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ANALYSIS OF RESONANCE PHENOMENON OF HYDROGEN-NATURAL GAS MIXTURES FLOWS IN PIPELINES

ANALIZA FENOMENA REZONANCE PROTOKA MEŠAVINA VODONIK-PRIRODNI GAS U CEVOVODIMA

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- hydrogen-natural gas mixtures
- resonance phenomenon
- method of characteristics
- natural gas pipelines

Abstract

This paper presents a method of studying resonance phenomenon of hydrogen-natural gas mixtures flows in pipelines. To simulate the resonance phenomenon, an oscillatory pressure at the upstream end of the pipe is considered while the downstream end is kept closed. The oscillation frequency is taken as a multiple of the fundamental frequency of the system. The Governing equations for such problem are two coupled, non-linear, hyperbolic, partial differential equations. The fluid pressure and velocity are considered as two principal dependent variables. The fluid is a homogeneous hydrogen-natural gas mixture for which the density is defined by an expression averaging the two gas densities where an isentropic process is admitted for the two components. The hydrogen-mixture mass ratio (or quality), assumed to be constant is used in the mathematical formulation, instead of the void fraction which varies with pressure. The problem has been solved by the non-linear method of characteristics. The obtained results show that the pressure evolution is well influenced by the excitation frequencies and it builds up to a steady-oscillatory behaviour (unless failure occurs). Shock waves with resonant frequency and antiresonant frequencies are numerically obtained and the influence of different hydrogen mass fractions in the hydrogen-natural mixtures and diameters of the pipe are also analysed. Furthermore, dissolution and permeation evolutions as functions of time, of hydrogen and mixtures, are plotted. These plots have shown too, the influence of the excitation frequencies on the dissolution and permeation rate.

Ključne reči
- mešavine vodonik-prirodni gas
- fenomen rezonance
- metoda karakteristika
- cevovodi prirodnog gasa

Izvod

U ovom radu je predstavljena metoda proučavanja fenomena rezonance protoka mešavina vodonik-prirodni gas u cevovodima. Radi simulacije fenomena rezonance, razmatra se oscilatorna promena pritiska na uzvodnom kraju cevovoda dok je nizvodni kraj zatvoren. Frekvencija oscilacija je uzeta kao deo osnovne frekvencije sistema. Jednačine koje definišu ovaj problem su dve spregnute, nelinearne, hiperboličke, parcijalne diferencijalne jednačine. Pritisak i brzina fluida se smatraju za dve glavne zavisno promenljive sistema. Fluid je homogena mešavina vodonika-prirodnog gasa sa gustinom definisanom izrazom za usrednjavanje dve gustine gasova, gde se dopušta izentropski proces za ove dve komponente. Maseni udeo vodonik-mešavina (ili kvalitet), koji se smatra konstantnim, uzima se u matematičkoj formulaciji, umesto udela šupljina koji se menja sa pritiskom. Problem je rešen primenom nelinearne metode karakteristika. Dobijeni rezultati pokazuju da na razvoj pritiska u velikoj meri utiču pobudne frekvencije, a koji poprima ravnotežno-oscilatorno ponašanje (ukoliko se ne pojavi lom). Udarni talasi sa rezonantnim i antirezonantnim frekvencijama se dobijaju numerički, a uticaji različitih masenih udela vodonika u mešavinama vodonik-prirodni gas sa prečnicima cevovoda su takođe analizirani. Dati su i dijagrami promene rastvaranja i zasićenja u funkciji vremena za vodonik i mešavine. Ovi dijagrami takođe pokazuju uticaj pobudnih frekvencija na brzinu rastvaranja i zasićenja.

INTRODUCTION

Hydrogen is considered a promising future fuel for vehicles. The absence of hydrogen infrastructure is seen as a major obstacle to the introduction of hydrogen fuel cell vehicles. Actually, during the transition period towards a full development of hydrogen market, the use of the existing natural gas network to transport hydrogen or hydrogen-natural gas mixtures from the production site to the storage areas or from the storage areas to the dispensers seems to be a good economic solution.

The durability and the mechanical resistance of the existing pipelines have been investigated for natural gas only, taking into account the pressure evolution during the permanent regime, the transient regime and resonance conditions coming from periodic excitations. Sources of periodic excitations such as pumps and compressors can induce heavy resonances in a lightly damped system /1/. The need to analyse vibrations of compressible fluids in piping systems arises in a variety of practical situations.

The resonance phenomenon is well studied for compressible fluids and mainly for natural gas. In many researches, resonance phenomenon in pipelines is simulated by considering a gas-filled tube driven by an oscillating plane piston at one end in the neighbourhood of the fundamental resonant frequency of the gas column. Periodic shock waves can be found travelling back and forth along the tube with a frequency equalled to that of the oscillating piston and velocity close to that of sound /2, 3/. Alexeev and Gutfinger /3/ investigated the two-dimensional turbulent gas oscillations and acoustic streaming in resonant tubes with a finite-difference algorithm supplemented by a two-equation Wilcox turbulent model, and found that the direction of gas streaming at resonance is opposite to that in non-resonant oscillations. Tang and Cheng /4/ solved the two-dimensional gas resonant oscillation in a cylindrical tube by a new finite volume method with second-order kinetic flux-vector splitting scheme for convective terms, and a third-order Runge-Kutta method for the time evolution. They claimed that their numerical results are similar to those from previous studies.

More recently, research has been performed to study gas resonant oscillations in a two-dimensional closed tube using the lattice Boltzmann method /5/.

As the thermodynamic properties of hydrogen differ significantly from those of natural gas, the pressure evolution of hydrogen or hydrogen-natural gas mixtures during the resonant frequencies will not be the same. Unfortunately, the resonant phenomenon in hydrogen-natural gas mixtures has not been studied.

This paper presents a method of studying resonance phenomenon of hydrogen-natural gas mixtures flows in pipelines. To simulate this problem, an oscillatory pressure is considered at the upstream end of the pipe while the downstream end is kept closed. The oscillation frequency is considered as a multiple of the fundamental or natural frequency of the system. The governing equations for such problem are two coupled, non linear, hyperbolic, partial differential equations. The numerical simulation was performed by the use of the characteristics irregular grid method. In this paper we study the influence of different hydrogen mass fractions in the hydrogen-natural mixtures and different diameters of the pipe on the pressure evolution. Furthermore, dissolution and permeation evolutions as functions of time, of hydrogen and mixtures, are examined.

ASSUMPTION

The mathematical model considers the following assumptions: the flow is compressible and includes rapid transients; variations in potential energy may be ignored; the viscous effects are modelled by considering the pipeline-wall shear stress. The calculation of the pressure loss is done by analogy with the permanent flows.

The transient flow is supposed one-dimensional and concerns a homogeneous fluid mixture of hydrogen and natural gas. The hydrogen-fluid mass ratio (or the quality) is noted $\theta = [M_h/(M_g + M_h)]$ where M_h and M_g represent the masses of hydrogen and natural gas respectively. The density of hydrogen and natural gas evolve according to the following isentropic laws:

$$\rho_h = \rho_{h_0}\left(\frac{p}{p_0}\right)^{1/n} \tag{1}$$

$$\rho_g = \rho_{g_0}\left(\frac{p}{p_0}\right)^{1/n'} \tag{2}$$

where ρ_{h0} is the density of hydrogen at the initial conditions, ρ_{g0} is the density of natural gas at the initial conditions, p_0 is the permanent regime pressure and p is the pressure of the transient regime.

The pipe is supposed to be rigid, that means that the section A of the pipe is constant:

$$A = \frac{\pi D^2}{4} = cte\ , \tag{3}$$

where D is the diameter of the pipe.

MATHEMATICAL FORMULATION

Equation of motion

By application of the mass conservation and momentum laws to an element of fluid between two sections of the pipe of abscissa x and $x + dx$, we get the following equations of continuity and motion /6/:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho V}{\partial x} = 0\ , \tag{4}$$

$$\frac{\partial \rho V}{\partial t} + \frac{\partial(\rho V^2 + p)}{\partial x} + \frac{\lambda \rho V|V|}{2D} = 0\ , \tag{5}$$

where λ is the coefficient of friction and V the velocity of the mixture.

Equations (4) and (5) form a system of two non-linear partial differential equations of hyperbolic type in which the pressure p and the velocity V are considered the main variables of the flow. To solve numerically these equations, we must express the density of the mixture ρ according to the fluid pressure.

Expression of the mixture density

The expression of the average density of the mixture is defined according to the hydrogen mass ratio θ /7/:

$$\rho=\left[\frac{\theta}{\rho_h}+\frac{1-\theta}{\rho_g}\right]^{-1}=\left[\frac{\theta}{\rho_{h_0}}\left(\frac{p_0}{p}\right)^{1/n}+\frac{(1-\theta)}{\rho_{g_0}}\left(\frac{p_0}{p}\right)^{1/n'}\right]^{-1} \quad (6)$$

Expression of the celerity of pressure waves

For a compressible fluid, the celerity of the pressure waves can be defined by the expression:

$$C=\left(\frac{\partial\rho}{\partial p}\right)^{-1/2} \quad (7)$$

Taking into account relation (6), we obtain:

$$C=\left[\frac{\theta}{\rho_{h_0}}\left(\frac{p_0}{p}\right)^{1/n}+\frac{(1-\theta)}{\rho_{g_0}}\left(\frac{p_0}{p}\right)^{1/n'}\right]\times$$
$$\times\left[\frac{1}{p}\left[\frac{1}{n'}\frac{\theta}{\rho_{h_0}}\left(\frac{p_0}{p}\right)^{1/n}+\frac{1}{n'}\frac{(1-\theta)}{\rho_{g_0}}\left(\frac{p_0}{p}\right)^{1/n'}\right]\right]^{-1/2} \quad (8)$$

Expression of the hydrogen permeation and dissolution

By the application of Sivert's laws, the permeation and dissolution of hydrogen are given by the following equations respectively /8/:

$$S=S_0 p^{1/2}\exp\left(\frac{-\Delta H_S}{RT}\right) \quad (9)$$

$$P=KS_0\Delta p^{1/2}\exp\left(-\frac{\Delta H_S+\Delta H_m}{RT}\right) \quad (10)$$

where $\Delta H_S = Q$ is the dissolution enthalpy (J), R is the universal gas constant (J°K^{-1}mol^{-1}), p is the pressure (atm or in bar), T is the temperature (°K) and ΔH_m is the free migration enthalpy.

NUMERICAL SOLUTION BY METHOD OF CHARACTERISTICS

The method of characteristics /9/ is often used to transform the governing partial differential equations into a system of ordinary differential equations that are valid along two sets of characteristic lines, Fig. 1. The ordinary differential equations, of (4) and (5), obtained by this method are:

$$C^+\begin{cases} dV+\dfrac{1}{\rho C}dp=-Jdt \\ dx=(V+C)dt \end{cases} \quad (11)$$

$$C^-\begin{cases} dV-\dfrac{1}{\rho C}dp=-Jdt \\ dx=(V-C)dt \end{cases} \quad (12)$$

where $J = \lambda V|V|/2D$ represents the pressure loss by unit of pipe length.

The + is for the waves coming from the upstream end while the – is for waves coming from the downstream end.

These equations can also be written under the following form:

$$dV\pm\frac{1}{\rho C}dp-Jdt=0 \text{ and } dx=(V\pm C)dt \quad (13)$$

Equations (13) determine the evolution of pressure and velocity according to time and space. They are much appropriated to be solved numerically on a microcomputer. The obtained solution constitutes a solution to the original system of (4) and (5). The transient flow is generated by a discontinuity of the initial steady state flow due to a rapid valve closure. This discontinuity propagates itself and the displacement is presented in the plane (x, t) by characteristic lines.

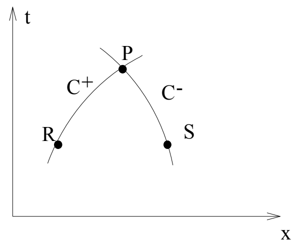

Figure 1. Characteristics lines.
Slika 1. Karakteristične krive.

Unknown values of (V, p, x, t), at any point P, as shown in Fig. 1, can be determined by knowing their values at points R and S lying on the two characteristics passing through P and by integrating the two simultaneous Eqs. (11) and (12). These equations can be written for the two signs, which results in four finite difference equations:

$$(V_P-V_R)+\int_R^P\frac{dp}{\rho C}+\int_R^P Jdt=0 \quad (14)$$

$$(x_P-x_R)=\int_R^P(V+C)dt \quad (15)$$

$$(V_P-V_S)+\int_S^P\frac{dp}{\rho C}+\int_S^P Jdt=0 \quad (16)$$

$$(x_P-x_S)=\int_S^P(V-C)dt \quad (17)$$

As the characteristics are curved on the (x, t) plane due to the non-linearity of (4) and (5), the integration is achieved by means of an iterative trapezoidal rule. Consequently, we obtain the unknown values t_P, x_P, V_P and p_P at point P:

$$t_P^k=\frac{x_S-x_R+F_R t_R-G_S t_S}{F_R-G_S} \quad (18)$$

$$x_P^k=x_R+F_R(t_P^k-t_R) \quad (19)$$

$$p_P^k=\frac{\left[M_R p_R+M_S p_S+V_R-V_S+H_R(t_P^k-t_R)-H_S(t_P^k-t_S)\right]}{M_R+M_S} \quad (20)$$

$$V_P^k=V_R+M_R(p_R-p_P^k)+H_R(t_P^k-t_R) \quad (21)$$

where: $F_R = (V + C)_R$, $G_S = (V - C)_S$, $M_{R,S} = (1/\rho C)_{R,S}$, $H_{R,S} = -J_{R,S}$ for $k = 1$ and

$$F_R=1/2\left[(V+C)_P^{k-1}+(V+C)_R\right],$$

$$G_S=1/2\left[(V-C)_P^{k-1}+(V-C)_S\right],$$

$$M_{R,S} = 1/2\left[(1/\rho C)_P^{k-1} + (1/\rho C)_{R,S}\right],$$

$$H_{R,S} = 1/2\left[(-J)_P^{k-1} + (-J)_{R,S}\right] \quad \text{for } k = 2..j.$$

In this study, the iteration number is limited to $j = 20$. The determination of the solution in the two extreme sections imposes the introduction of appropriate boundary conditions.

APPLICATION AND RESULTS

To illustrate the resonance phenomenon of high-pressure hydrogen-natural gas mixtures in pipelines, an oscillatory pressure $p = p_0 + \Delta p \sin(\omega t)$ is considered at the upstream end of the pipe ($x = 0$), and reflected by the other closed end ($x = L$), Fig. 2. As initial condition, we assume a static temperature $T = 15°C$ and an absolute pressure $p_0 = 70$ bar.

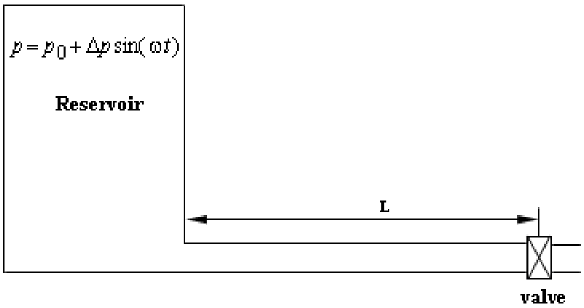

Figure 2. Installation of the resonant pipe.
Slika 2. Instalacija rezonantnog cevovoda.

In this study the pressure gradient $\Delta p = 5$ bar. The total length of the pipe is 500 m and its diameter is 0.4 m. The properties of hydrogen and natural gas in working conditions ($p = 70$ bar, $T = 15°C$) used in calculations are presented in Tables 1 and 2, respectively.

Table 1. Hydrogen properties.
Tabela 1. Osobine vodonika

Symbol	Designation	Value	Unit
C_p	Specific heat at constant pressure	14600	J/(kg°K)
C_v	Specific heat at constant volume	10440	J/(kg°K)
R	gas constant	4160	J/(kg°K)

Table 2. Natural gas properties.
Tabela 2. Osobine prirodnog gasa

Symbol	Designation	Value	Unit
C_p	Specific heat at constant pressure	1497.5	J/(kg°K)
C_v	Specific heat at constant volume	1056.8	J/(kg°K)
R	gas constant	440.7	J/(kg°K)

The oscillation period is given by the following equation:

$$T = \frac{4L}{C} \tag{22}$$

By use of (22), the fundamental resonant frequency of the pipe is:

$$\Omega = \frac{2\pi}{T} = \frac{\pi C}{2L} \tag{23}$$

Figure 3 shows plots of numerically obtained results for pressure evolution, as a function of time, at the downstream end of the pipe and for different values of hydrogen mass ratio θ. These plots are considered for two harmonic frequencies which are multiples of the natural or fundamental frequency Ω: an odd frequency $\omega = \Omega$ and an even frequency $\omega = 2\Omega$.

Numerical results clearly show that resonance phenomenon is obtained for odd harmonics. As a consequence, the pressure evolution obtained by frequency $\omega = \Omega$ is much important than that obtained by even harmonic $\omega = 2\Omega$. This latter is close to the antiresonant frequency, and the pressure is almost neutralised as can be noted in Fig. 3.

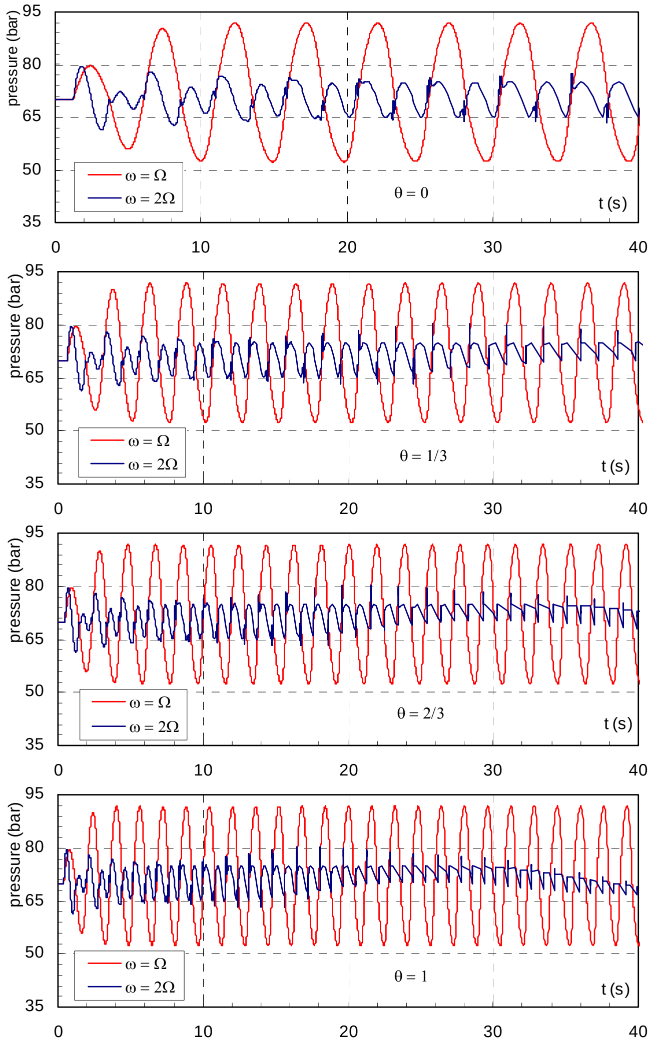

Figure 3. Pressure evolution for frequencies $\omega = \Omega$ and $\omega = 2\Omega$ at closed valve side, for different values of θ.
Slika 3. Razvoj pritiska za frekvencije $\omega = \Omega$ i $\omega = 2\Omega$ na strani zatvorenog ventila, za različite vrednosti θ.

Figure 3 shows too, the influence of different hydrogen mass fraction on pressure oscillations. In fact, the number of oscillations for hydrogen and hydrogen-natural gas mixtures is higher compared to that for natural gas. This result is due to the celerity of waves which is higher in the case of hydrogen and hydrogen-natural mixtures than that in the case of natural gas. In this case, hydrogen waves will propagate more rapidly than those of natural gas. As a result, for the same time interval, the number of pressure oscillations in the case of hydrogen is three times bigger than that in the case of natural gas as mentioned in Fig. 3.

Figures 4 and 5 show a comparison of the numerically obtained plots for pressure distribution considered for odd and even frequencies, respectively. These plots are at the downstream end of the pipe and for hydrogen mass fraction $\theta = 1$. Numerical results show again that the resonance phenomenon is obtained for odd harmonics as shown in Fig. 4.

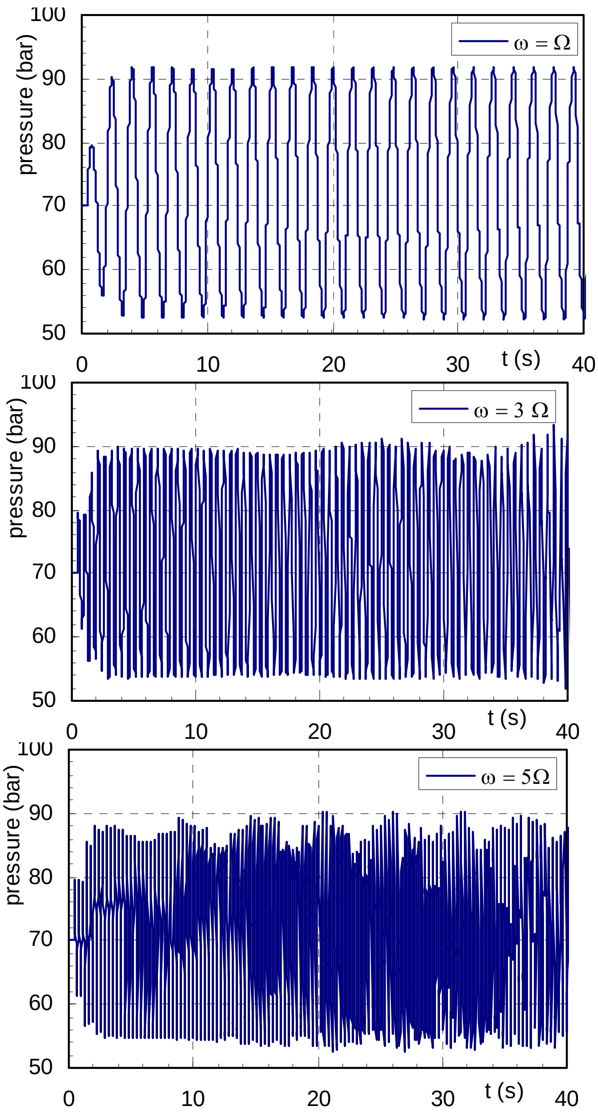

Figure 4. Pressure evolution for odd frequencies at downstream end of pipe, for $\theta = 1$.
Slika 4. Razvoj pritiska za neparne frekvencije u nizvodnoj strani cevi, za $\theta = 1$

This figure shows that resonance obtained by first harmonic frequency $\omega = \Omega$ represent certain stability and the amplitude of pressure oscillations are the same. However, for frequencies $\omega = 3\Omega$ and $\omega = 5\Omega$ the minimum the maximum pick values of pressure oscillations represent a certain irregularity. It can be noted that for frequency $\omega = 3\Omega$ the maximum pressure picks vary between the values of 88 bar and 90 bar and the time interval which separates these two values is about 16 s. For the frequency $\omega = 5\Omega$, the maximum pressure picks vary between values of 86 and 90 bar and the time interval which separates these two values is about 6 s. Figure 5 shows the antiresonance phenomenon obtained by even frequencies. It can be noted that for the different even frequencies, the amplitude of pressure oscillations is largely reduced if compared to those provoked by odd or resonant frequencies. Nevertheless, for certain even frequencies, the maximum of the pressure picks is significant. It can be seen that for $\omega = 2\Omega$ the maximum pick of pressure oscillations is 80 bar, it reaches 86 bar for $\omega = 4\Omega$ and 88 bar for $\omega = 6\Omega$. These disturbances mainly seen for the antiresonant frequencies and cause excessive pressure growth are due to nonlinearity of the problem. This nonlinearity is due to the celerity of waves which depends on pressure. As a consequence, the determination of the exact value of natural frequency, given by Eq. (23), is difficult to obtain. In general for compressible fluids, the determination of exact values of resonant and antiresonant frequencies needs a meticulous research. One technique /5/, among many others, uses a frequency range in the neighbourhood of the theoretical resonant or antiresonant frequency and calculates by numerical approaches the

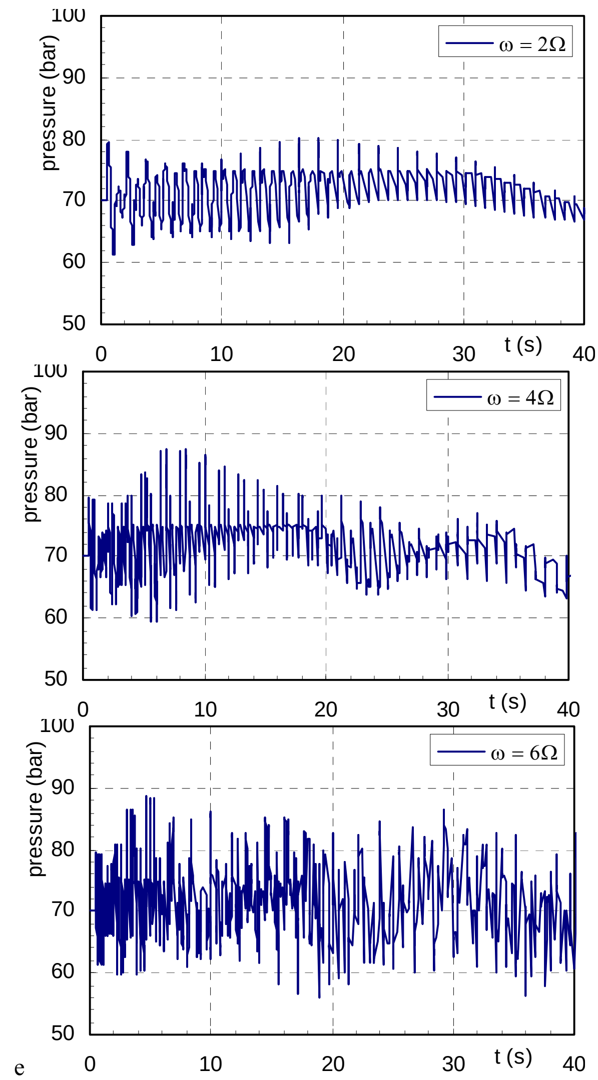

Figure 5. Pressure evolution for even frequencies at downstream end of pipe, for $\theta = 1$.
Slika 5. Razvoj pritiska za parne frekvencije u nizvodnoj strani cevi, za $\theta = 1$

best result. In fact, Fig. 6 shows the pressure oscillations by considering a frequency range in the neighbourhood of the antiresonant frequency ω = 2Ω and for hydrogen mass fraction θ = 0 and θ =1.

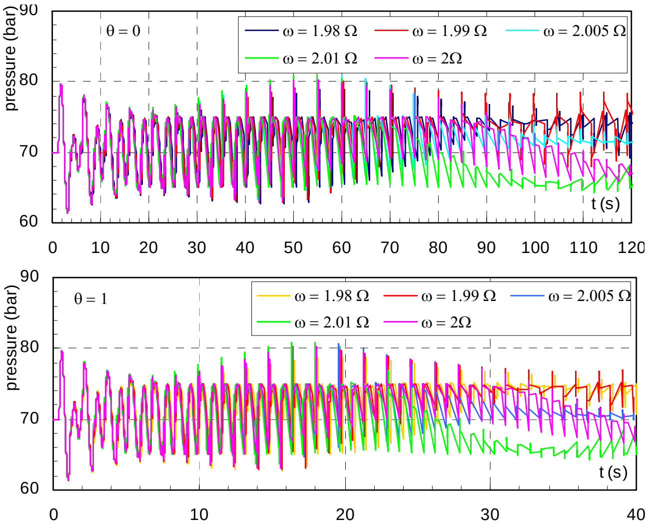

Figure 6. Pressure evolution in the neighbourhood of ω = 2Ω at the downstream end of pipe, for hydrogen mass fraction θ = 0 and 1.
Slika 6. Razvoj pritiska u okolini ω = 2Ω na nizvodnoj strani cevi, za maseni udeo vodonika θ = 0 i 1.

It may be seen from Fig. 6, for θ = 0 and for the time interval $0 \leq t \leq 75$, that amplitudes of pressure oscillations have a certain similarity for all frequencies considered in the neighbourhood of ω = 2Ω. However, for the time interval 75 < t ≤ 120 the behaviour of pressure oscillations, for these frequencies, has been changed. It can be noted that for frequencies ω = 1.98Ω and ω = 1.99Ω the pressure oscillations are above the initial pressure p_0. For frequencies ω = 2Ω and ω = 2.01Ω the pressure oscillations are under initial pressure p_0. For frequency ω = 2.005Ω the amplitude of the pressure oscillations has been practically neutralized and stabilizes close to initial pressure p_0. It can be deduced then, that the frequency that gives an ideal antiresonant phenomenon belongs to the interval]2Ω, 2.005Ω[instead of ω = 2Ω. It can be noted, from Fig. 6, that, for θ = 1, the behaviour of pressure oscillations is almost the same than those in the case of θ = 0. However, the two time intervals in the case of θ = 1 became $0 \leq t \leq 25$ and $25 \leq t \leq 40$. In the first time interval and for all the considered frequencies, the pressure oscillations are almost the same. Nevertheless, in the time interval $25 \leq t \leq 40$ the same behaviour of pressure oscillations is observed as in the case of θ = 0.

It is important to comment the similar behaviour of pressure oscillations in the case of natural gas and in the case of hydrogen. But, this similarity is obtained for two different time intervals: $0 \leq t \leq 120$ in case of natural gas (θ = 0) and $0 \leq t \leq 40$ in case of hydrogen (θ = 1). It can be noted that the time interval in case of hydrogen is three times bigger than that in case of natural gas. Moreover, the celerity of waves in case of hydrogen (C = 1252 m/s) is almost three times faster than that in case of natural gas (C = 410 m/s). From Eq. (22), it can be deduced that the oscillation period in case of hydrogen is three times smaller than that in case of natural gas. Then, one can state that the similarity in case of hydrogen and natural gas requires the same number of oscillations. Since the oscillation period in case of hydrogen is three times smaller than that of natural gas, and in order to have the same number of oscillations, the time interval in case of natural gas should be three times bigger than that of hydrogen as shown in Fig. 6.

Figure 7 shows plots of numerically obtained results for pressure distribution as a function of time, at the downstream end of pipe, for different diameters of the pipe and for hydrogen mass fraction θ = 1. Figure 7 clearly shows the influence of pipe diameter on the amplitude of the pressure oscillations. It can be noted that, the maximum pressure is 92 bar for the diameter 0.4 m while it reaches 107 bar for the pipe having 1 m in diameter.

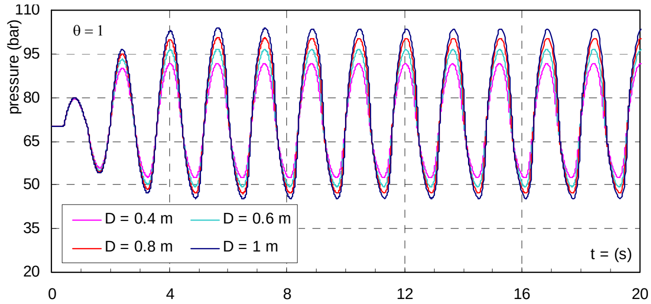

Figure 7. Pressure evolution for different pipe diameter at downstream end of pipe and for hydrogen mass fraction θ = 1.
Slika 7. Razvoj pritiska za različite prečnike cevi na nizvodnom delu cevi za maseni udeo vodonika θ = 1

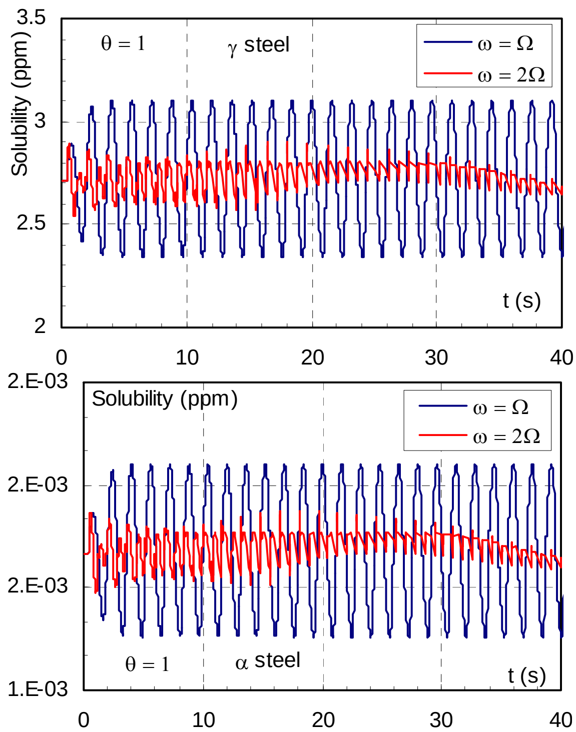

Figure 8. Solubility evolution in case of hydrogen (θ = 1), for frequencies ω = Ω and ω = 2Ω, for α and γ steels.
Slika 8. Razvoj rastvorljivosti za slučaj vodonika (θ = 1), za frekvencije ω = Ω i ω = 2Ω, za α i γ čelike

Figures 8 and 9 show plots of numerically obtained results for solubility and permeability evolutions, as functions of time and in the case of hydrogen (θ = 1), respectively. These plots are considered for two harmonic frequencies ω = Ω and ω = 2Ω and for α and γ steels. It can be noted that the solubility and permeability evolution follow the same oscillatory behaviour of the pressure in cases of resonant and antiresonant frequencies. From Fig. 8, it can be seen that the evolution of the solubility is much important in the case of γ steel than that in the case of α steel. However, the permeability evolution is much significant in the case of α steel than that in the case of γ steel as shown in Fig. 9. Nevertheless, these two complementary parameters are important in the embrittlement mechanism by hydrogen and they should be controlled in the case of α and γ steels during resonance phenomena.

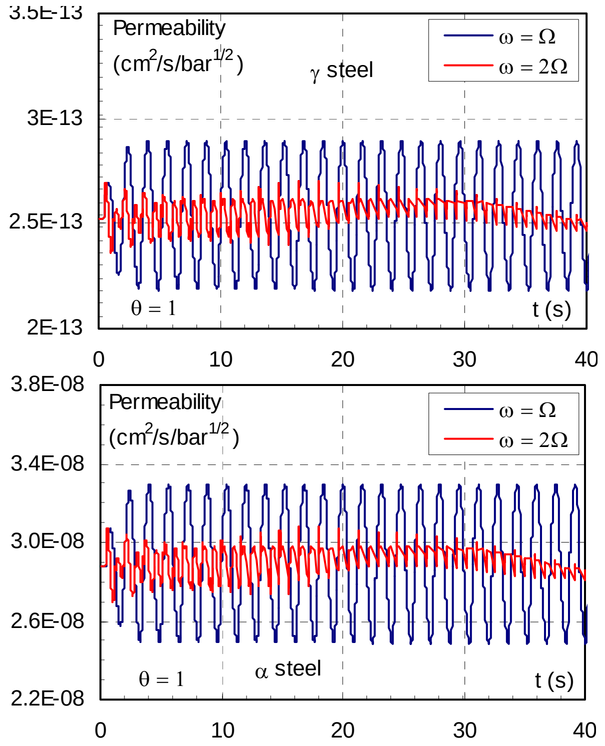

Figure 9. Permeability evolution in case of hydrogen (θ = 1), for frequencies ω = Ω and ω = 2Ω, for α and γ steels.
Slika 9. Razvoj zasićenja za slučaj vodonika (θ = 1), za frekvencije ω = Ω i ω = 2Ω, za α i γ čelike

From Fig. 3 and since the solubility and permeability depend on pressure, the following can be deduced: first, the pick values of these two parameters in case of hydrogen-natural mixtures will be the same than those obtained in the case of hydrogen; secondly, the solubility and permeability evolution, in case of hydrogen-natural mixtures, will follow the same oscillatory behaviour of pressure in cases of resonant and antiresonant frequencies as shown in Fig. 3.

CONCLUSION

In this study, the numerical solution of the resonant phenomenon in rigid pipelines of hydrogen-natural gas mixtures has been presented. This problem is governed by coupled two linear partial differential equations of hyperbolic type. The numerical method employed is the method of characteristics.

To simulate the resonance phenomenon, the boundary conditions were imposed by considering an oscillatory pressure at the upstream end of the pipe while the downstream end is kept closed.

Numerical results have shown that resonance is obtained for odd harmonics and antiresonance is obtained for even harmonics. During resonance, the results show that the pressure evolution is well influenced by excitation frequencies and it builds up to a steady-oscillatory behaviour (unless failure occurs). The effect of different values of hydrogen mass fractions θ on the pressure oscillations has also been analysed. The obtained results show that pressure oscillations for hydrogen and hydrogen-natural gas mixtures are higher compared to those obtained in the case of natural gas. Also, due to the nonlinearity of the problem, it was deduced that the ideal frequency that produces a good antiresonance effect is in the neighbourhood of theoretical even frequencies. Furthermore, dissolution and permeation evolutions as functions of time are analysed in the case of hydrogen and mixtures.

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