiabate κ as parameter. Remaining parameter values are nominal, $T_i = 25$ s.

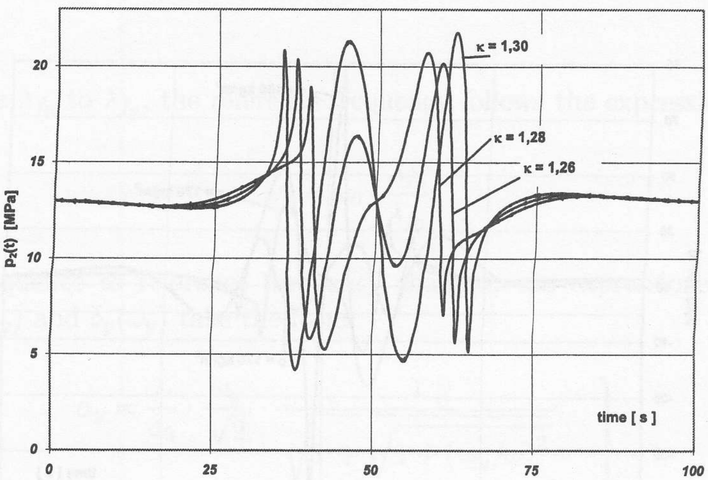

Figure 6. Gas pressure changes $p_2(t)$, at different index of adiabate κ as parameter. Remaining parameter values are nominal, $T_i = 25$ s.

$$\mathrm{Ma}_x = \mathrm{Ma}_0 \cdot \sqrt{\frac{\rho_0}{\rho_x}}. \qquad (25)$$

In consequence, the changes (23), (24) and (25) have influence on real and imaginary part of frequency characteristics $\phi(j\omega)$ and $\psi(j\omega)$, according to following equations:

$$\left.\begin{aligned}
\alpha_x &= \frac{L}{a_x}\cdot\frac{\omega_x}{\sqrt{2}}\cdot\frac{1}{\sqrt{1+\sqrt{1+(\omega_x/\omega)^2}}}\\
\beta_x &= \frac{L}{a_x}\cdot\frac{\omega_x}{\sqrt{2}}\cdot\frac{1}{\sqrt{-1+\sqrt{1+(\omega_x/\omega)^2}}}\\
\gamma_x &= \kappa_0\,\mathrm{Ma}_x\cdot\sqrt{\frac{1+\sqrt{1+(\omega_x/\omega)^2}}{2}}\\
\delta_x &= \kappa_0\,\mathrm{Ma}_x\cdot\sqrt{\frac{-1+\sqrt{1+(\omega_x/\omega)^2}}{2}}
\end{aligned}\right\}. \tag{26}$$

The influence of density changes on gas flow dynamics has been shown in Figs. 7 and 8.

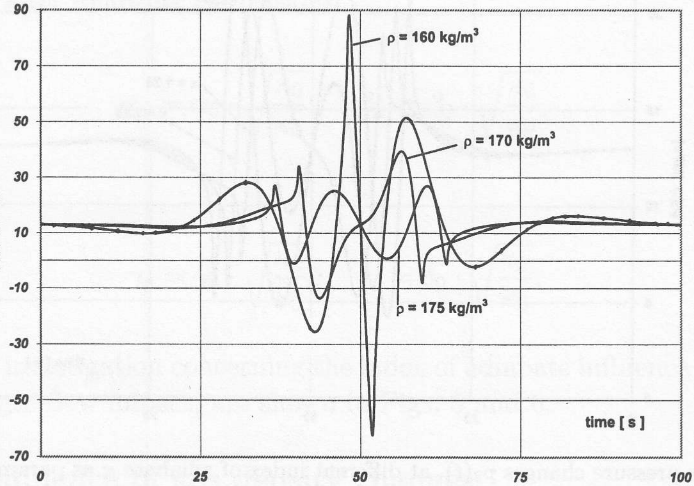

Figure 7. Gas pressure changes $p_2(t)$, at different density ρ_{13} as parameter. Remaining parameter values are nominal, $T_i = 25$ s.

3.4 The influence of number of roughness r/k changes

The pipeline – roughness changes result in variation of friction coefficient λ_f value. In consequence the reference frequency ω_0 varies too. If the λ_f changes

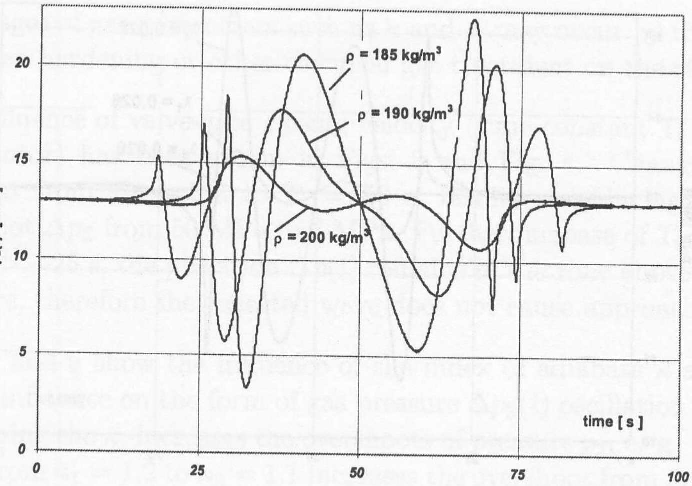

Figure 8. Gas pressure changes $p_2(t)$, at different density ρ_{13} as parameter. Remaining parameter values are nominal, $T_i = 25$ s.

from a value λ_{f0} to λ_{fy}, the reference frequency follows the expression:

$$\omega_y = \omega_0 \cdot \frac{\lambda_{fy}}{\lambda_{f0}}. \tag{27}$$

In consequence to reference frequency changes, the expressions of $\alpha_y(\omega_y)$, β_y, $\gamma_y(\omega_y)$ and $\delta_y(\omega_y)$ take the form:

$$\left.\begin{aligned}
\alpha_y &= \frac{L}{a_0} \cdot \frac{\omega_y}{\sqrt{2}} \cdot \frac{1}{\sqrt{1 + \sqrt{1 + (\omega_y/\omega)^2}}} \\
\beta_y &= \frac{L}{a_0} \cdot \frac{\omega_y}{\sqrt{2}} \cdot \frac{1}{\sqrt{-1 + \sqrt{1 + (\omega_y/\omega)^2}}} \\
\gamma_y &= \kappa_0 \mathrm{Ma}_0 \cdot \sqrt{\frac{1 + \sqrt{1 + (\omega_y/\omega)^2}}{2}} \\
\delta_y &= \kappa_0 \mathrm{Ma}_0 \cdot \sqrt{\frac{-1 + \sqrt{1 + (\omega_y/\omega)^2}}{2}}
\end{aligned}\right\} . \tag{28}$$

The calculated results of the friction coefficient changes' influencing the gas flow dynamics have been shown in Figs. 9 and 10.

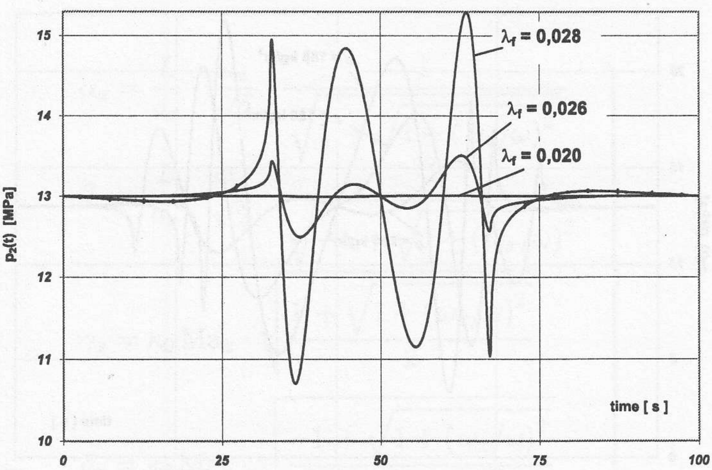

Figure 9. Gas pressure changes $p_2(t)$, at different coefficient of friction λ_t (as a result of roughness r/k changing). Remaining parameter values are nominal, $T_i = 25$ s.

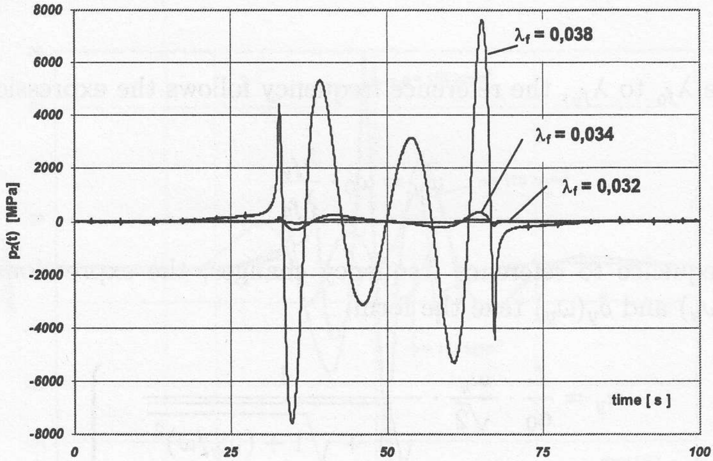

Figure 10. Gas pressure changes $p_2(t)$, at different coefficient of friction λ_t (as a result of roughness r/k changing). Remaining parameter values are nominal, $T_i = 25$ s.

4 Final remarks

In general, the influence of gas flow parameters changes on the dynamical behavior of the disturbed flow, is very significant, especially in the case of valve-gate closing.

The main gas flow parameters are: index of adiabate κ, density ρ, roughness of pipeline r/k and velocity of valve-gate out-off.

The changes of gas parameters such as κ and ρ, may occur by the gas enrichment, nitrogen hardening or other chemical gas treatment on the stations.

1. The influence of valve-gate closing velocity (time constant T_i of valve-gate servomotor) has been shown in Figs. 3 and Fig. 4. Changing the time constant from $T_i = 5$ s to $T_i = 50$ s, results in reducing the pressure overshoot Δp_2 from 50 MPa to 6 MPa. Further increase of T_i is ineffective. For $T_i > \sim 25$ s, the pulsation $\Delta p(t)$ remains in the zone above atmospheric pressure, therefore the reflected wave does not cause approach of vacuum.

2. Figs. 5 and 6 show the influence of the index of adiabate κ alteration. A strong influence on the form of gas pressure $\Delta p_2(t)$ oscillation may appear. Decreasing the κ, increases the overshoots of pressure p_2, e. g. changing the index from $\kappa_1 = 1.2$ to $\kappa_2 = 1.1$ increases the overshoot from $\Delta p_1 = 20$ MPa to $\Delta p_2 = 57$ MPa.

3. The influence of density changing has been shown in Figs. 7 and 8. Increasing this parameter, the amplitude of gas overshoot is decreases. Changing the density from $\rho_1 = 160$ kg/m^3 to $\rho_2 = 190$ kg/m^3, we get the overshoots: $\Delta p_{2,1} = 77$ MPa to $\Delta p_{2,2} = 10$ MPa.

4. Among the all considered gas flow parameters' influence, the greatest significance has the coefficient of friction λ_f, changed as a result of pipeline roughness r/k changes. This parameter has the greatest influence on the overshoot amplitude value. Changing λ_f from $\lambda_{f_1} = 0.028$ to $\lambda_{f_2} = 0.038$ we have the overshoot change adequately $\Delta p_{2,1} = 2$ MPa to $\Delta p_{2,2} = 7500$ MPa! Variation of λ_f changes also significantly the forms of overshoot oscillation. For the low values of λ_f about 0.02 there are observed two predominant amplitudes overshoots, for $\lambda_f \approx 0.03$ three predominant overshoot, and to $\lambda_f = 0.038$ four predominant overshoots – see Figs. 9 and 10.

Recapitulating the final remarks, it may be said, that in the consideration of the gas transportation in a long pipelines, the possibility of gas parameters changes must be taken into account, which may significantly influence on dynamic flow processes, especially by stopping the flow.

Received 10 May 2003

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