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Tensometry Analysis of the State of Stress and Strain of a Heat Exchanger Submitted to a Hydraulic Pressure Testing

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Abstract

In order to eliminate the risk of predictable technical and operational unacceptable of mechanical structures such as welded construction cylindrical shells, pressurized inside, you need to quantify the effects of stress concentrators. This paper deals with an experimental analysis of the state of stress and strain. This paper is an experimental study to analyze the state of stress and deformation of specific structural elements within a cylindrical type heat exchanger pressurized. The main purpose of this paper is to highlight the state of tensions appeared in the set measuring points to the value maximum permissible working pressure and hydraulic pressure too. There were calculated the state of stresses and strains caused by internal pressure and also state of the residual stresses.

Key words: *tens meters, electro-resistive transducer, voltage, specific strain.*

Introduction

Determination at a point of stress and strain for a mechanical structure with electrical tensometry techniques are generally based on the transformation of the specific strain variation in a point, into a variation of electrical parameters (voltage) via an electronic transducer - strain gauge (resistive, inductive, capacitive or semiconductor).

Electro-resistive strain gauge, used in most cases as technical investigation of stress and strain, mechanical structures, is used in many practical engineering applications. This technique has the following advantages:

- allows measurement of specific strains of the order of 10-6m / m with high accuracy,
- transducers used are simple and relatively inexpensive (compared to other types of transducers), and
- measuring equipment is relatively simple.

In general, there are used electro-resistive transducers (electro-resistive strain gauge or tens resistive - TER) because of their simplicity, almost negligible mass, low-cost price, metrological parameters lift, high reliability, ease of application structure and precision and for the possibilities it offers in complicated and difficult working and loading conditions [1,2].

In this paper the authors propose to apply this technique to verify the measured resistance of cylindrical shell type equipment (Fig. 1) subjected to internal pressure, for a value of factor β:

$$\beta = \frac{D_e}{D_i} = \frac{2500}{2180} = 1.147\,. \tag{1}$$

where D_e and D_i are external diameter of the cylindrical part (exchange) and respectively, the internal diameter. The calculated stress state by shells theory is compared with that obtained by measurements, establishing the effect of the configuration change to the state of local stresses.

Theoretical Aspects

The relationships used to calculate the membrane tension state, axial (σ_1) and circumferential (σ_2) in a cylindrical shell subjected to internal pressure (p_c), are as follows [3]:

$$\sigma_1 = \frac{p_c \cdot R}{2 \cdot \delta}; \qquad \sigma_2 = \frac{p_c \cdot R}{\delta}\,, \tag{2}$$

where R is the median radius of the shell and δ, thickness of the shell.

Equivalent membrane stress (σ_{ech}) for flat application status is determined, for tenacious material with one of the theories of resistance, as follows:

- with the third theory of resistance

$$\sigma_{ech}^{III} = \sigma_{\max} - \sigma_{\min} \tag{3}$$

where σ_{max} and σ_{min} are maximum strain, respectively minimum strain,

- with the fourth theory of resistance

$$\sigma_{ech}^{IV} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}\,. \tag{4}$$

The pressure value for the hydraulic test is

$$p_{ph} = 1{,}25 \cdot p_c \cdot \frac{\sigma_a^{20}}{\sigma_a^{T}} \tag{5}$$

where σ_a^{20} is the allowable strength of the material at 20°C, and σ_a^{T} is the allowable strength of the material at working temperature.

The analyzed exchanger, made of steel P355GH/SR EN 10028-2/1996SR EN 10028 (welded), is designed to operate at the pressure p_c = 15.6MPa. Building material resistance values are: admissible strength at 20°C is σ_a^{20} = 180MPa, allowable strength of the material at working temperature is σ_a^{T} = 167.14MPa. Value of the hydraulic test pressure, according to relation (5), is p_{ph} = 21MPa.

If the exchanger functions with an internal pressure p_c, the stresses in wall are (rel. 2): $\sigma_2 = 2 \cdot \sigma_1$ = 113.36MPa and the equivalent strengths calculated by the two theories of resistance are:

σ_{ech}^{III} = 113.36MPa and σ_{ech}^{IV} = 98.173MPa. The both values are below allowable strength value at working temperature, which leads to the conclusion that the exchanger wall withstands to the applied internal pressure p_c = 15.6MPa.

If the exchanger functions with an internal pressure equal with the hydraulic test pressure, the tensions in wall are (rel. 2): $\sigma_2 = 2 \cdot \sigma_1$ = 152.6MPa. The equivalent hydraulic strengths are σ_{ech}^{III} = 152.6MPa and σ_{ech}^{III} = 164.63MPa. Both values are below allowable strength value at a temperature of 20°C: σ_a^{20} = 180MPa, which leads to the conclusion that the exchanger wall withstands to the hydraulic test pressure p_c = 21MPa.

Experiments

Organization of experiments

Conducting a study using electro-experimental analysis of the state of stress and strain in cylindrical welded shells of the pressure equipment is necessary to quantify the local effects of the stress (stress concentrators) in order to eliminate the technical predictable and unacceptable risk [4]. The experiments were made on a pressure vessel (heat exchanger) whose dimensional sketch (with the double measurement points P_i, i = 1, 2, ..., 34) is shown in Figure 1.

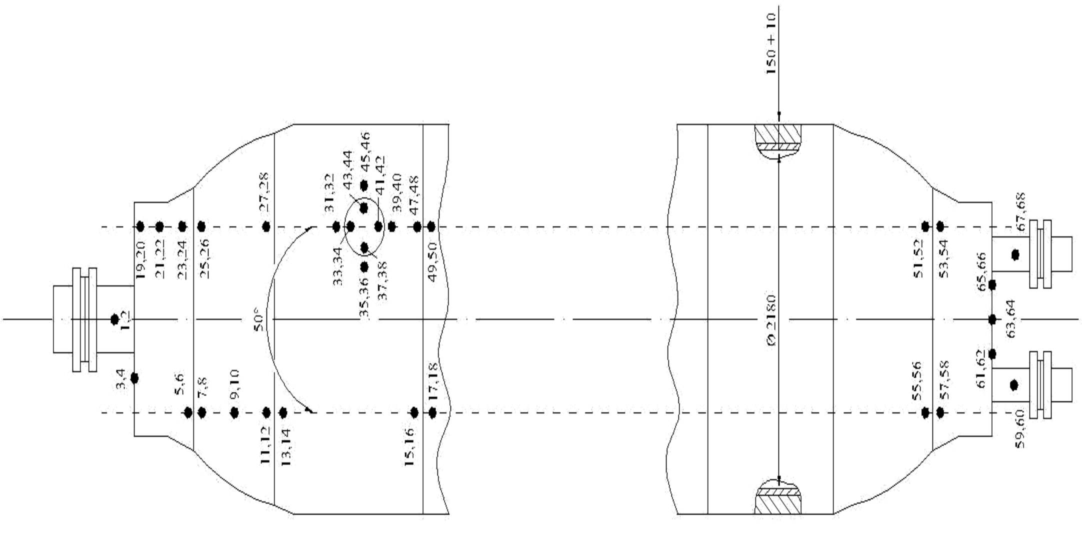

Fig. 1. Drawing with measurement points on the surface of the heat exchanger

In each of the 38 points chosen for measurement (marked on Figure 1) were installed two electro-strain gauge transducers for each main direction of stress (circumferential, odd numbered, and axial, even numbered).

There were performed two cycles of measurements of shell deformations arising as a result of pressure application:

- load in steps and
- to download at full load hydraulic test pressure, equal to the maximum allowable working pressure value and to complete discharge pressure.

In the first cycle, specific circumferential and axial deformations were measured for five ascending levels of pressure: 5, 10, 15.6, 20 and 21MPa.

In the second cycle, specific circumferential and axial deformations were measured for a hydraulic test pressure (21MPa), for the maximum allowable working pressure (15.6MPa) and for the complete discharge pressure.

Cycle of experiments revealed that the deformations occurring in measurement points, according to default steps of the pressure vessel, have proportional variations to pressure, and that at complete unloading in equipment residual deformations (residual) remain.

The equipment

For measurements electro-strain gauge transducers (also called strain gauges as stick on pieces like stamps) were used, having as basic element a wire-thin, seated in a kind of spiral (to be relatively large length to a small area) - forming grid sensor - on an insulating base (Fig. 2).

Metal wire, thicker in the connecting portions of its core areas, located along the grid has this geometry for a minimum influence in the transverse direction, on measurement results.

Global dimensions of resistive electro-strain gauge transducers are usually small, of the order of millimeters, that the area of the piece that read deformations, to be kept small. The Sticking of the marks in measuring points is done using special adhesives for these applications, and when the coating / studied piece (s) deforms under the action of loads to be borne, the transducers grids will deform together with small portions of the track that are stuck .

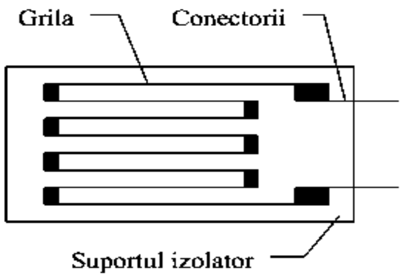

Fig. 2. Schematic drawing of an electro-resistive sensor

The operation of such a transducer is: the variations of the metallic wire size changes the electrical resistance and the intensity of a current which passes through it will have variations that can be read on a measuring device. In fact, the electrical signal will be proportional to the variations of the specific elongations "ε" products at the point of measurement, following the request applied.

An important issue is the accuracy of power measurements, because (especially for metal parts) specific deformations are very small and so will be also the current changes that will occur. It is necessary to use very sensitive measurement circuits, and currently they are montages Wheatstone bridge.

The measurement results were recorded, stored and processed using the latest data acquisition system, fully configurable MGCplus, with the following main features:

- allows user to configure the system as required by the standard built-in PC, PCMCIA slots and modular architecture;
- provides both analog measurement signal on each channel and a digital acquisition of high resolution;
- it works with any transducer (with strain gauges 1/1, 1/2, 1/4 bridge, inductive, piezoelectric, potentiometers, thermocouples, voltage, current, etc.);

- it comes with desktop chassis 19 "and allows mounting of maximum 16 modules;
- it uses interface (IEEE488, RS-485, RS-232, Ethernet, PC Card slot, hard drive, CANbus, Profibus DP), low-pass filters;
- it memories peaks;
- the acquisition rate is: 19200 values / second / channel, in parallel, it can be operated independently or via computer;
- the accuracy class is: 0.03%.

On a MGCplus device up to 128 points can be measured.

An internal PC with a Credit card collects data with o full speed up to 300,000 samples per second. All measuring signals can be captured in parallel, because each channel has its own converter A / D. In MGCplus no Sample & Hold or multiplexer device is used. This ensures continuous digital filtering and the highest possible stability of the signal. Using the Ethernet or USB interface, data is sent to an external computer or PLC.

Results

Among measurements there were presented only those who have interest (Table 1).

For experimental data processing (to calculate circumferential and axial stress presented in Table 1), relationships corresponding to the plane stress state [3, 5] were used:

$$\sigma_{cir} = \frac{E}{1-\mu^2}\left(\varepsilon_{cir} + \mu \cdot \varepsilon_{mer}\right); \quad \sigma_{mer} = \frac{E}{1-\mu^2}\left(\varepsilon_{mer} + \mu \cdot \varepsilon_{cir}\right), \tag{6}$$

where: ε_{cir} represents circumferential specific strain [µm/m]; ε_{mer} – axial specific strain, [µm/m]; E – longitudinal modulus ($2{,}1 \cdot 10^5$ MPa); $\mu = 0{,}3$ – transversal contraction coefficient or Poisson's ratio.

Conclusions

Analyzing the specific deformations measured in points P1 - P68, corresponding to maximum hydraulic pressure step (21MPa) and to the values circumferential and axial stress calculated with relations (6), as shown in Table 1, it is found that:

- the maximum value measured ($\sigma_{mer,\,max}$ = 209.1MPa) was obtained at the point P54, on axial direction, when the pressure increases to the hydraulic pressure;
- the maximum value measured ($\sigma_{mer,\,max}$) is about 77% of the yield strength at 20°C (for material P355GH according P355GH/SR EN 10028-2/1996SR EN 10028, σ_c^{20} = 270MPa) and residual values are insignificant.

The calculated stress values for the hydraulic pressure load (rel. 2), $\sigma_2 = 2 \cdot \sigma_1$ = 152.6MPa are lower than those obtained experimentally, σ_{cir} = 171.4MPa, σ_{mer} = 209.1MPa.

The state of strain in the exchanger wall, in operation and at hydraulic test, has different values from those calculated with relations (2) - (4), it shows increases in the areas where there are variations of geometry shell, welding seams etc., and theoretical relations for membrane stress should be replaced by some which take into consideration the influence of these factors. This means that it must be used the theory with bending moments and then it will be decided if the equipment resists to the pressure load.

Table 1. The measurement results

Measuring points P_i		$p = 21$ MPa			
		Specific strains		**Stresses**	
		ε_{cir} [μm/m]	ε_{mer} [μm/m]	σ_{cir} [MPa]	σ_{mer} [MPa]
1	2	-11	68	2,2	14,9
3	4	96	100	29,1	29,8
5	6	463	311	128,5	103,9
7	8	441	415	130,6	126,4
9	10	191	7	44,6	14,9
11	12	39,6	39,0	118,5	117,5
13	14	448	590	144,4	167,3
15	16	32	34	9,7	10,1
17	18	-10	-190	-15,5	-44,6
19	20	-219	-10	49,9	12,9
21	22	196	-1	45,2	13,4
23	24	410	561	133,6	158,0
25	26	561	471	162,2	147,7
27	28	443	288	122,3	97,2
29	30	31,8	60,6	115,5	162
31	32	413	611	137,7	169,8
33	34	257	113	67,2	43,9
35	36	545	618	168,7	180,5
37	38	167	-66	34,0	-37
39	40	250	530	94,5	139,8
41	42	37	60	12,7	16,4
43	44	159	-60	32,6	-28
45	46	-	615	-	-
47	48	127	39	32	17,8
49	50	80	-15,7	7,6	-30,7
51	52	467	540	145,3	157,1
53	54	517	750	171,4	209,1
55	56	684	579	198,1	181,2
57	58	574	608	174,7	180,2
59	60	245	220	71,8	67,8
61	62	279	214	79,3	68,8
63	64	175	84	46,2	31,5
65	66	254	122	67,1	45,8
67	68	-	-	-	-

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Analiza tensometrică a stării de tensiuni mecanice şi de deformaţii la încercarea la presiune hidraulică a unui aparat de tip schimbător de căldură

Rezumat

În vederea eliminării riscului tehnic previzibil şi inacceptabil în exploatare a structurilor mecanice de tipul învelişurilor cilindrice în construcţie sudată şi presurizate la interior, este necesară cuantificarea efectelor concentratoare de tensiuni mecanice. Prezenta lucrare reprezintă un studiu experimental de analiză a stării de tensiuni mecanice şi de deformaţii specifice a elementelor structurale proprii învelişurilor cilindrice din cadrul unui recipient de tip schimbător de căldură sub presiune. Scopul principal al lucrării îl reprezintă punerea în evidenţă a stării de tensiuni apărute în punctele de măsurare stabilite, atât la valoarea presiunii de lucru maxim admisibilă, cât şi la presiunea încercării hidraulice, precum şi verificarea variaţiei proporţionale a deformaţiilor şi tensiunilor în funcţie de variaţia presiunii, respectiv stabilirea deformaţiilor remanente/reziduale la descărcarea completă de sarcini a recipientului.