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THERMO MECHANICAL FATIGUE ANALYSIS OF MOLECULAR SIEVE GAS DRYERS
TERMOMEHANIČKA ANALIZA ZAMORA MOLEKULARNE FILTER GASNE SUŠARE

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Keywords
- gas dryer
- numerical simulation
- thermomechanical fatigue

Abstract

In this work, we are interested in an analysis of thermo mechanical fatigue on a molecular sieves gas dryer. This analysis is designed to predict the behaviour of the material and especially the continued evolution of the stress in the four phases of work of this dryer. We have considered in this study the effect of temperature fluctuations on the production and the location of a crack. After verification of the molecular sieve dryer by ASME code, the stress variations as a function of time, in a node located in the area of the crack, are numerically simulated by ABAQUS software. The results of this analysis permit to determine that the theoretical number of cycles may not be exceeded using the Wöhler curve and taking into account all the safety and correction factors.

Ključne reči
- gasna sušara
- numerička simulacija
- termomehanički zamor

Izvod

U ovom radu, analizira se termomehanički zamor na primeru gasne sušare sa molekularnim filterom. Ovom analizom je predviđeno ponašanje materijala, a posebno kontinualni razvoj naponskog stanja u okviru četiri faze rada ove sušare. U ovoj studiji, razmotrili smo uticaj temperaturnih fluktuacija na formiranje i lokaciju prsline. Posle verifikacije molekularne filter sušare prema ASME standardu, urađena je varijacija napona u funkciji vremena, za čvor lociran u oblasti prsline, i to numeričkom simulacijom softverskim paketom ABAQUS. Rezultati ove analize dozvoljavaju da se odredi teorijski broj ciklusa koji se ne sme prekoračiti prema Velerovoj krivoj i uzimanjem u obzir sve stepene sigurnosti i korekcione faktore.

INTRODUCTION

Currently, the discovery of large deposits of natural gas has encouraged people to spread the use of this gas being relatively cheap compared to oil prices. The use of this gas is very diverse. It is used in the field of transport in the medical field, in the domestic sphere, etc. One of the largest companies producing natural gas in Tunisia is the company 'British Gas Tunisia'. It provides more than 60% of gas requirements from Miskar deposit, located 125 km off the Gulf of Gabes. Natural gas is transported by pipeline to the reservoir Miskar treatment plant land called 'Hannibal'. In this station, the gas undergoes processing and purification before being used. It eliminates various impurities from gas fuel such as hydrogen sulphide H_2S, carbon dioxide CO_2 and N_2. After removing these impurities, they proceeded to dry natural gas. This is important because it determines the degree of purity of natural gas. The drying operation is performed by dryers that are in most cases pressure tanks, providing gas dehydration by removing a definite percentage of water vapour, according to the needs and the process adopted. The selection of the dryer is determined, firstly, by the requirements of the customer (product quality, drying capacity, production rates, etc.) and, secondly, by working conditions (pressure, volume flow, mass, acidity, gas, etc.). For this, there is a large variance in the design of these dryers and also in the technique used for drying. The design of these devices is in accordance with ASME code, /1/. For this standard, particularly the clauses relating to the design of aircraft under pressure, the details of the choice of the plate, the means of assembly are very severe. These criteria take into account the dynamic and thermal changes during the purification process. While this standard is strictly adhered to by British Gas, cracks on gas dryer molecular sieves are found, /2/. Hence, the importance of this study is to make a numerical simulation taking the actual conditions of work in order to know exact causes of this failure and the effect of thermo-mechanical stress in the global structure. Since the change in temperature is cycle based, we will determine the number of cycles the dryer can be make before the appearance of any sort of cracks or damages under a given pressure and temperature fluctuations.

DESCRIPTION OF MOLECULAR SIEVE GAS DRYERS

Utility of gas dryers

Gas dryers, in most cases, are pressure tanks providing gas dehydration by removing a definite percentage of water vapour. Here, the dehydration operation (or drying) is the removal of water vapour contents in the natural gas. In fact the industry that deals in treating of this type of gas has recognised that dehydration prevents the formation of gas hydrate and reduces the rate of corrosion in pipes and in all equipment operating in the processing circuit. For this reason, several methods are developed to dehydrate the gas and to ensure a smooth transmission through pipelines. The method of dehydration used here is the adsorption technique with molecular sieves.

Description of molecular sieve

The molecular sieve is a crystalline form of alkaline metal (calcium or sodium) and it is very similar to natural clay (see Fig. 1).

Figure 1. Different types of molecular sieves.
Slika 1. Različiti tipovi molekularnih filtera.

This type of dryer has a large surface area and is very porous, with a very narrow range of pore size which acts as extremely effective sites for adsorption of polar compounds such as water and hydrogen sulphide. The dehydration process is not continuous and sometimes dryers are saturated with water vapour which creates an unacceptable level of water in the output. So, regeneration will be necessary as to dehydrate the molecular sieves and make them ready to enter a new cycle. The regeneration process consists of two phases:

– Hot phase: during this phase the molecular sieves are subjected to a hot stream of dehydrated gas to absorb the water trapped in them. The molecular sieve regeneration temperature in this phase is very high and it can exceed 300°C.

– Cold phase: during this phase a cold gas will flow through the molecular sieves to cool and return them to their original state.

The fluctuation in temperature between the hot phase and the cold phase can cause a problem of thermal fatigue of the gas dryer.

DESCRIPTION OF THE PROBLEM

On April 25, 2008, during an ordinary inspection of the natural gas dryer D0601B (see Fig. 2), a crack at the interior weld inside the manhole M1 was observed (see Fig. 3). The crack propagated almost the entire circumference of the connection between the head of the dryer and the manhole M1 (Fig. 4).

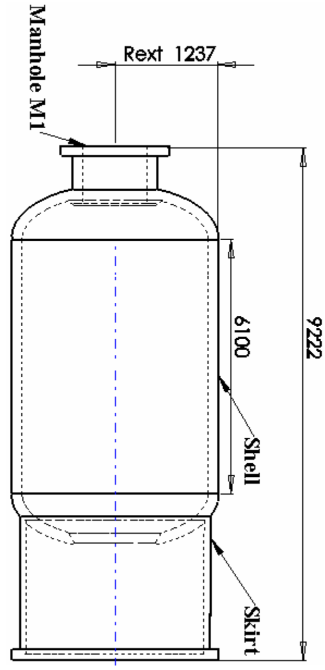

Figure 2. The drafting of DO601 B.
Slika 2. Skica i gabariti DO601 B.

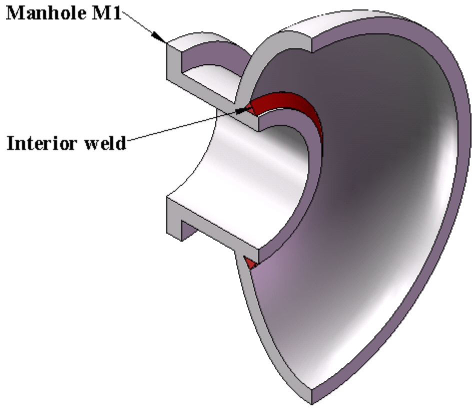

Figure 3. Localisation of the interior weld.
Slika 3. Lokalizacija unutrašnjeg šava.

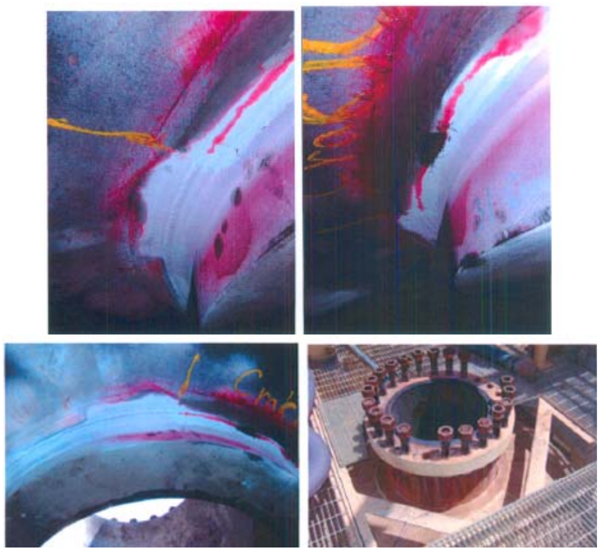

Figure 4. Localisation of cracks in the manhole M1.
Slika 4. Lokalizacija prslina na otvoru M1.

Figure 5 shows dryers D 0601 A and D 0601 B which are in the adsorption cycle and dryer D 0601 C in a regeneration cycle.

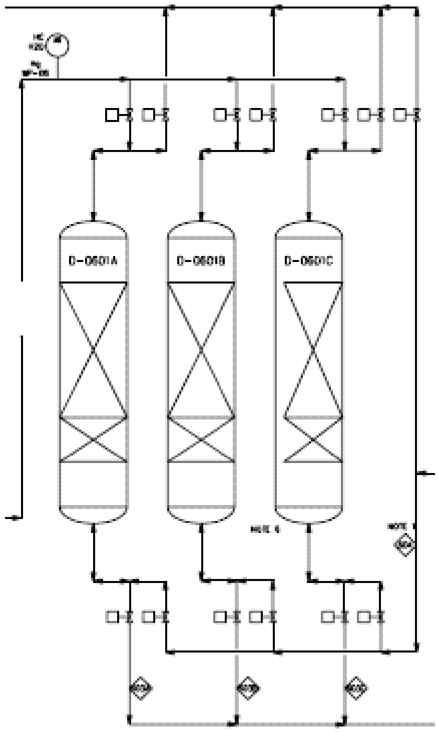

Figure 5. Dryers of the processing circuit.
Slika 5. Sušare u kolu procesa.

MANNER OF OPERATION OF D 0601 B

As said previously, the D 0601 B is a natural gas dryer and its role is to dehydrate the natural gas and adsorb the water. To accomplish this role, the molecular sieve must be exposed to three principal phases.

- Phase of adsorption: It lasts 70 hours during which the gas passes continuously through the molecular sieve beds. At the exit of the D 0601B the gas is completely dehydrated. For this phase, $p = 66$ bar and $T = 36°C$.
- Phase of regeneration: It consists of three sub-phases:
  – Warm-up phase. After the adsorption phase, molecular sieves are saturated with water vapour, for this reason we need the warm-up phase that lasts 10 hours during which the molecular sieves will be subjected to a flow of hot gas at 290°C for dehydration and renew their absorptive capacities.
  – Cooling phase. After warm-up phase, molecular sieves are at very high temperatures which can increase the temperature of the gas if it comes back into a cycle of adsorption. For this reason we need a cooling phase which lasts 5 hours to cool these molecular sieves to their initial temperature (36°C).
  – Waiting phase. Dryers work alternatively which always puts two dryers in the adsorption phase and the third in the waiting phase. During this phase, which lasts 5 hours, the gas is trapped in the dryer which raises its temperature to 46°C. The gas pressure in the waiting and cooling phases equals to 66 bar.

Figure 6 shows the evolution of temperature during the four phases. The diagrams in this figure will explain the alternation between the three dryers D-0601 A/B/C by adopting a lag of 20 hours between them from the very first start. Note that the cycles of absorption and regeneration are fixed while the waiting phase ranges on a periodic basis (5-35-5 hours).

A complete cycle is defined as a cycle including the adsorption phase, the regeneration phase (heating + cooling) and the waiting phase, which will create two different complete cycles through the periodicity of the time of the waiting phase. In fact, the first cycle lasts 90 h and the second takes 120 h.

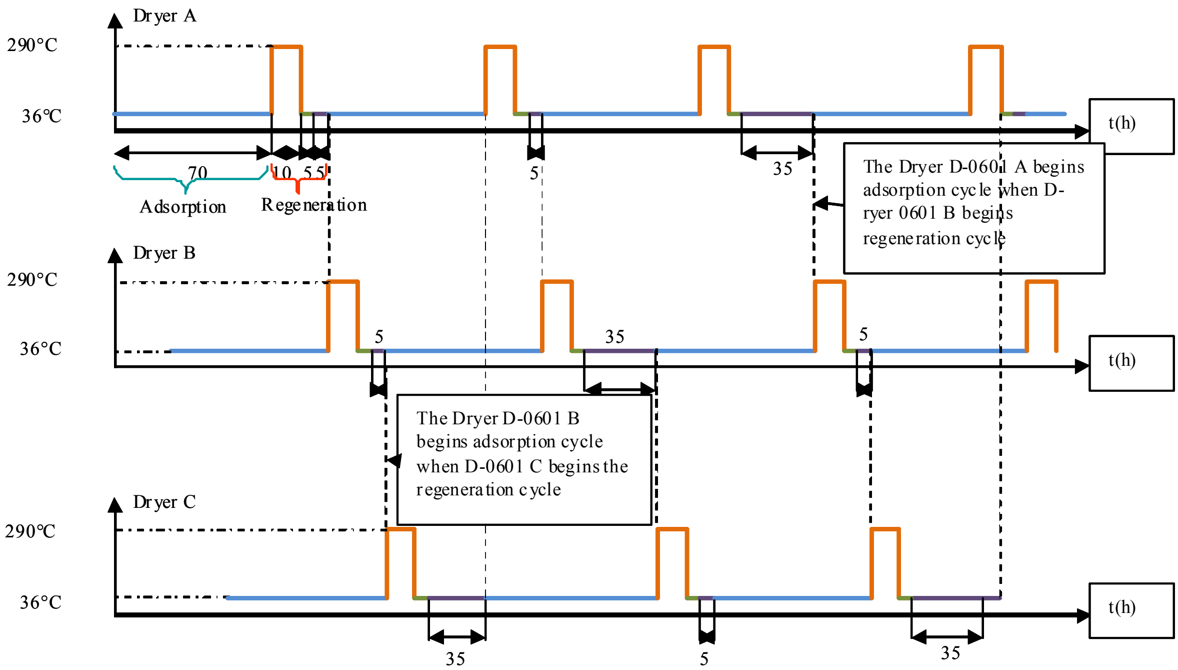

Figure 6. Gas dryer operation scheme.
Slika 6. Shema operacija gasne sušare.

Table 1 shows pressures and temperatures of gas at the inlet and the outlet of the dryer D-0601 B during the adsorption and regeneration cycles (heating). It is noted that the variation in temperature between the entrance and the exit of the dryer for each cycle is almost negligible.

Table 1. Physical properties of gas.
Tabela 1. Fizičke osobine gasa.

	Adsorption phase		Regeneration phase	
	Inlet	Outlet	Inlet	Outlet
Pressure (bar)	65.5	64.8	64.1	63.5
ΔP (bar)	0.7		0.6	
Temperature (°C)	36.8	36.5	287.8	286.1
ΔT (°C)	0.3		1.7	
Adopted values	Pressure (bar)	66	Pressure (bar)	66
	Temper. (°C)	36	Temper. (°C)	290

VERIFICATION OF DRYER DESIGN BY ASME CODE

Design parameters of the dryer D-0601 B are verified by using ASME code (edition 1987) because this dryer is built in 1994 and is manufactured and certified according to this edition. At the same time this verification is needed as a basis for analysing thermomechanical fatigue. The calculation of design pressure is done for verification reinforcements at the manhole M1 and the values of principal stress at the cylindrical part of the dryer are also given.

The design pressure or maximum allowable working pressure is the most important factor to check for any pressure vessel. Checking here will be based on formulas given in the ASME boiler and pressure vessel code, /1/. The ASME code establishes the design pressure for pressure vessels internally by the following rule: "The maximum allowable working pressure of a cylindrical tank side surface should be the minimum pressure of three values":

$$p=\left[\min\left\{\frac{SEt}{R+0.6t}=82\text{ bar}\quad\frac{2SEt}{R-0.4t}=176\text{ bar}\quad\frac{SEt}{R+0.1t}=85\text{ bar}\right\}\right] \quad (1)$$

where t = 81 mm is the wall thickness; R = 1143 mm is the inside radius of the cylindrical tank; S is the maximum allowable stress of the material (S = 121 MPa); and E is the efficiency of the joints (E = 1). The minimum is p = 82 bar which is the same as that set by the manufacturer of the dryer as the design pressure. So dryers can handle the pressure of gas (66 bar) without any problem.

By noting p = 66 bar the work pressure; R_i = 1143 mm the inner radius of the cylindrical part of the dryer; and R_e = 1224 mm the outer radius of the cylindrical part of dryer, the three principal stresses are:

$$0\leq\sigma_{rr}=p\frac{R_i^2}{R_e^2-R_i^2}\left(1-\frac{R_e^2}{r^2}\right)\leq-p=-6.6\text{ MPa}$$

$$90\text{ MPa}\leq\sigma_{\theta\theta}=p\frac{R_i^2}{R_e^2-R_i^2}\left(1+\frac{R_e^2}{r^2}\right)\leq 96.6\text{ MPa} \quad (2)$$

$$\sigma_{zz}=p\frac{R_i^2}{R_e^2-R_i^2}=\frac{\sigma_{\theta\theta_{\min}}}{2}=45\text{ MPa}$$

These stresses are related only to the pressure and the geometry of the dryer and they do not take into account thermal stresses due to temperature variation in the dryer.

We note that the circumferential stress is the larger, which usually favours the appearance of longitudinal cracks but this is not the case since the crack of D-0601 B is circumferential. Then, the question which arises here: what is the origin of the crack and what are the factors involved in their appearances.

NUMERICAL SIMULATION OF THE DRYER BY ABAQUS CODE

We saw in the previous section that the static calculations do not account for changes in temperature and may not lead to results that can help us to solve the problem.

The analytical calculation of thermal stresses is very difficult if not impossible, especially in the case where there is a coupling between the mechanical loads (pressure, constraints imposed by the pipeline) and thermal load (cyclic variation in temperature), then we must seek a computational tool that will allow us to solve this problem.

The solution will be obtained with ABAQUS software which is more sophisticated than the COSMOS-WORKS as it can solve similar problems.

Description of the dryerD-0601 B

Figure 7 shows the dryer D-0601 B in three dimensions. In fact this dryer is composed of two manholes M1 and M2, a nozzle N2, a bracket-shaped skirt and dryer housing comprising a head, one bottom and cylindrical side part.

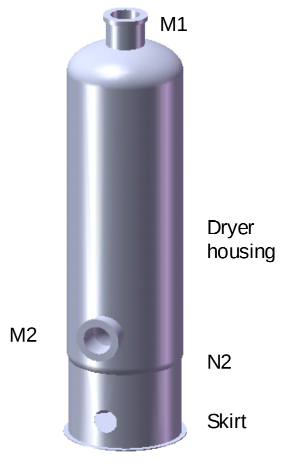

Figure 7. The dryer D-0601 B.
Slika 7. Sušara D-0601 B.

- M1 is the connection between the gas transmission pipe and the dryer.
- M2 is a manhole which is intended as an entry port at an inspection operation.
- N2 is a nozzle that is mounted on the bottom of the dryer and represents a connection between the dryer and piping associated with it. It acts as an outlet for gas phase adsorption, so it turns into a hole during cyclical heating and cooling.
- The skirt is a mounting bracket dryer which is itself attached to a field hardened.
- The body of the dryer is formed of a head, a bottom and a cylindrical side portion, that is itself divided into two cylindrical parts welded circumferentially.

Thermal and mechanical characteristics of the dryer

In this section we will give all the mechanical and thermal components of the dryer by entering the nuances of materials, their yield, maximum and permissible stresses. Table 2 shows the grades of materials for each component of the dryer while Table 3 provides the mechanical and thermal characteristics of these materials within three working temperatures (36°C, 46°C, and 290°C).

Table 2. Materials for each component of the dryer.
Tabela 2. Materijali svake komponente sušare.

	SA 516 Gr 70	SA 105 N
Dryer housing	•	
Skirt mounting	•	
Manhole M1		•
Manhole M2		•
Nozzle N2	•	

Table 3. Mechanical and thermal characteristics of dryer materials at 36°C, 46°C and 290°C.
Tabela 3. Mehaničke i termičke karakteristike materijala sušare na 36°C, 46°C i 290°C.

	SA 516 Gr 70			SA 105 N		
	36°C	46°C	290°C	36°C	46°C	290°C
σ_e (MPa)	260			248.22		
E (GPa)	202.7	202.8	186	200.6	200.2	184.8
ν	0.29			0.29		
ρ (kg/m^3)	7830	7830	7800	7810	7810	7790
λ (W/m°K)	60.013	59.77	49.81	60.013	59.77	49.81
α (1/°C)·10^6	11.7	11.82	14.67	11.7	11.82	14.67

Both materials SA 516 Gr 70 and SA 105 N are classified in the ASME section 8 div. 1 as carbon steels and in the ASME section 8 div. 2, which defines the thermal characteristics of materials, as materials of group A. For this reason, they have the same thermal characteristics.

Numerical simulation of the dryer D-0601 B

In this section we will look at the numerical simulation of the dryer D-0601 B in respect of the working phase of this dryer and the mechanical and thermal loads that are imposed. First, we will assign to each component of the material their mechanical and thermal characteristics which are: the Young's modulus E, the density of the material ρ, the thermal conductivity λ and the coefficient of thermal expansion α.

Next, we will introduce all phases of work of the dryer D-0601 B with their operating times. These phases are listed below in chronological order:

- Adsorption phase lasts 70 hours, during which the gas temperature is equal to 36°C. In this phase the gas enters the manhole M1 and exits through the nozzle N2.
- Warm-up phase lasts 10 hours, during which the gas temperature is equal to 290°C. In this phase the gas enters the nozzle N2 and exits through the manhole M1.
- Cooling phase lasts 5 hours, during which the gas temperature is equal to 36°C and the direction of flow of gas is the same as in the warm-up phase.
- Waiting phase that lasts 5 or 35 hours of an alternate way (see Fig. 6). During this phase the gas is trapped in the dryer and its temperature rises to 46°C thanks to the heat trapped in the molecular sieve which will be released during this phase.

The pressure in the four phases is constant and equal to 66 bar. Even if there is a pressure variation it does not exceed 1 or 2 bar.

After the assignment of different work here, we shall apply the mechanical loading. In this case, the gas pressure is applied to the inner wall of the dryer and the heat load is the heat flux carried by the natural gas and which consequently raises or lowers the temperature of the material of the dryer.

Figure 8 shows the coefficient of heat transfer h of different types of natural gas as a function of the mass fraction of gas vapour x_v.

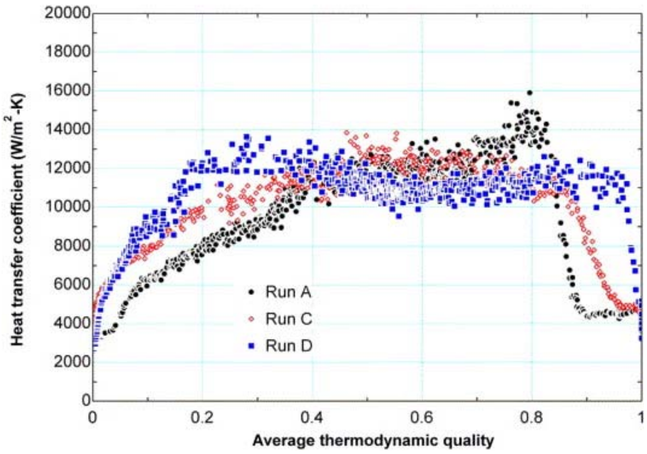

Figure 8. Coefficient of heat transfer h in terms of x_v.
Slika 8. Koeficijent prenosa toplote h u zavisnosti od x_v.

The natural gas flowing into the dryer D-0601 B has the same chemical composition as gas type D which has a mass fraction of vapour equal to $x_v = 1$. So the coefficient h in our case is equal to 3000 W/m^{2}K.

The meshed model is the last step before the simulation. The dryer system is subdivided into small volumes of controls. We have here used tetrahedral elements with more dense mesh in the weld area to ensure good results.

The tetrahedral mesh has four faces and six edges. This type of mesh has a high degree of freedom which enables it to mesh all the same geometric shapes so the joint control can be examined and the faults that may occur in the solder joint can be showed.

The Von Mises criterion is one of the most used criterion for materials and its correspondence with experimental results is very good. For this reason we choose it to define the equivalent stress in terms of principle stresses, /3/:

$$\sigma_{eq} = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \qquad (3)$$

The numerical results representing the four phases of work of the dryer are shown in Figures 9.

The figures presented above show the concentrations of stresses in different zones of the dryer with a scale factor of deformation equal to 167 times. In these figures the inclination of the dryer in the opposite side of the manhole M2 is very remarkable. In fact this angle shows the role of the manhole M2 as a supporting structure of the dryer and this effect cannot take place if the dryer is not properly reinforced.

We are mainly concerned by the stress value in the area of the crack. We choose one node from the area in order to visualize the stress variation in this node during the 4 phases of work.

Figure 10 shows a longitudinal section of the dryer D-0601 B and the location of the selected node.

The legend associated with Fig. 11 shows variation of:
- The main stress (S_{max}, S_{mid}, S_{min}), which are expressed in a main base for which the stress tensor is diagonal.
- Stresses (S_{ij}) expressed in the basis chosen by the software during the design of the numerical model.
- The equivalent stress from the criterion of Von Mises which is marked in mauve triangles.
- The equivalent stress from Tresca criterion.

It can be noticed from Fig. 11 that the equivalent stress does not exceed the limit of elasticity which is equal to 260 MPa. That means that the dryer works in the elastic state, but in some areas, the stress has exceeded the maximum allowable stress, which equals 121 MPa. This does not pose major problems because we are still in the elastic domain and these areas are very limited and tend to be concentrated in a very small number of nodes.

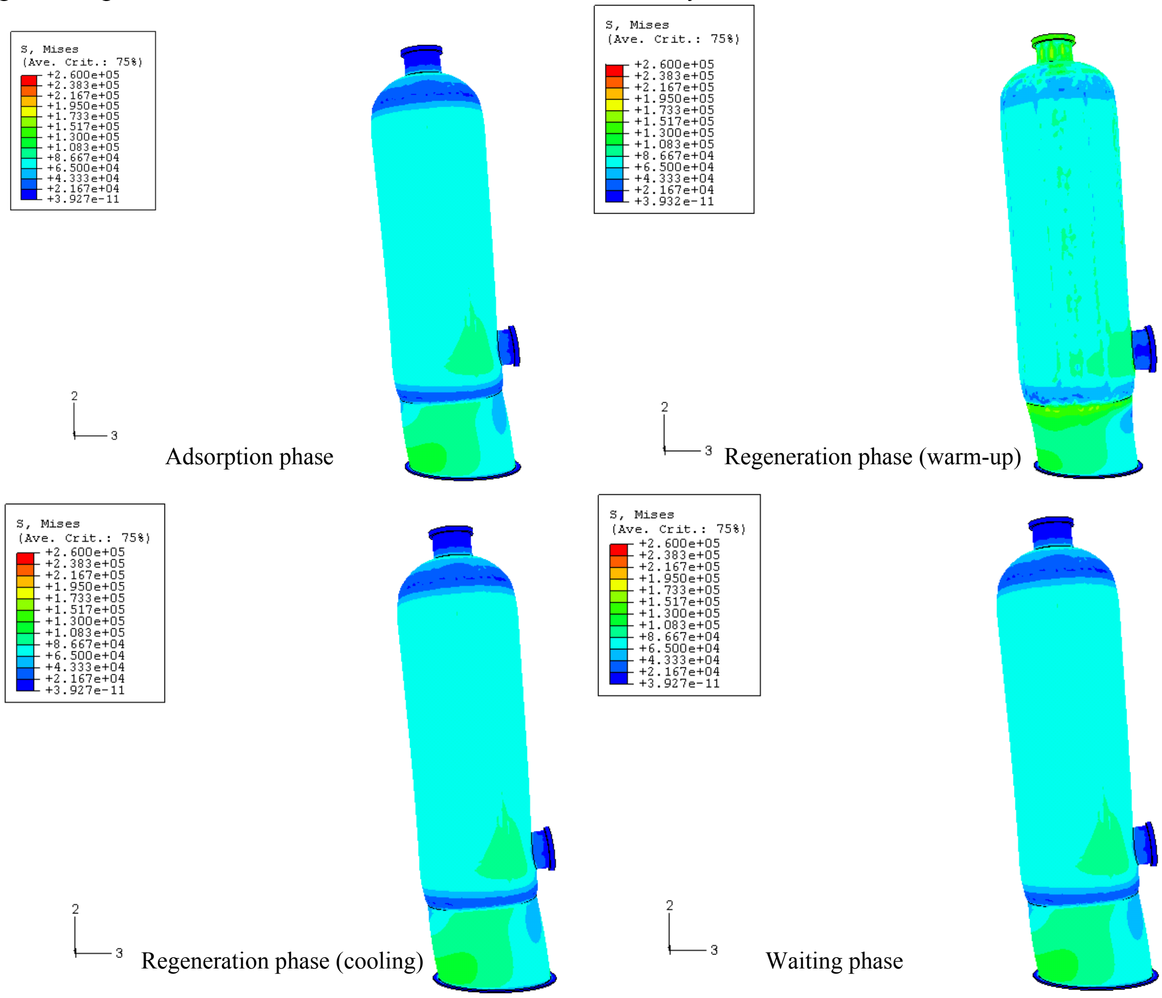

Figure 9. Stresses applied to the dryer in kPa for different phases.
Slika 9. Naponsko stanje sušare u kPa kod različitih faza rada.

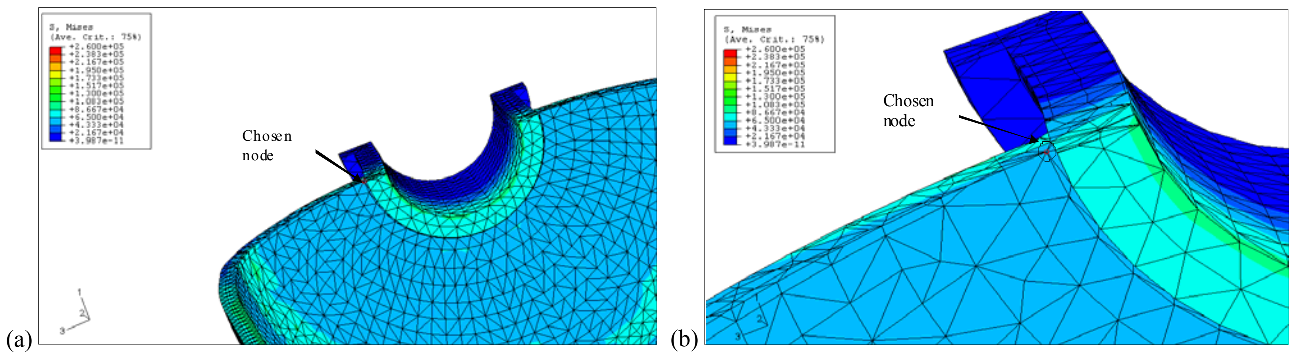

Figure 10. Concentration of the mesh at the crack area. (a) position of the node; (b) zoom in the area
Slika 10. Koncentracija mreže u oblasti prsline. (a) položaj čvora; (b) zumirana oblast.

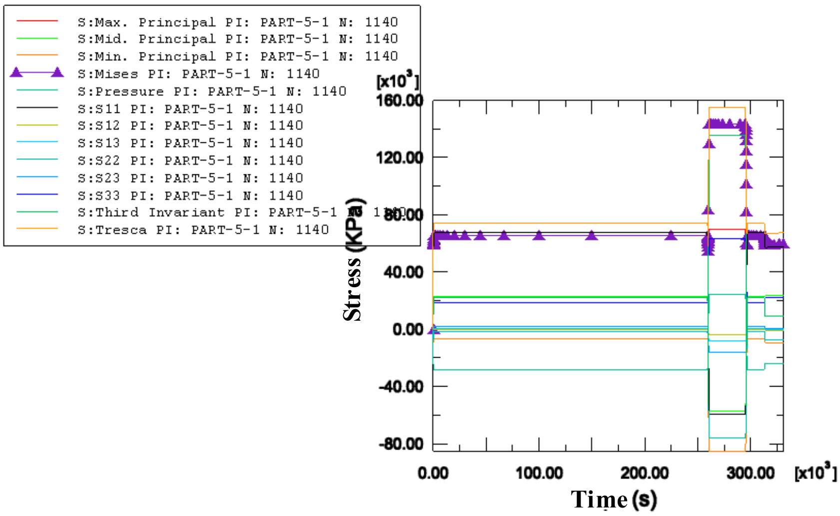

Figure 11. Variation of the different stresses with time.
Slika 11. Varijacija različitih napona sa vremenom.

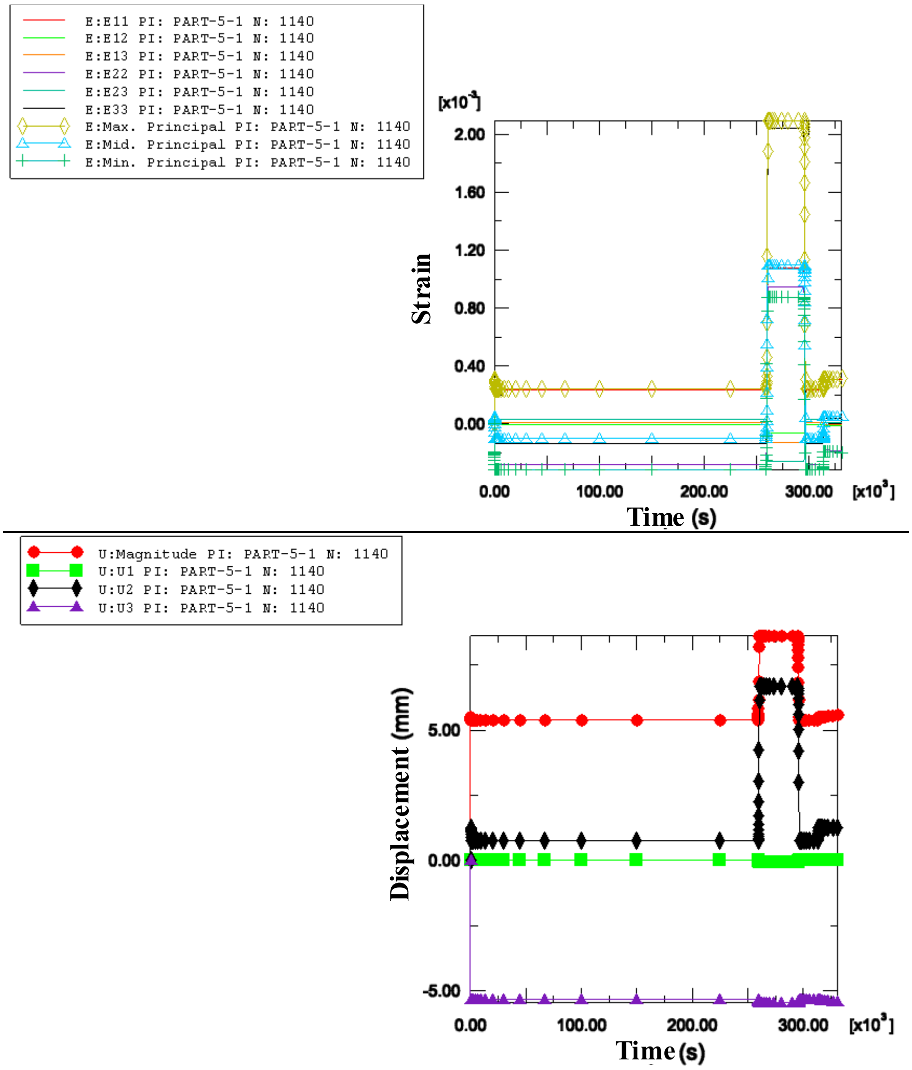

Figure 12. Variation of strains and displacements with time.
Slika 12. Varijacije deformacija i pomeranja sa vremenom.

We note that:

- For adsorption, cooling and waiting phases the equivalent stress is almost equal to 67 MPa.
- For warm-up phase the equivalent stress equals 140 MPa.

We note as well the general effect of elevated temperature on the value of the equivalent stress (it is almost double than that of the adsorption phase). So the problem of crack is thermal fatigue only.

Figures 12 represent the variation of strains and displacements with time to give an idea about the behaviour of the material in this node.

U_1, U_2, U_3 are the components of the displacement in three directions of coordinates shown in Figs. 9 and 10.

DRYER LIFE ESTIMATION

Analytical dryer life

For the dryer D-0601 B, the estimation of its life since fabrication is based on the corrosion rate per year which is equal to 0.08 mm/year. However, the maximum allowable corrosion thickness is here equal to 1.6 mm. Therefore, the life of the dryer D-0601B is equal to 20 years.

This estimate of life based only on the corrosion rate and maximum allowable thickness of corrosion is very far from reality, as an estimate of life must take into account several factors and the most important factor is the material fatigue, whatever its type (mechanical fatigue, thermal fatigue and thermo-mechanical fatigue).

The estimated life span according to the criterion of fatigue is based in most cases on the Wöhler curve. This curve connects the value of a purely alternating stress, exerted on a sample, to the number of cycles before failure /4/.

Figure 13 shows the Wöhler curve for carbon steels with a lower ultimate stress of 551.6 MPa and a temperature less than 371°C. This curve represents the magnitude of a cyclic stress (σ_a) against the logarithmic scale of cycles to failure (N_f). In the case of dryer D-0601B, the altered stress is σ_a = 140 MPa, the ultimate stress is σ_u = 485 MPa. So /4/:

$$\sigma_{a_{eq}} = \frac{k}{1/\sigma_u + 1/\sigma_a - \sigma_m/\sigma_a\sigma_u} \approx \frac{k\sigma_a}{1-\sigma_m/\sigma_u} = \frac{3\cdot 140}{1-103.5/485} 534 \text{ MPa} \quad (4)$$

where $\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} = \frac{140+67}{2} = 103.5$ MPa , k is a coefficient that equals 3.

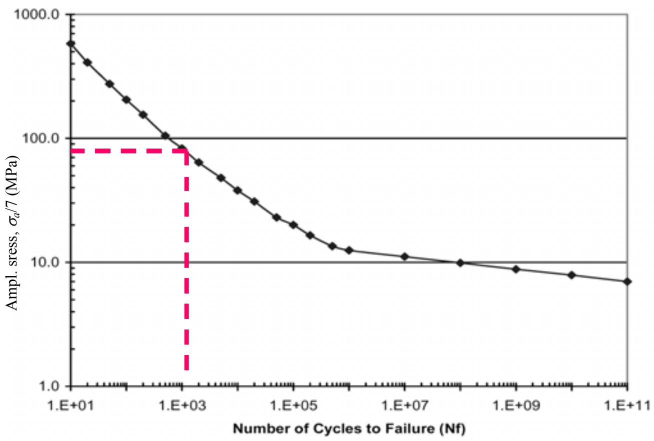

Figure 13. Wöhler curve for C steels (T < 371°C and σ_u < 550 MPa).
Slika 13. Velerova kriva za ugljenične čelike (T < 371°C i σ_u < 550 MPa)

Along the stress axis, the dashed (red) line shows the corrected equivalent alternating stress of 534.4 MPa and, along the axis of abscissas, the dashed (red) line shows the number of cycles performed by the dryer near the selected node. We note here that the number of cycles that can be implemented to the dryer based on the Wöhler curve equals 1200 cycles.

Experimental dryer life

The dryer goes through four phases of work. Let C be the cycle consisting of two successive cycles, then the length of C = 210 hours. The launch of British Gas was in 1995 and the date of the crack discovery was 25-04-2008. Thus the number of cycle C made by the dryer equals:

$$\frac{(2008-1995)(365)(24)+4(30)(24)+4(24)}{210} = \frac{116788}{210} = 556$$

And consequently the number of cycles performed by the dryer equals 556·2 = 1112 cycles. We note here that the number of cycles agrees with the number determined using the Wöhler curve.

CONCLUSION

We have shown in this paper the action of the gas flow on the behaviour of the dryer material in the zone where a crack is produced. It is clear that the 4 phases of work play an important role in thermomechanical fatigue problem to improve the life of the dryer. The numerical simulation results gave a good idea on the behaviour of the dryer during the 4 phases of work. These results show the stress variation as a function of time in a node located in the area of the crack. After verification of the molecular sieve dryer by ASME code, we concluded that the designers of this unit have complied with the requirements of this code. The analysis confirms that the thermomechanical fatigue cracking that occurred in the dryer is due to the cyclic variation in temperature under the given pressure. Under these conditions, the number of cycles, which is about 1200 before failure, has been determined from the Wöhler curve. This result is very real for the crack that occurred in the dryer that had suffered in 1112 cycles. This leads us to say that the approximation of life based on the corrosion rate is insufficient and that only cyclic analysis is necessary. In fact, this study represents a first step of simulation of the crack in dryer D-0601B without taking into account the pipes connected to it. The effect of these pipes cannot be neglected and should be soon studied.

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