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Yassine Haj Kacem[1], Taieb Haj Ezzeddine[1], Guy Pluvinage[2]

IMPORTANCE OF OIL PIPELINE SECURITY FOR MINIMISING PIPELINE DAMAGE

ZNAČAJ SIGURNOSTI NAFTOVODA RADI SMANJENJA OŠTEĆENJE CEVOVODA

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Author's address:
[1] UMF, Ecole Nationale d'Ingénieurs de Sfax, BP 1173, 3038 Sfax Tunisie
[2] LFM, Ecole Nationale d'Ingénieurs de Metz, Ile du Saulcy, 57045 Metz, France

Keywords
- oil pipe network
- security analysis
- Hardy Cross method

Abstract

This paper presents a model for predicting pressure and velocity in the Franco-Tunisian oil company network. This oil company produces a flammable mixture of natural gas, oil and water. To protect the oil pipelines, the Company has limited the maximum velocity when transporting these effluents to 6 m/s. If the velocity becomes more important, the friction forces may provoke the fire of the effluent. The main objectives of the present study are to verify this condition. The FTOC network is very complex composed of interconnected pipes forming several loops or circuits. To verify the security condition, a FORTRAN computer programme based on the Hardy-Cross method is elaborated. The programme determines the variables of the network (discharge, velocity, pressure, head loss) in steady state flow. Computed results are analysed and solutions are proposed to satisfy the network security.

Ključne reči
- mreža naftovoda
- analiza sigurnosti
- *Hardy Cross* metod

Izvod

U ovom radu je predstavljen model za predviđanje pritiska i brzine u naftovodnoj mreži francusko-tunižanske kompanije. Ova naftna kompanija proizvodi zapaljivu smešu prirodnog gasa, nafte i vode. Radi zaštite naftovoda, kompanija je ograničila najveću brzinu pri transportovanju ovih protočnih fluida na 6 m/s. Kada brzina postane veoma bitna, sile trenja mogu izazvati paljenje ovih protočnih fluida. Glavni ciljevi sadašnje studije sastoje se u verifikovanju ovog uslova. Naftovodna mreža FTOC je vrlo složena sastavljena iz međusobno povezanih cevovoda koje formiraju nekoliko petlji ili kola. Da bi se verifikovao uslov sigurnosti, razvijen je računarski program u FORTRAN-u koji se zasniva na Hardy-Cross metodu. Program određuje veličine u mreži (pražnjenje, brzina, pritisak, gubitak) za stacionarno strujanje. Rezultati proračuna su analizirani i rešenja su predložena za zadovoljavajuću sigurnost mreže.

INTRODUCTION

There are many networks of oil pipelines in the world. A network should safely and efficiently transport the fuel /1/. Many oil companies deliver the energy needed for our mobile lifestyle and crude oil that refineries convert into essential materials which are a vital part of the global infrastructure and the economy. As the world becomes more reliant on oil and the prices continue to rise, it is realistic to expect accidents of oil transport pipe networks to become more frequent and more costly.

The oil companies have taken many actions to protect these vital liquid pipelines and have increased their security measures. These security measures include the surveillance of pipeline, the limiting of effluent flow velocities and pressures in the pipe. Velocities and pressures should in general be kept low enough to prevent problems with friction, water hammer, noise, vibration and reaction forces. In some cases a minimum velocity is required, /2/.

The Franco Tunisian Oil Company (FTOC), based in Sfax, a town in Tunisia, produces a flammable mixture of natural gas, oil and water.

This company has limited the maximum velocity when transporting these effluents to 6 m/s. Due to pipe wall roughness, when the velocity becomes larger than this value, the friction forces may provoke the fire of the effluents. The actual pipe networks of the FTOC satisfy this security condition.

The main objectives of the present study are to verify this condition when increasing the production of the company by changing pumps or by adding new oil wells.

The FTOC network is very complex, composed of interconnected pipes forming several loops or circuits. In such systems, it is required to determine the distribution of flow through the various pipes of the network. Generally, the solution of real pipe networks, assumed in engineering practice, is difficult to be obtained analytically. Hence the methods of successive approximations are used and are running by the help of digital computers.

In this study, a FORTRAN computer programme based on the Hardy-Cross method is elaborated. The programme determines the variables of the network (discharge, velocity, pressure, head loss) in steady state flow and verifies the security condition. The paper presents this method for predicting pressure losses and velocities in the network pipes of the FTOC.

PIPE FLOW RELATIONSHIPS

The equations which describe steady-state one-dimensional flow in a cylindrical pipe can be adapted from the analytical model developed by Streeter /3/ and Bansal /4/.

Continuity equation

The equation based on the principle of conservation of mass is called continuity equation. Thus for a fluid flowing through the pipe at full cross section, the quantity of fluid per second or the discharge is constant. For an incompressible fluid, the discharge Q is related to velocity V by the equation:

$$Q = VA \tag{1}$$

where A is the area of the pipe.

Bernoulli's equation

Bernoulli's equation for real fluids is written between the two end sections of a pipe. The upstream section is given the subscript 1 and the downstream section the subscript 2. In this equation the loss term is included, thus,

$$\frac{V_1^2}{2g} + \frac{p_1}{\varpi} + z_1 = \frac{V_2^2}{2g} + \frac{p_2}{\varpi} + z_2 + h_f \tag{2}$$

where h_f is the loss of energy between points 1 and 2.

The mechanical energy at section 1 is equal to the sum of mechanical energy at section 2 and all the losses between the two sections.

Darcy-Weisbach equation

The Darcy-Weisbach equation for energy loss due to steady flow of a fluid in a pipe is generally adopted for pipe flow computations. It is:

$$h_f = \lambda \frac{L}{D} \frac{V^2}{2g} \tag{3}$$

where hf is the head (energy) loss in the length of pipe L of inside diameter D, for average velocity of flow V. The friction factor λ is a dimensionless factor which is a function of relative roughness k/D and Reynolds number Re. This factor is given by the Colebrook implicit formula:

$$\frac{1}{\sqrt{\lambda}} = -2\log_{10}\left(\frac{k}{3.71D} + \frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right) \tag{4}$$

For a given k/D and Re, this formula must be solved by trial and error.

NETWORKS OF PIPES

A pipe network is an interconnected system of pipes forming several loops or circuits. An example of a pipe network is shown in Fig. 5. In such a system, it is required to determine the distribution of flow through various pipes of the network. This problem, in general, is complicated and requires trial solutions in which the elementary circuits are balanced in turn until all conditions for the flow are satisfied.

Steady flow

The fluid flow in pipe networks may be steady or unsteady. In this study the flow will be considered steady.

In these conditions, the following are the necessary conditions for any network of pipes:

(i) The flow into each junction must be equal to the flow out of the junction. This is due to the continuity equation.

(ii) The algebraic sum of head losses round each loop must be zero. This means that in each loop, the loss of head due to flow in clockwise direction must be equal to the loss of head due to flow in anticlockwise direction.

(iii) The head loss in each pipe is expressed as $h_f = rQ^n$. The value of r depends upon the length of pipe, diameter of pipe and coefficient of friction of pipe. The value of n for turbulent flow is 2. We know that,

$$h_f = \frac{8\lambda L}{\pi^2 g D^5} Q^2 = rQ^2 \tag{5}$$

This head loss will be positive, when the pipe is a part of loop and the flow in the pipe is clockwise. Generally, the pipe network problems are difficult to solve analytically. Hence the methods of successive approximations are used. The 'Hardy Cross Method' is one such method which is commonly used.

Hardy Cross Method

The procedure for Hardy Cross Method is as follows:

1. In this method a trial distribution of discharges Q_0 is made arbitrarily but in such a way that continuity equation is satisfied at each junction (or node).

2. With the assumed values of Q_0, the head loss in each pipe is calculated according to equation (5).

3. Now consider any loop (or circuits). The algebraic sum of head losses round each loop must be zero. This means that in each loop, the loss of head due to flow in clockwise direction must be equal to the loss of head due to flow in anticlockwise direction. An example of loop is shown in Fig. 1.

4. Now calculate the net head loss around each loop considering the head loss to be positive in clockwise flow, and to be negative - in anticlockwise flow.

If the net head loss due to assumed values of Q_0 round the loop is zero, then the assumed values of Q_0 in that loop is correct. But if the net head loss due to assumed values of Q_0 is not zero, then the assumed values of Q_0 are corrected by introducing a correction ΔQ for the flows, till the circuit is balanced.

The source of the corrective term is obtained as follows:

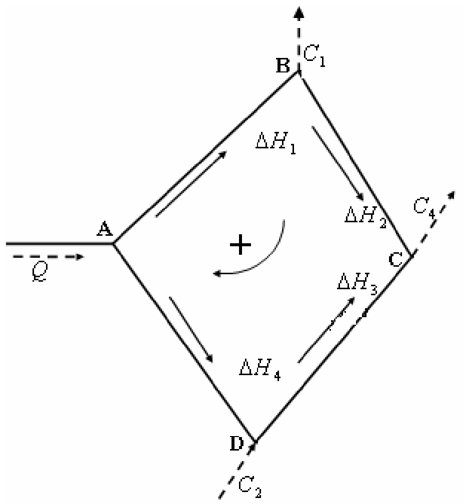

Figure 1. A loop of pipes balanced when $\sum_{\text{alg}} \Delta H_i = 0$

Slika 1. Cevovodna kontura u ravnoteži kada je $\sum_{\text{alg}} \Delta H_i = 0$

For any pipe

$$Q = Q_0 + \Delta Q \tag{6}$$

where Q is the correct discharge, Q_0 the assumed discharge, and ΔQ the correction. Then, for each pipe

$$h = rQ^2 = r\left(Q_0 + \Delta Q\right)^2 = r\left(Q_0^2 + nQ_0\Delta Q + \cdots\right) \tag{7}$$

If ΔQ is small compared with Q_0 all terms of the series after the second one may be dropped. Now for a circuit,

$$\sum h = \sum rQ^2 = \sum rQ_0^2 + \Delta Q \sum 2rQ_0 = 0 \tag{8}$$

where ΔQ has been taken out of the summation as it is the same for all pipes in the circuit. Solving for ΔQ,

$$\Delta Q = -\frac{\sum rQ_0^2}{2\sum \left|rQ_0\right|} \tag{9}$$

In applying ΔQ to a circuit, it has, the same sense in every pipe, e.g. it adds to flows in the counter-clockwise direction and subtracts from flows in the clockwise direction. Since ΔQ contains the sign change, the denominator of the correction term is the sum of the absolute terms.

5. If the value of ΔQ comes out to be positive, then it should be added to the flows in the clockwise direction (the flows in clockwise direction in a loop are considered positive) and subtracted from the flows in the anticlockwise direction.

6. Some pipes may be common to two circuits (or two loops), then the two corrections are applied to these pipes.

7. After corrections have been applied to each pipe in a loop and to all loops, a second trial calculation is made for all loops. The procedure is repeated till ΔQ becomes negligible.

APPLICATIONS AND RESULTS

The above model and the numerical schemes presented in the previous sections are applied to the pipe network of the FTOC. This network is constituted of manifold sits (oil wells) as shown in Fig. 2 representing an actual view of a pipe manifold. This figure shows that the pipes are underground.

This oil manifold sit, plotted in 3D (see Fig. 3), has been transformed to a 2D representation to give the pipe network in the Fig. 4.

Figure 2. The actual manifold SIT 41.
Slika 2. Stvarni cevni sistem grane 41.

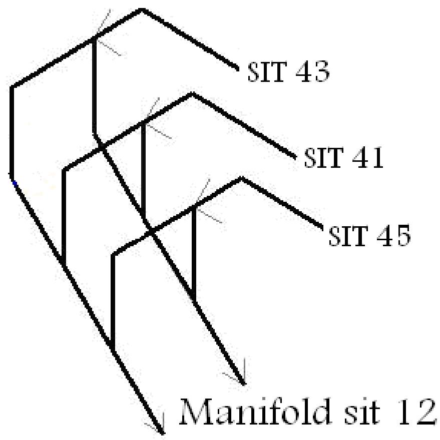

Figure 3. The manifold SIT 41 in 3D representation.
Slika 3. Cevni sistem grane 41 u 3D prikazu.

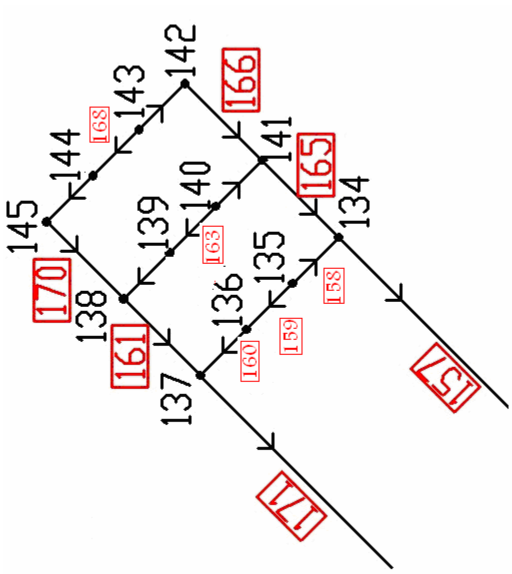

Figure 4. The manifold SIT 41 in 2D representation (142: node number 166 pipe number).
Slika 4. Cevni sistem grane 41 u 2D prikazu (142: broj čvora; 166: broj cevovoda).

Actual pipe network

Figure 5 represents a 2D representation view of the actual FTOC pipe network. The actual system consists of 171 pipes, 145 nodes, and 27 loops.

A 3D representation of the FTOC pipe network is given in Fig. 6.

The transported fluid is a mixture of oil, water and natural gas. This mixture is assumed to be incompressible and the discharge of effluents transported by each pipe is estimated as:

$$Q = Q_{\text{water}} + Q_{\text{oil}} + Q_{\text{gas}} \qquad (10)$$

where: $\rho_{\text{water}} =$ 1070 kg/m^3, $\rho_{\text{oil}} =$ 827 kg/m^3, and $\rho_{\text{ogasil}} =$ 1.33 kg/m^3.

Some experimental tests permitted to obtain an average value of the effluent density $\rho_{\text{effluents}} = 345.57$ kg/m^3.

For the actual network, the production is presented in Table 1. The corresponding steady state results, obtained after 16 iterations, when applying the Hardy Cross method, are summarized for some nodes and pipes in Tables 2 and 3.

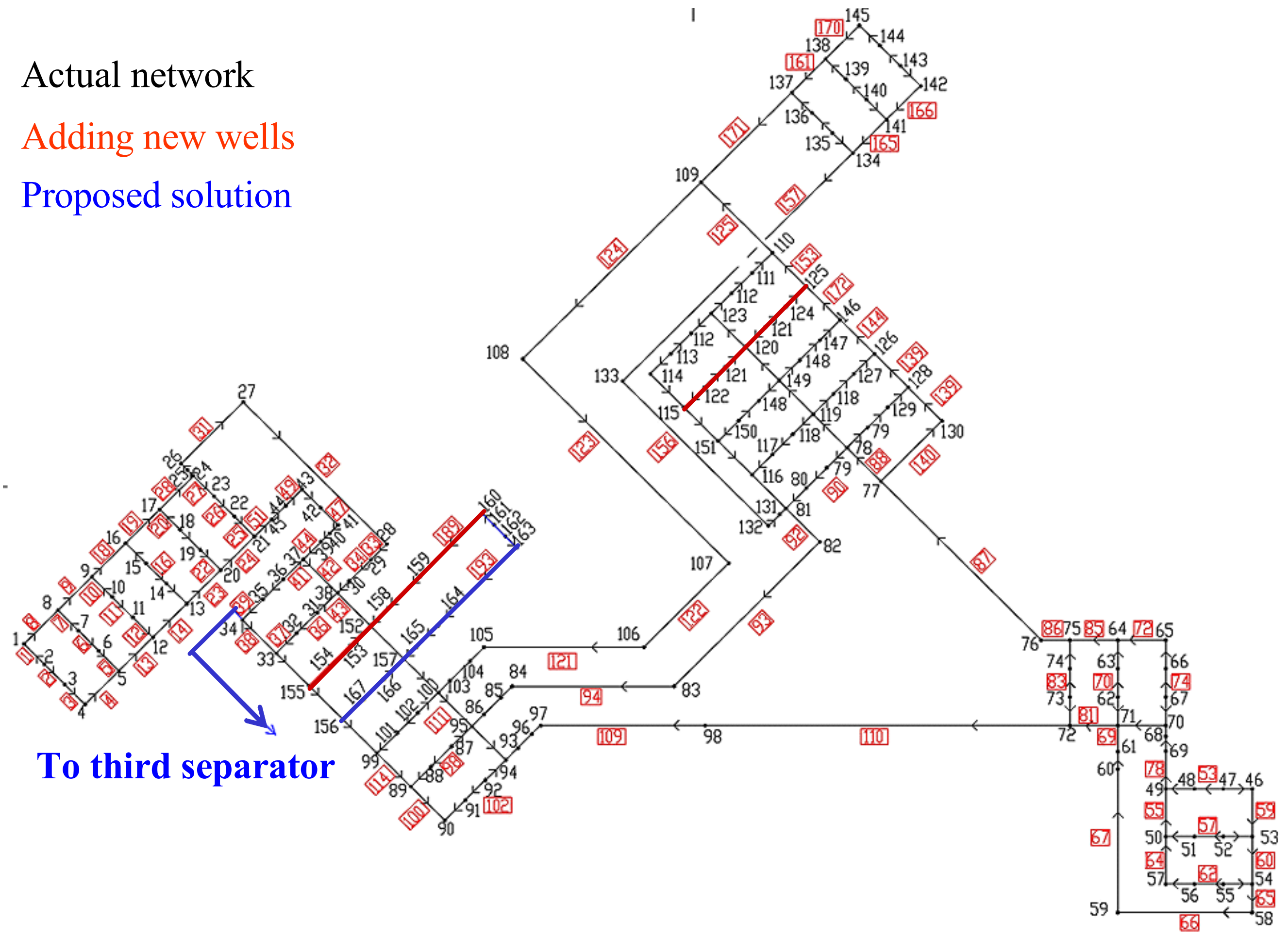

Figure 5. Pipe network of the FTOC (2D representation).
Slika 5. Cevovodna mreža FTOC (2D prikaz).

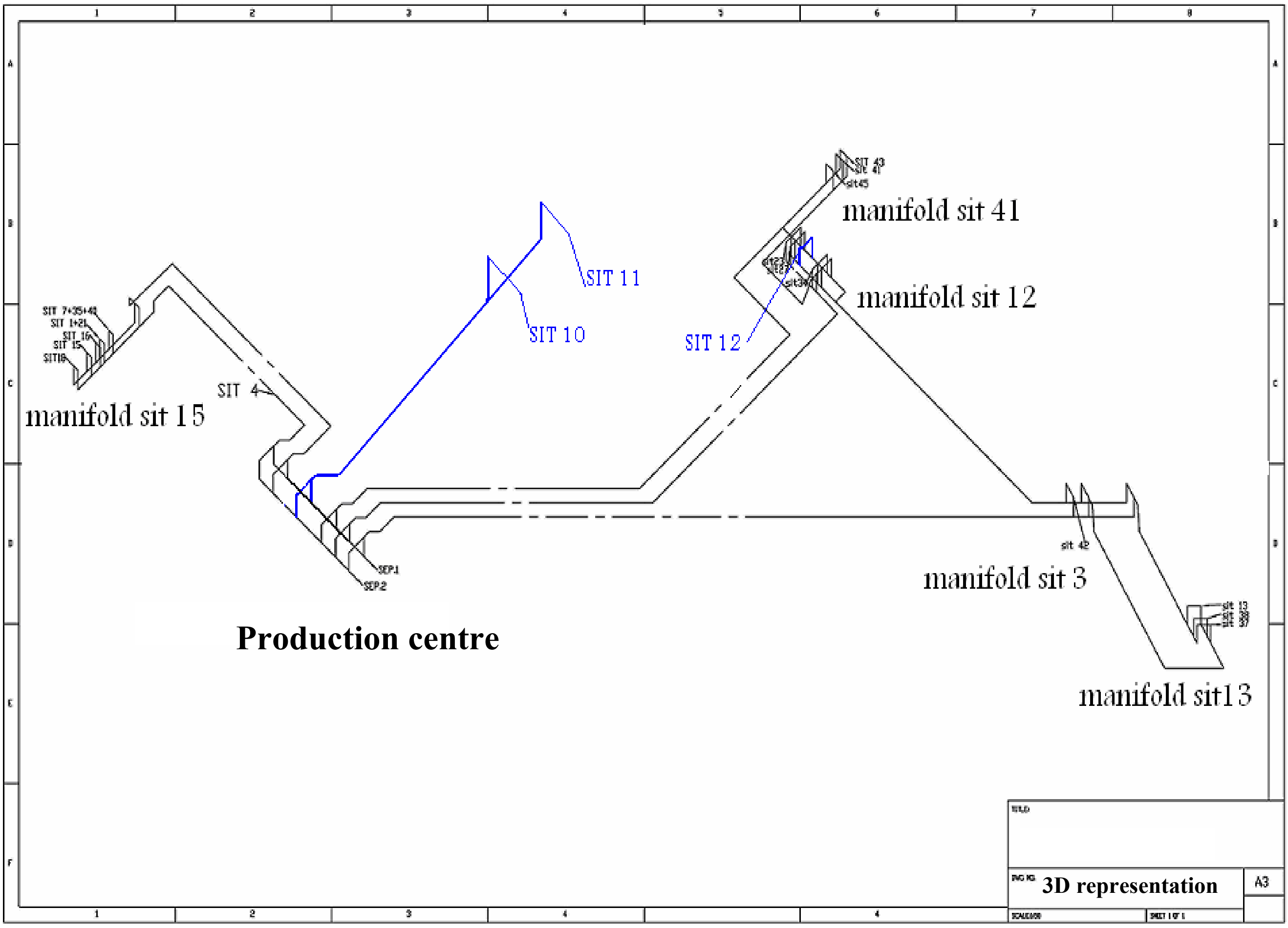

Figure 6. Pipe network of the FTOC (3D representation).
Slika 6. Cevovodna mreža FTOC (3D prikaz).

Table 1. Production of network wells.
Tabela 1. Proizvodnja mrežnih bušotina.

Well N°	Corresponding nodes	Discharge (m^3/h)
SIT 18	2	–18.36
SIT 15	7	–7.92
SIT 16	10	–10.08
SIT 1+21	15	–47.16
SIT 7+35+40	18	–67.68
SIT 4	42	–16.56
SIT 13	47	–18.72
SIT 38	52	–24.12
SIT 37	55	–10.44
SIT 42	73	–18.72
SIT 41	140	–10.8
SIT43	143	–16.2
SIT 45	135	–55.8
SIT 23	113	–14.76
SIT 27	122	–7.2
SIT 34	117	–14.4

Table 2. Pressures at nodes of the network.
Tabela 2. Pritisci u čvorovima mreže.

		Pressure (bar)	
Well N°	Node N°	Measured	Computed
SIT 18	2	5	5.00
SIT 15	7	5	4.99
SIT 16	10	5	4.99
SIT 1+21	15	5	5.00
SIT 7+35+40	18	5	5.00
SIT 4	42	5	4.20
SIT 13	47	7	7.72
SIT 38	52	7	7.72
SIT 37	55	7	7.72
SIT 42	73	8	7.62
SIT 41	140	7	7.98
SIT43	143	7	7.98
SIT 45	135	7	7.99
SIT 23	113	7	7.74
SIT 27	122	7	7.74
SIT 34	117	7	7.74
Production centre		2.8 to 3.3	3.4 to 3.5

Also head losses and discharges summarisations are presented in Table 3. The results well satisfy the condition of security since the velocity, in all pipes as indicated in Fig. 7, is less than 6 m/s. The maximum velocity is 3.39 m/s and is produced in the pipe number 103.

Table 3. Velocities at nodes of the actual network.
Tabela 3. Brzine u čvorovima stvarne mreže.

N° pipe	Discharge (m^3/h)	Head loss (m)	Velocity (m/s)	λ (–)
100	167.525	0.0772	2.50	0.0265
101	21.475	0.0109	0.73	0.0308
102	21.475	0.0121	0.73	0.0308
103	100.331	0.0955	3.39	0.0297
104	78.856	0.1426	2.67	0.0298
105	22.308	0.0118	0.75	0.0307
106	90.344	0.1958	3.06	0.0298
107	100.331	0.0377	1.49	0.0267
108	100.331	0.2963	1.49	0.0267
109	100.331	39.1165	1.49	0.0267
110	100.331	45.8204	1.49	0.0267
111	68.036	0.1115	2.30	0.0299
112	49.126	0.2066	1.66	0.0300
113	118.634	0.1376	1.77	0.0266
114	152.316	0.0639	2.27	0.0265
115	33.682	0.0265	1.14	0.0303
116	33.682	0.0294	1.14	0.0303

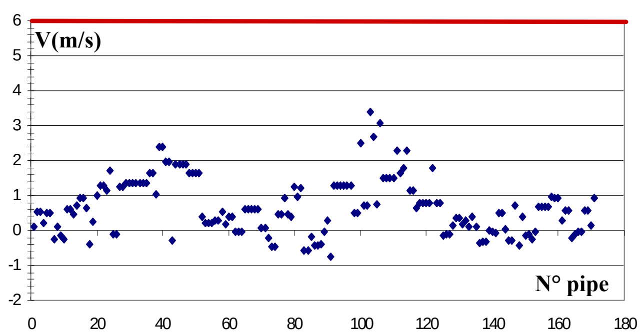

Figure 7. Velocity in the pipes of the actual network.
Slika 7. Brzina u cevovodima stvarne mreže.

SIMULATION OF THE NEW PLANT

The FTOC suggest increasing oil production by adding new oil wells and augmenting discharges by using electrical pumps.

The branching of new oil wells (SIT 10, SIT 11 and SIT 12) to the actual network given in Fig. 6 and the conversion of handling pumps into electrical pumps permit to increase oil flow capacities of the manifold sits SIT 35, SIT 41 and SIT 42. The new production is presented in Table 4.

However, the velocity in the pipe line SIT 10 – production centre, for the discharge $Q = Q_{SIT10} + Q_{SIT11} =$ 493.2 m^3/h, equals 7.36 m/s. So, before computing the network with the new productions, we have proposed to install, in parallel, a second pipeline as shown in Fig. 8.

Table 4. Increasing of network well productions.
Tabela 4. Povećanje proizvodnje u mreži bušotina.

Well N°	Well discharges (m^3/h)			
	Oil	Water	Gas	TOTAL
SIT 18	0.32	6.68	11.36	18.36
SIT 15	0.2	0.73	6.99	7.92
SIT 16	0.175	3.7	6.205	10.08
SIT 1+21	0.85	16.4	29.91	47.16
SIT 7	0.875	15.125	30.625	46.625
SIT 4	0.382	2.685	13.493	16.56
SIT 13	0.42	3.33	14.97	18.72
SIT 38	0.625	1.625	21.87	24.12
SIT 37	0.25	1.125	9.065	10.44
SIT 42	**0.825**	**11.275**	**28.875**	**41**
SIT 41	**0.7**	**14.6**	**24.5**	**39.8**
SIT43	0.35	3.605	12.245	16.2
SIT 45	0.3	45	10.5	55.8
SIT 23	0.4	0.35	14.01	14.76
SIT 27	0.55	1.2	5.45	7.2
SIT 34	1.05	3.2	10.15	14.4
SIT 10	**0.5**	**15**	**35**	**66**
SIT 11	**11**	**31.2**	**385**	**427.2**
SIT 12	**3**	**7.3**	**105**	**115.3**
SIT 35	**1.5**	**10.55**	**52.5**	**64.55**
SIT 40	0.3	3.325	10.05	14.4

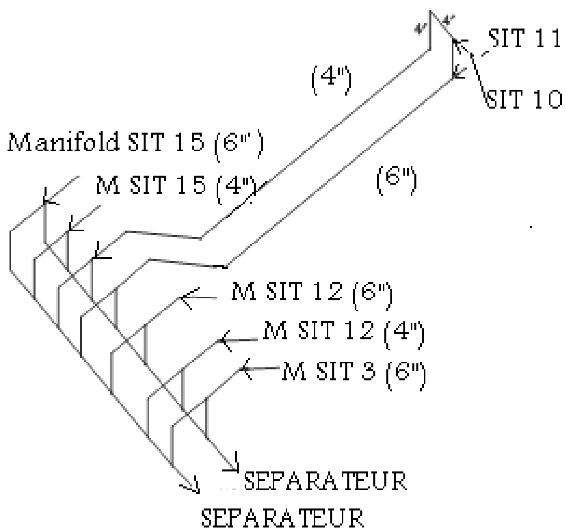

Figure 8. Modification of the actual network.
Slika 8. Modifikacija stvarne mreže.

The computed results, obtained for the modified network by the Hardy Cross method, are shown in Fig. 9. These results show that the security condition ($V < 6$ m/s) is not satisfied for the selected pipes in Table 5.

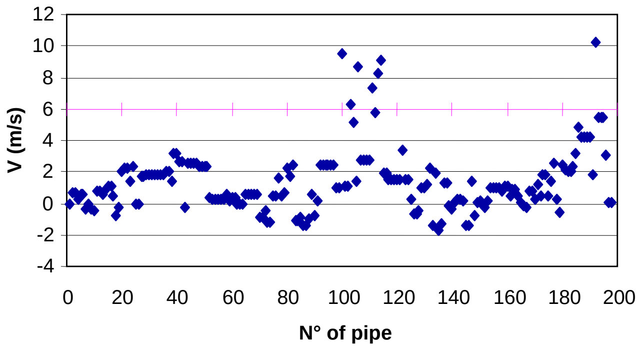

Figure 9. Velocity in the pipes of the modified network.
Slika 9. Brzina u cevovodima modifikovane mreže.

Table 5. Pipes where the security condition is not satisfied.
Tabela 5. Cevovodi kod kojih uslov sigurnosti nije ispunjen.

N° pipe	Discharge (m^3/h)	Head loss (m)	Velocity (m/s)	λ (–)
100	638.633	1.1107	**9.51**	0.0262
103	186.041	0.3270	**6.29**	0.0296
106	257.846	1.5837	**8.72**	0.0295
111	214.852	1.1004	**7.27**	0.0296
113	557.353	1.1971	**8.30**	0.0262
192	301.502	2.0658	**10.20**	0.0295

For the previous modifications (new wells, new discharges, installing a second pipe SIT 10 – production centre) the network is no more conform to ISO norm since the velocity is larger than 6 m/s and may provoke an effluent fire. Actually, the effluent viscosity together with relative velocity causes shear stresses acting between the fluid layers and produces heat /5/. So, mechanical energy is steadily degraded into thermal energy and may set fire to the transported oil.

PROPOSED SOLUTION

It can be established that the pipes, where the security condition is not verified (Table 5), are localized in the production centre.

To reduce velocity, we have proposed, in addition, the following modifications:

– pipe N°103 (D = 4”) changed pipe of diameter 6”,
– pipe N°192 (D = 4”) changed pipe of diameter 6”,
– connecting to the third separator as shown in Fig. 10.

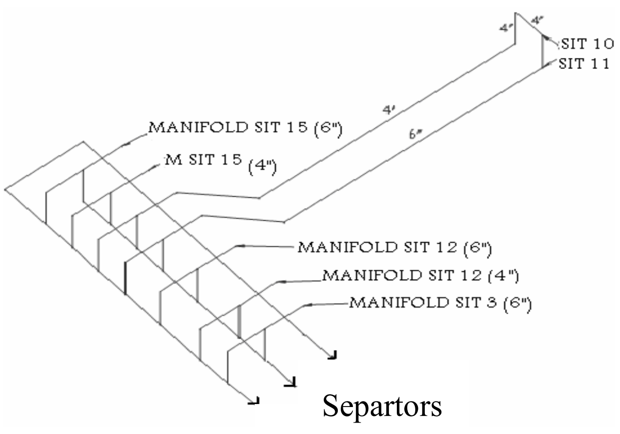

Figure 10. Connecting of an oil well to the third separator.
Slika 10. Povezivanje naftne bušotine na treći separator.

The computed results issued from the Hardy Cross for the proposed solution, are presented in Fig. 11. It can be seen that the change of pipe diameters and the connection of one oil well to the third separator yields to velocities less than 6 m/s in all the pipes of the FTOC network.

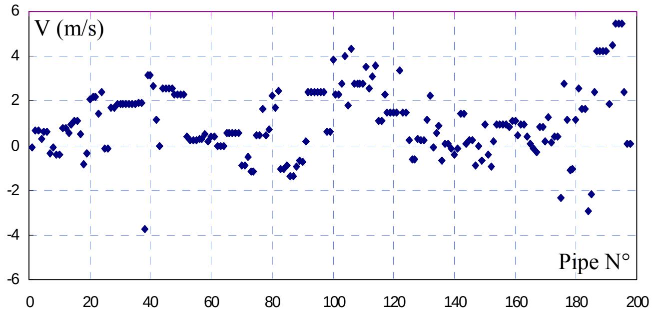

Figure 11. Computed velocity in the pipes network for the proposed solution.
Slika 11. Izračunate brzine u cevovodnoj mreži za predloženo rešenje.

CONCLUSION

In the present study, security anti-fire analysis of the Franco-Tunisian Oil Company network has been performed using the Hardy Cross Method. This method simulates steady flow in pipe network of liquids or gases under pressure. The security condition considered here is that the velocity in each pipe of the network must be less than 6 m/s. When this condition is not satisfied, fire can be provoked in the pipe system. For the actual network, the results show that the condition of security is well satisfied. However, if the oil production should be increased by adding new oil wells and by using electrical pumps, the computed results issued from the Hardy Cross Method give, for the pipes near the production centre, velocities larger than the security.

From the results it is found that proposed modifications of the actual system significantly affect the characteristics of the flow in the pipe network and the velocities in all pipes are reduced below the limit value of security.

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