HYDROGEN BEHAVIOUR IN REPAIR WELDING OF THE MAIN PIPELINES UNDER PRESSURE

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Possibility of diffusion hydrogen penetration from hydrocarbon gas transported through the gas pipeline during repair welding performance on an operating pipeline has been analyzed. It is shown that at partial pressure of diffusion hydrogen on the inner surface of steel pipe in the range of 0.10–0.75 MPa at residual wall thickness in the defect zone of more than 5 mm increase of the parameter of hydrogen (cold) cracking risk is not higher than 5–11 %. Values of experimental measurements of diffusion hydrogen flow through the pipe wall in operating pipelines are given.

Keywords: *repair arc welding, operating gas pipelines, diffusion hydrogen, gas pipeline wall, hydrogen cracks, risk of formation*

A typical problem in repair welding of the main gas pipelines in stringent modes (low heat input) is the risk of appearance of cold (hydrogen) cracks, the formation of which is essentially affected by diffusion hydrogen in the welded joint metal. Application of consumables with a low hydrogen content in combination with reliable protection of the weld pool from the environment allows an essential lowering of the content of diffusion hydrogen in the HAZ. However, there still remains one more source of diffusion hydrogen — natural gas transported through the pipeline, which contains hydrogen in the form of chemical compounds (methane, propane, ethane, butane), or in the molecular form H_2 which does not diffuse into the pipeline wall metal. However, depending on pressure and temperature, natural gas can be in the two-phase state, i.e. the liquid phase also exists alongside the gas phase. Figure 1 gives the two-phase state diagram of natural gas, from which it follows that at working pressures of about 7.5 MPa and temperatures of 40–50 °C the liquid phase is equal to approximately 20 % of the mixture volume. In the liquid phase free hydrogen can dissolve in the atomic form. Considering the high degree of gas turbulization in the main gas pipeline, higher density of the liquid phase and lower temperature in the pipe section at its walls, it can be assumed that the liquid phase concentrates at the pipe walls and from the liquid phase the dissolved atomic hydrogen diffuses into the pipe wall metal, respectively. Under the stationary conditions of natural gas transportation, hydrogen flow J through the wall can be presented in the following form [1]:

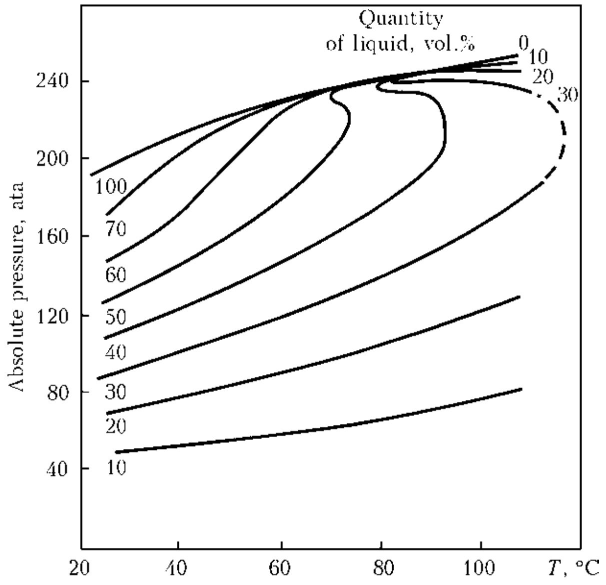

Figure 1. Phase diagram characteristic for natural hydrocarbon mixture

$$J = -D\frac{\partial C}{\partial r}\ (\text{ml}/(\text{cm}^2\cdot\text{s})), \qquad (1)$$

where D is the average coefficient of hydrogen diffusion through the pipe wall metal; $C(r)$ is the concentration of diffusion hydrogen across the pipe wall thickness (coordinate r).

At the stationary flow and small wall thicknesses

$$J \approx \frac{C(R_{out}) - C(R_{in})}{\delta} D, \qquad (2)$$

where $C(R_{out})$ is the hydrogen concentration on the outer surface $r = R_{out}$; $C(R_{in})$ is the same on the pipe inner surface $r = R_{in}$.

Assuming that $C(R_{out}) \approx 0$, and $C(R_{in}) \approx \sqrt{P_{H_2}}K(T)$ according to Sievert's law, where P_{H_2} is the partial pressure of hydrogen on the surface $r = R_{in}$, ata; $K(T)$ is the diffusivity of hydrogen in the pipe wall metal at temperature T (Figure 2), $\text{cm}^3/(100\ \text{g}\cdot\text{ata}^{1/2})$, we obtain

$$C(R_{in}) = J\frac{\delta}{D(T)}\ (\text{ml}/100\ \text{g}) \qquad (3)$$

or in the most often used dimension

Table 1. Calculated values of $J\delta$ depending on T and P_{out}

T, °C	$D\cdot 10^6$, cm^2/s	K, ml/(100 g·ata$^{1/2}$)	$J\delta\cdot 10^3$, ml/(cm^2·h), at P_{out}, ata				
			1	4	6	8	10
20	0.20	1.9	0.1069	0.214	0.262	0.302	0.338
40	0.46	1.8	0.2320	0.464	0.570	0.659	0.736
60	0.98	1.7	0.4680	0.938	1.147	1.325	1.482
80	1.91	1.6	0.8590	1.721	2.105	2.431	2.718

$$\overline{C}(R_{\text{in}}) = J\,\frac{\delta}{D(T)}\,\frac{100\text{ g}}{\gamma}\quad(\text{ml}/100\text{ g}),$$

where γ is the specific weight of pipe wall steel (7.8 g/cm^3).

From the data in Figure 2 (Sievert's law), it follows that at the same partial pressure of hydrogen P_{out} hydrogen concentration on the pipe inner surface $C(R_{\text{in}})$, and, therefore, across the wall thickness can rise significantly, at the expense of increase of metal temperature in repair welding. This is, naturally, valid provided P_{out} remains constant, i.e. convective supply of hydrogen in the near-wall region rather quickly compensates its diffusion removal into the pipe wall.

Using data from [2, 3] of relative value D at temperature T of pipe wall in the form of

$$D(T) = 0.12\exp\left(-\frac{3900}{T+273}\right),\quad T < 200\ ^\circ\text{C},$$

we obtain from (1)–(3), allowing for the data of Figure 2 at $20 \le T \le 80$ °C, the dependence of value $J\delta\cdot 3600$, ml/(cm·h) on P_{out} (Table 1), where

$$J\delta = K\sqrt{P_{\text{out}}}D\,\frac{\gamma}{100}\cdot 3600\ (\text{ml}/(\text{cm}^2\cdot\text{h})). \tag{4}$$

From the data of Table 1 it is seen that at δ = = 1 cm, the magnitude of hydrogen flow J from 1 cm^2/h area essentially depends on wall temperature, and at T = 40 °C and P_{out} = 1 ata it does not exceed $0.232\cdot 10^{-3}$ ml/(cm^2·h), and at P_{out} = 10 ata this value does not exceed $0.736\cdot 10^{-3}$ ml/(cm^2·h), i.e. sufficiently sensitive equipment is required to record such flows and determine values P_{out} and $C(R_{\text{in}})$, respectively, particularly within the limits of $P_{\text{out}} <$ < 5 ata and T < 40 °C.

In the total volume of pumped gas, these losses through the wall of 1420 × 20 mm pipe at the pressure P = 75 ata, P_{out} = 8 ata and transportation velocity v = 10 m/s = 36,000 m/h are equal (T = 80 °C) to just $0.25\cdot 10^{-10}$ %, i.e. they are of little concern for gas producers.

In this connection the purpose of this work is drawing the attention of researchers to the problem of hydrogenation of pipeline wall at the expense of diffusion hydrogen flow from the transported hydrocarbons. It should be noted that this question is quite actively discussed in foreign publications [4, et al.]. Therefore, this paper considers P_{out} influence on diffusion hydrogen distribution at welding heating in the zone of pipe wall thinning, depending on its thickness in the welding heating region, when making the first pass by arc welding in the following modes: I = 90 A, U = 24 V, v_{w} = 0.2 cm/s. Pipe material is steel of 17G1S type.

Hydrogen distribution should be considered allowing for distribution of metal microstructure and its stressed state in the joint zone at welding heating. High stress level in the considered repair pressure welding in the HAZ metal is quite obvious, and as regards microstructural changes, their distribution is of a quite local nature, and requires the respective correlation with diffusion hydrogen distribution.

Calculations were performed using «ArcWeldSys» computer system developed at PWI [1, 3], which was applied to determine by successive tracing in time t (starting from the moment t = 0) of the arc passing through this cross-section, the temperature field $T(x, y, z)$, base metal fusion zone (FZ) characterized by isotherms of maximum temperatures $T_{\max}(x, y) = T_{\text{L}}$, $T_{\max}(x, y) = T_{\text{S}}$, where T_{L} and T_{S} are the temperatures of liquidus (about 1490 °C) and solidus (about 1420 °C), zone of microstructural changes characterized by isotherm $T_{\max}(x, y)$ = 800 °C, for the mid-section along the deposited pass z = const in plane x,

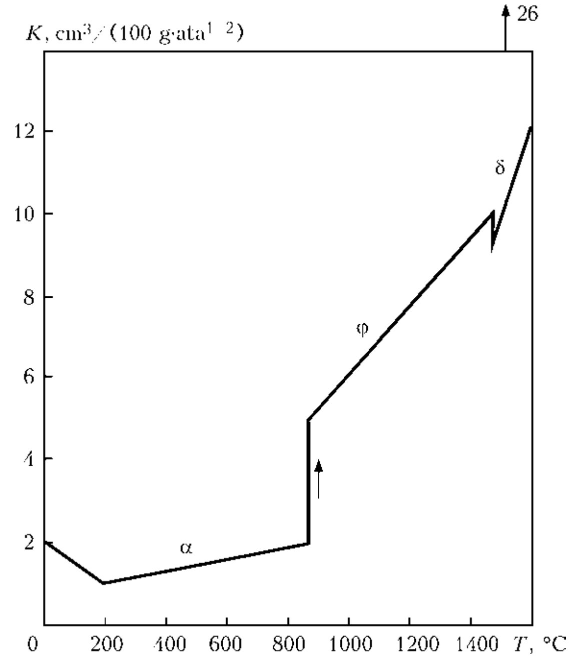

Figure 2. Temperature influence on hydrogen solubility K in iron

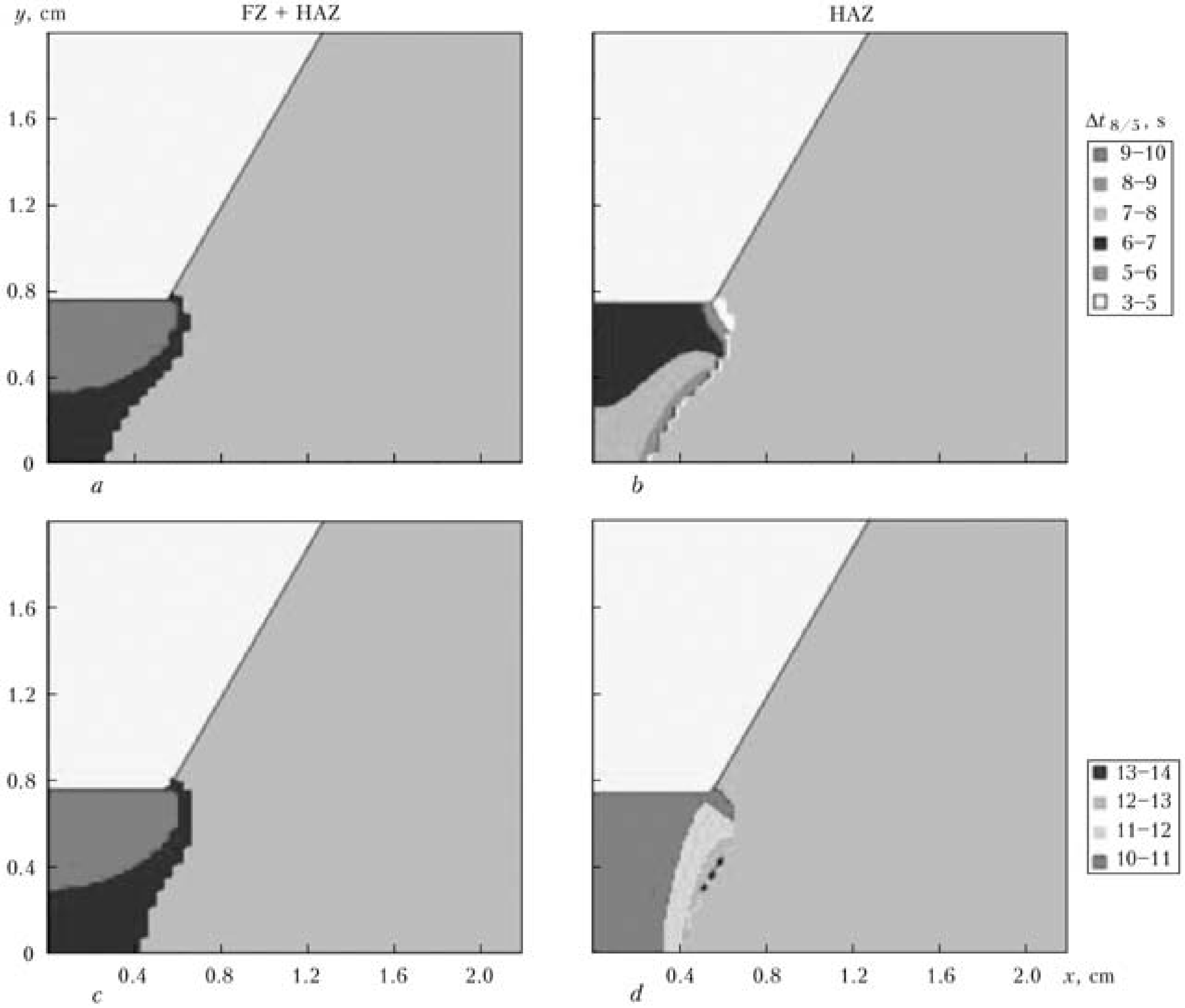

Figure 3. Results of calculation of FZ and HAZ dimensions (*a*), $\Delta t_{8/5}$ (*b*) for the first pass of arc welding-up of groove defect along the pipe circumference at δ_{min} = 5 mm, P_{H_2} = 7.5 ata and gas velocity in the pipe of 6 m/s (without preheating), and the same but at preheating to 150 °C (*c*, *d*)

y. In the HAZ $\Delta t_{8/5}$ — time of metal staying in the temperature range of 800–500 °C in the FZ and HAZ at cooling, was calculated. Figure 3 gives the calculation data associated with heating in the zone with minimum metal thickness δ_{min} = 5 mm without preheating, i.e. T_0 = 20 °C and with preheating up to T_0 = 150 °C. Velocity of gas motion in the pipe on the level of 6 m/s and coefficient of heat exchange on the inner surface [5] equal to 0.05 J/(cm^2·s·°C), respectively, were taken into account. Figure 4 gives the calculation data of $\Delta t_{8/5}$ for the zone with minimum thickness δ_{min} = 10 min without preheating and with preheating to T_0 = 150 °C.

Table 2 gives the calculation data of $\Delta t_{8/5}$ for four variants, which in combination with APA diagram [6] for 17G1S steel in Figure 5 allow judging the quantity of martensite V_M and bainite V_B in the microstructure of HAZ metal at cooling. These data show that the microstructural condition in the welding heating zone in the considered steel in repair welding is sufficiently favourable in terms of formation of cold cracks in the presence of the appropriate content of diffusion hydrogen in the HAZ metal (condition of high tensile stresses in the considered repair pressure welding is always observed). Calculation data are given below.

Figures 6–9 give the kinetics of variation in time t of hydrogen concentration in the weld cross-section for two thicknesses of pipe wall in the defect zone (welding) at P_{H_2} = 0 and 7.5 ata at its content of 10 cm^3/100 g in the deposited metal. It is seen that at the considered welding heating in the zone of small pipe wall thicknesses (Figure 6, *a*, *b*) and intensive restoration of partial pressure of hydrogen P_{H_2} = = 7.5 ata a considerable saturation of metal by diffusion hydrogen occurs inside the pipe in the zone of the wall local heating (concentration reaches values of approximately 26 cm^3/100 g), compared to the variant, when P_{H_2} = 0 and respective concentration of hydrogen reaches values of approximately 4 cm^3/100 g. At metal cooling, however, this high concentration of hydrogen drops abruptly and already at t = 58 s it differs not so significantly for both the cases.

Increase of δ_{min} to 10 mm (Figure 9, *a*, *b*) noticeably lowers the influence of hydrogen flow from the

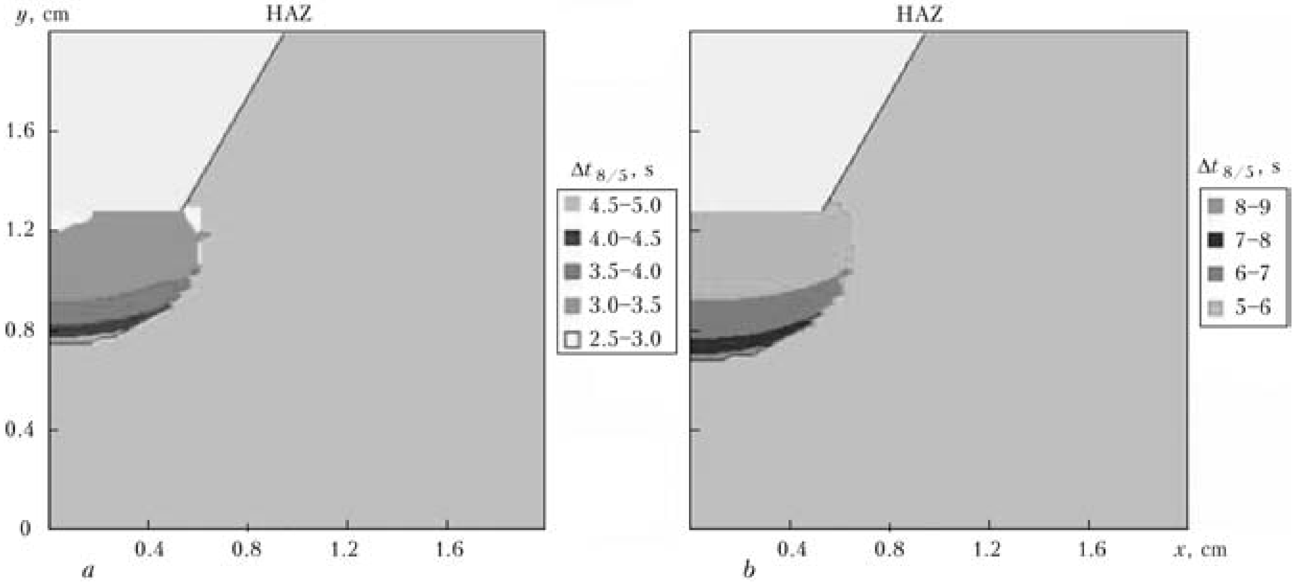

Figure 4. Time of metal staying in the HAZ at cooling $\Delta t_{8/5}$ for zone of thickness δ_{min} = 10 mm, T_0 = 20 (*a*), 150 (*b*) °C

pipe at P_{H_2} = 7.5 ata on distribution of the latter in the HAZ metal, as this zone is located markedly farther from the pipe inner surface. Eventually, maximum concentration reaches not more than 7 cm^3/100 g (Figure 9, *b*) compared to 26 cm^3/100 g in Figure 8, *b*.

As regards the conditions of cold crack formation, analysis of the data in Figures 6, 7 and Table 2 leads to the following conclusions.

For variant 1 in the HAZ metal at $\Delta t_{8/5}$ = 3–5 s in point 1 diffusion hydrogen content [H] ≈ 2.0 cm^3/100 g at V_M = 100 %, and at $\Delta t_{8/5}$ = 7–8 s and v_M = 35 %, [H] ≈ 1.5 cm^3/100 g (see Figure 6, *a*, point 2), i.e. the most stringent conditions for hydrogen are observed in HAZ metal in the corner of weld metal surface meeting the base metal (point 1).

According to [7] sensitivity index

$$\wp = 12P_{cm} + \log H, \qquad (5)$$

where

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B; \qquad (6)$$

H is the content of diffusion hydrogen in the deposited metal.

Table 2. Values of $\Delta t_{8/5}$ and volume fraction of microstructural components in the HAZ metal for the four variants

Parameter	Variant			
	1 (Figure 3, *a*, *b*)	2 (Figure 3, *c*, *d*)	3 (Figure 4, *a*)	4 (Figure 4, *b*)
$\Delta t_{8/5}$, s	7–8	11–12	4–5	6–8
V_M, vol.%	35–40	25–30	55–60	50–40
V_B, vol.%	65–60	75–70	45–40	50–60

For the considered steel (see Figure 5) at P_{H_2} = 0 P_{cm} = 0.272; for point 1 in Figure 6, *a*, P_1 = 4.264, respectively. In the case of P_{H_2} = 7.5 ata (Figure 6, *b*) at the same microstructure local concentration of diffusion hydrogen $[H]_{loc}$ changes markedly: in point 1 $[H]_{loc}$ = 3.0 cm^3/100 g, in point 2 [H] = = 4.9 cm^3/100 g. Accordingly, equivalent value H_{eq} for formula (5), allowing for linear dependence of results in Figures 6 and 7 on hydrogen in the deposited metal (10 cm^3/100 g) can be determined from the following dependence:

$$H_{eq} = 10\ cm^3/100\ g\ \frac{[H]_{loc}(7.5)}{[H]_{loc}(0)}, \qquad (7)$$

where $[H]_{loc}(7.5)$, $[H]_{loc}(0)$ are the local concentrations in points 1 and 2 at P_{H_2} = 7.5 and 0 ata.

Table 3 gives for the considered in Figures 6, 7 variants 1–4 the respective initial data on microstructure and local values of hydrogen concentration $[H]_{loc}$ (P_{out}) in points 1, 2 and results of calculation by (5)–(7), demonstrating the degree of the possible in-

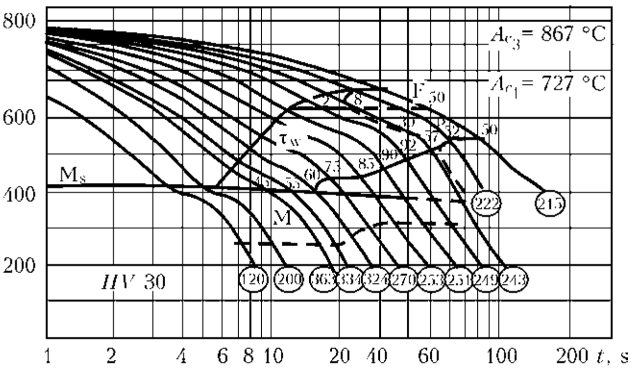

Figure 5. APA diagram for steel of 17G1S type

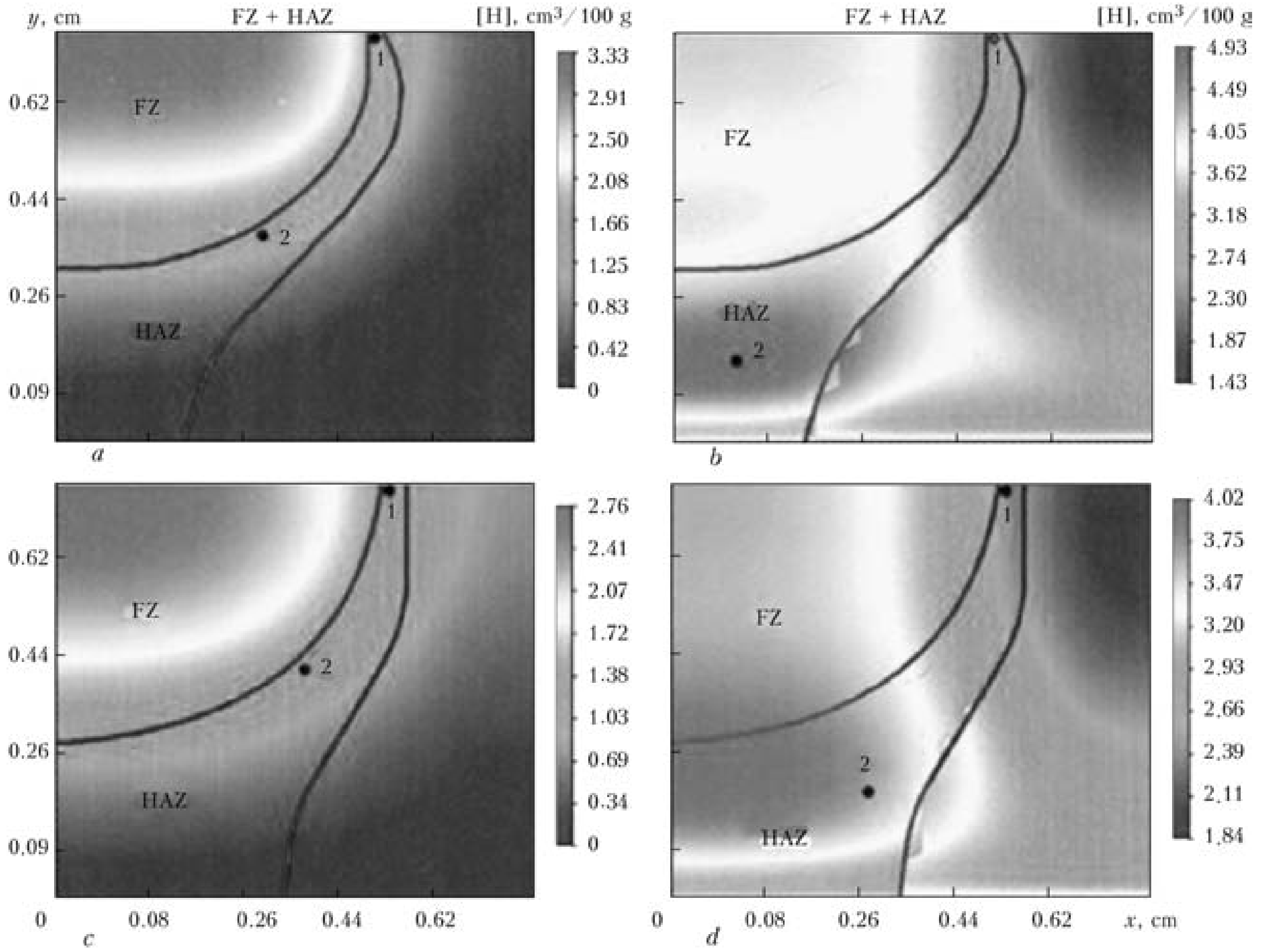

Figure 6. Distribution of diffusion hydrogen in the cross-section of the first pass at Δ_{min} = 5 mm at the moment of time t = 98 s at P_{H_2} = = 0 (a, c) and 7.5 (b, d) ata at T_0 = 20 (a, b) and 150 (c, d) °C in FZ and HAZ

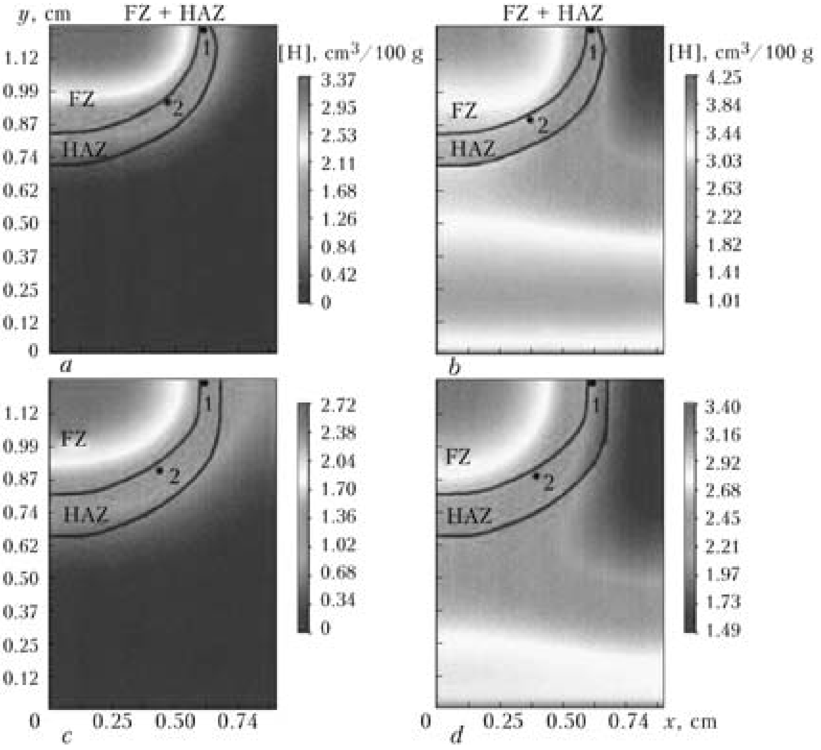

Figure 7. Same as in Figure 6, but at δ_{min} = 10 mm

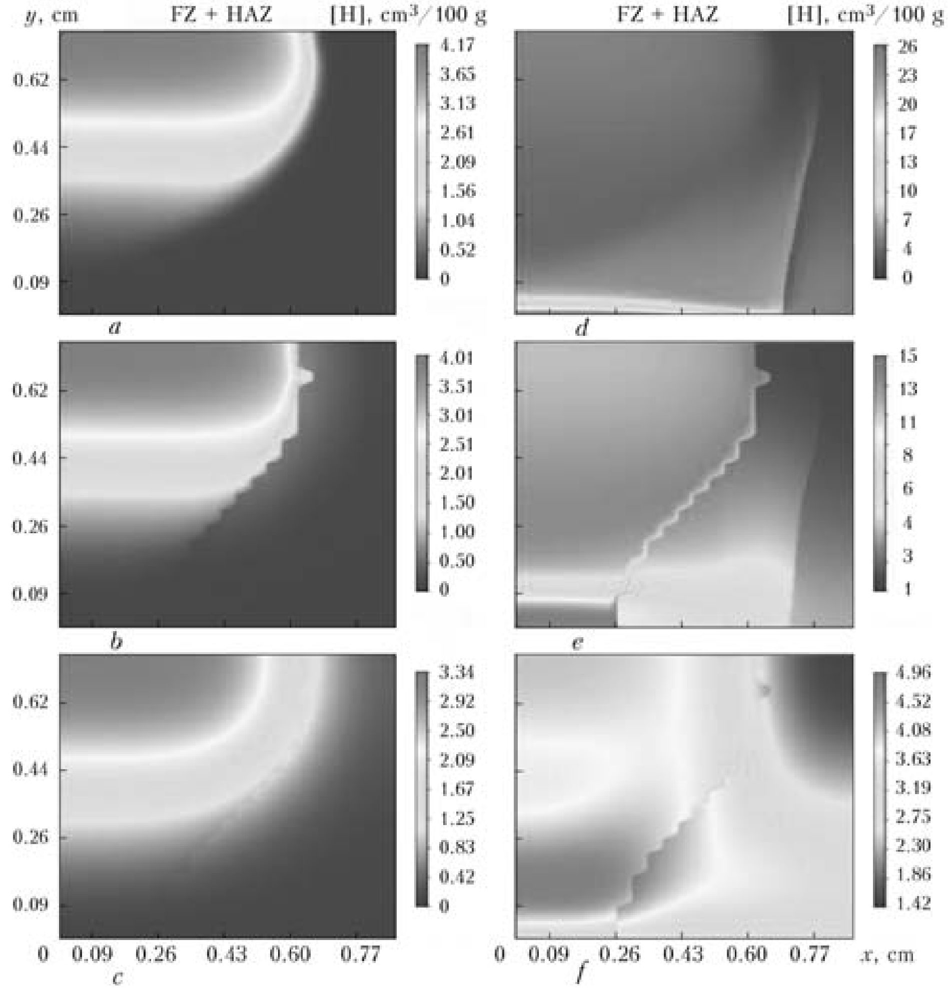

Figure 8. Concentration of diffusion hydrogen at δ_{min} = 5 mm and T_0 = 20 °C in different moments of time t = 2 (*a*, *d*), 10 (*b*, *d*) and 58 (*c*, *f*) s since the moment of welding heat source passing through this section at P_{H_2} = 0 (*a*–*c*) and 7.5 (*d*–*f*) ata in the FZ and HAZ

fluence of diffusion hydrogen entering the HAZ metal on the risk of formation of cold (hydrogen) cracks.

The given data lead to the conclusion that the additional source of diffusion hydrogen, related to natural gas transported through the pipeline, in repair pressure welding can lead at small δ_{min} to an essential saturation of welding heating zone by diffusion hydrogen in the high temperature range. However, during cooling of the pipe walls diffusion hydrogen concentration is equalized, both in the wall metal and between the wall and hydrogen containing layer in the near-wall region with partial pressure P_{H_2}. As a result, at temperatures below 150 °C and $P_{H_2} < 7.5$ ata (≈ 0.75 MPa) the influence of additional diffusion hydrogen source on cold crack formation is low and can be quite well compensated by low hydrogen content in the filler metal. At higher partial pressures of diffusion hydrogen, however, $P_{H_2} > 7.5$ ata the risk of cold cracking rises considerably.

Determination of real P_{H_2} values or its level in the operating main gas pipelines is a quite urgent task. With this purpose the paper authors organized experimental measurements in the operating gas pipelines:

- in the area of CU «Boyarka» (P_{op} = 4.8 MPa, $D \times \delta$ = 700 × 16 mm, T = 8 °C);
- CU «Kremenchug» (P_{op} = 7.5 MPa, $D \times \delta$ = = 700 × 16 mm; T = 48 °C);
- in the area of GDS of TEP 5 (P_{op} = 4.5 MPa, $D \times \delta$ = 350 × 11 mm; T = 13 °C).

The essence of measurements consisted in application of a layer of glycerin 3–5 mm thick on the section of pipeline outer surface, having first cleaned it to remove paint and rust to metal luster.

It was assumed that bubbles of diffusion hydrogen going out through the pipe wall, will be fixed in the glycerin layer (standard procedure of glycerin test [8]). Observations in the above facilities were made for 7–10 days. As a result, not a single bubble was found in the glycerin sample, leading to the conclusion that the magnitude of hydrogen flow through the pipeline wall is below the resolution of the used method.

Thus, as a result of the conducted rather extensive experimental measurements using the glycerin test to determine the actual hydrogen flow through the wall of the main pipelines in Ukraine, allowing for the resolution of about 1 $mm^3/(cm^3 \cdot h)$, it was found that the real sought flow is below the resolution of the

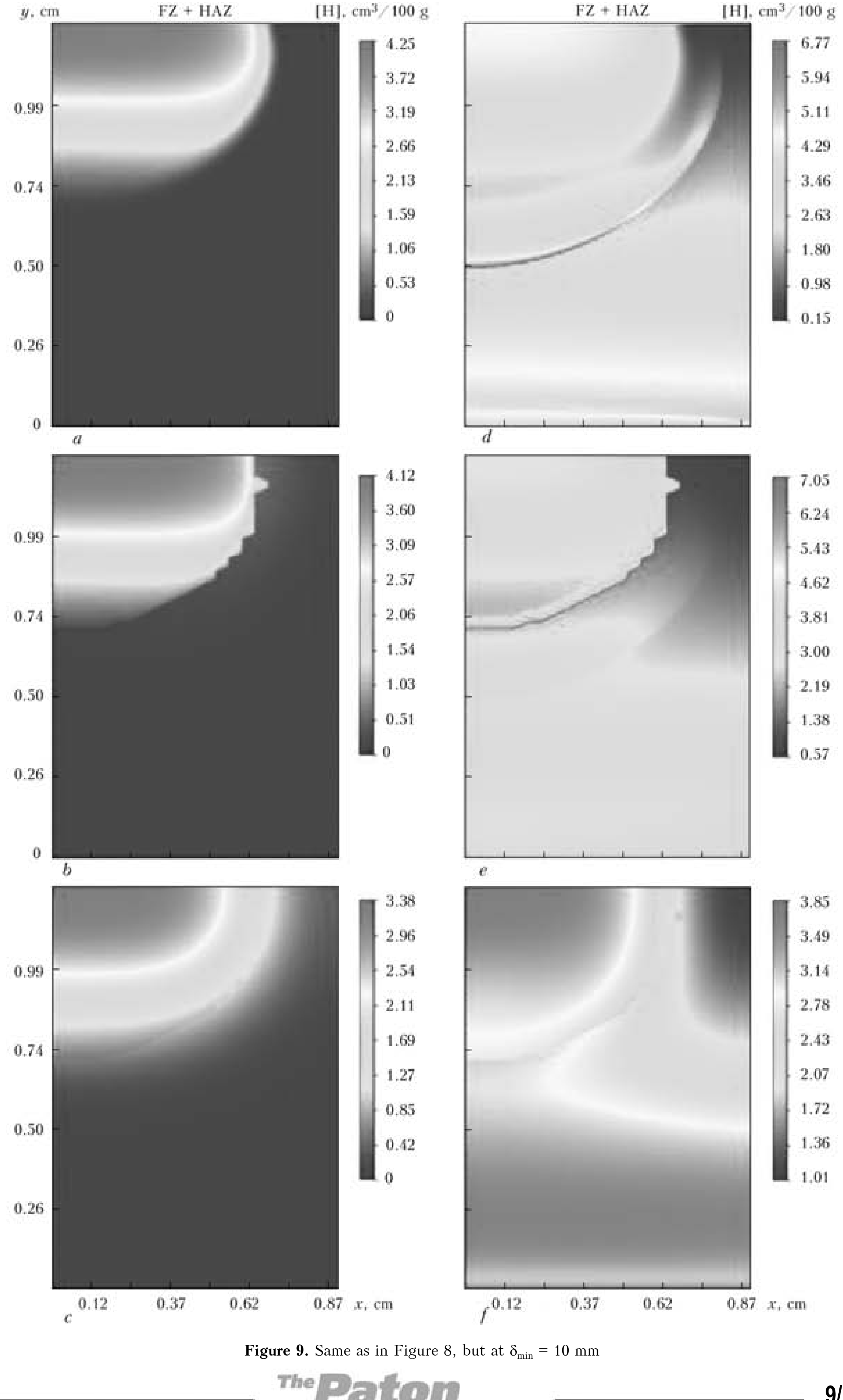

Figure 9. Same as in Figure 8, but at δ_{min} = 10 mm

Table 3. Results of calculation of the parameter of cold cracking risk for variants 1–4

Variant number	T_0, °C	Points	V_M, %	P_{H_2}, ata	$[H]_{loc}$, cm^3/100 g	$\wp$	$\frac{\wp}{4.264}$
1 (Figure 6, *a*, *b*)	20	1	95	0	2.0	4.264	1.0
				7.5	3.0	4.440	1.03
		2	50	0	1.5	4.264	1.0
				7.5	4.9	4.750	1.11
2 (Figure 6, *c*, *d*)	150	1	30	0	1.5	4.264	1.0
				7.5	2.5	4.490	1.05
		2	20	0	1.7	4.264	1.0
				7.5	3.0	4.510	1.06
3 (Figure 7, *a*, *b*)	20	1	100	0	1.5	4.264	1.0
				7.5	2.5	4.490	1.05
		2	55	0	1.5	4.264	1.0
				7.5	2.5	4.490	1.05
4 (Figure 7, *c*, *d*)	150	1	50	0	1.5	4.264	1.0
				7.5	2.0	4.390	1.03
		2	45	0	1.5	4.264	1.0
				7.5	2.5	4.490	1.05

used method, i.e. according to Table 1 partial pressure of diffusion hydrogen in the main pipelines is much lower than 1 ata (0.1 MPa), which allows regarding the influence of diffusion hydrogen from hydrocarbon gas transported trough the pipeline, on hydrogen cracking to be quite negligible in repair welding on pipeline wall.

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