Experimental study of heat transfer on the rubber-cord cased pneumatic element surfaces under the natural convection

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Abstract. One of the ways of improving the calculations accuracy of the stationary objects and vehicles protection systems from vibrations and impacts is taking into account the influence of heat exchange processes with the environment occurring in the rubber-cord cased pneumatic elements and obeying Fourier’s law of heat conduction and Newton’s heat-transfer law. In the conducted study, the heat transfer coefficient values on the pneumatic element walls in the natural convection conditions are defined experimentally. The test bench, testing technique and used measuring instruments which are the heat flux sensors with the internal thermocouple are described. The heat transfer coefficient on the rubber-cord casing curved surface and on the metal flanges flat ones is found out to assume constant values being sufficient for practical application in the operating temperature range based on the process data. When applying the heat exchangers technical theory methods for the pneumatic elements calculation, it is acceptable to consider as a first approximation that the heat transfer coefficient has the identical values on all outer surfaces of the pneumatic element.

Key-words: pneumatic element, heat transfer coefficient, test bench

1. Introduction
The pneumatic elements (PE) with rubber-cord casing (RCC) became widely used in vibration protection and vibration isolation systems of stationary objects and vehicles, they are used both as air springs and air damping shock absorbers [1-6]. When air in PE is compressed, gas temperature rises, resulting in the heat release into the environment. On the contrary, when the gas expands, the temperature decreases and related heat input from the environment takes place. Since under the sprung mass stationary variations the expansion and compression processes succeed one another, heat will periodically take turns to be supplied and released. Traditionally [1-5] PE gas (air) expansion and compression processes are described by the polytropic equation with non-defined (assigned) index n: at low frequencies n is recommended to be equal to 1 (isothermal process), while at high frequencies it is n=1.4 (adiabatic process). In some cases the mathematical model using the polytropic processes engineering thermodynamics specified method leads to the unacceptable discrepancy between the calculated and experimental data, especially when describing the air damping shock absorbers operation [6]. This is due to the fact that the polytropic mathematical model assumes the heat exchange with the environment processes reversibility. To overcome the given and other drawbacks, the extended mathematical model based on Fourier’s law of heat conduction and Newton’s heat transfer law is proposed in paper [6]. It is performed following the example of the reciprocating compressors technical theory by using the heat exchangers technical theory methods. The given direction main difficulty is defining the coefficient of heat transfer α between solid walls and gas included into the empirical dependence.
where \( q \) is the heat flux \([\text{W/m}^2]\); \( T \), \( T_0 \) is the temperature of the wall and gas correspondingly \([\text{K or } ^\circ\text{C}]\). According to [7] the indicative values of the gases heat transfer coefficient under the natural convection is \( \alpha = 0.5...1000 \text{ W/(m}^2\text{-K)} \). Such values range objectively requires experimental studies to specify the heat transfer coefficient numerical values under the natural convection on the RCC and PE flanges surfaces. The experimental data obtained in this case is of great practical importance during the calculation of PE applied in vibration protection and vibration isolation systems of stationary objects and vehicles pneumatic suspensions.

2. Problem statement and test bench description

The test bench scheme and its general view are represented in figure 1 and figure 2 correspondingly. The cylinder-stored type and N-50 model RCC manufactured by FSUP «FRPC «Progress» was used as a test object. The test bench consists of two fixed grips of Instron testing machine (position 1 in figure 1 and figure 2). The grips hold the RCC in the middle position (position 5 in figure 1, position 2 in figure 2) with two flanges. The electric heater of the clamp type (position 4 in figure 1) and the THA 9608-00 brand temperature sensor (position 6 in figure 1) designed for temperature monitoring in the vicinity of the heater are installed inside the RCC. The DTP 0924-R-P-90-25-1 brand heat flux sensor with the internal thermocouple (position 7 in figure 1, position 3 in figure 2) is glued on the RCC end surface. Six heat flux sensors of the DTP 0924-E-D-27-1 brand with the internal thermocouple (position 8 in figure 1) are glued on the metal flanges covering the RCC. The sensor readings are taken and digitized by the multichannel temperature meter IT-6-16 (position 4 in figure 2) and the data are subsequently transmitted to the PC. The measurements results are displayed on the computer screen in the form of tables and graphs. The heater is supplied with power from the household wiring by the laboratory autotransformer of the regulating LT-1M (position 5 in figure 2). The power supplied to the heater is measured by using the M890 series digital multimeters (position 6 and position 7 in figure 2).

The thermoelectric transducer THA 9608-00 is designed for liquid and gaseous media and solids temperature measuring in hard-to-reach places due to the possibility of the attachment section bending when installed on the monitoring object. The measured temperatures range from 40\(^\circ\)C to 800\(^\circ\)C; the thermal inertia index is 0.5 ... 2.5 sec; the error is not more than 2.5\(^\circ\)C. The filling compound of the DTP 0924-R-P-90-25-1 brand heat flux sensor installed onto the RCC is rubber, while the filling compound of the DTP 0924-E-D-27-1 brand heat flux sensor installed on metal flanges is epoxy. The sensors of both types have an internal thermocouple, the heat flux measured densities range is from 10 to 1000 \text{ W/m}^2\), the operating temperature range is from 10\(^\circ\) to 100\(^\circ\)C, the error is less than 8\%. I, II, III heat flux sensors centres at the top flange are apart from the RCC axis at the distance of 83 mm, 55 mm, 33 mm and IV, V, VI sensors centres at the bottom flange are apart from the RCC axis at the distance of 56 mm, 31 mm, 83 mm respectively (figure 3).
Figure 1. The test bench scheme.

Figure 2. The general view of the test bench.
3. Theory with test procedure description
During testing, the air inside the rubber-cord casing hermetically sealed by two flanges is heated according to four stages followed by cooling to ambient temperature (the fifth stage) in the conditions of the slow natural process. In this case the voltage supplied, the current magnitude and the power consumed by the heater at every stage are presented in table 1.

| Stage | 1   | 2   | 3   | 4   | 5   |
|-------|-----|-----|-----|-----|-----|
| Voltage, V | 58  | 78  | 94  | 110 | 0   |
| Current, A  | 0.18| 0.25| 0.31| 0.37| 0   |
| Power, W     | 10.3| 19.5| 29.6| 40.7| 0   |
| Duration, minute | 100 | 100 | 85  | 90  | –   |

4. Experimental results
The temperature change in the vicinity of the heater during the tests, as well as the ambient temperature value are shown in figure 4. The readings of the heat flux sensors with the internal thermocouple at the top flange (sensors I, II, III), at the bottom flange (sensors IV, V, VI) and on the casing surface (RCC sensor) are represented in figure 5, figure 6, figure 7 correspondingly.
Figure 5. The readings of the heat flux sensors with the internal thermocouple at the top flange (sensors I, II, III): \(a\) is the temperature \(T\); \(b\) is the heat flux \(q\).

Figure 6. The readings of the heat flux sensors with the internal thermocouple at the bottom flange (sensors IV, V, VI): \(a\) is the temperature \(T\); \(b\) is the heat flux \(q\).

Figure 7. The readings of the heat flux sensor with the internal thermocouple outside on the casing surface (RCC sensor): \(a\) is the temperature \(T\); \(b\) is the heat flux \(q\).
The ambient temperature sensor readings were processed first. The average value was $T_0 = 21.53^\circ\text{C}$ with a standard deviation of the mean $\sigma_{T_0} = 8.87 \cdot 10^{-3}^\circ\text{C}$. The warming area during which the sensor temperature increased by $1^\circ\text{C}$ from the initial value was separated and thrown away from the heat flux sensors experimental data. The heat transfer coefficient $\alpha$ included in Newton’s empirical law (1) and supposed to be the constant value was defined by minimizing the discrepancy

$$\Omega_q = \sum_{k=1}^N [q_k - \alpha(T_k - T_0)]^2$$

calculated according to the readings $T_k$, $q_k$ ($k = 1...N$) of each sensor separately ($N$ is the total number of test points). The results obtained by the standard least squares method are compiled in table 2. The heat flux calculated value standard deviation (1) from the experimental data was also presented

$$\sigma_q = \sqrt{\frac{1}{(N-1)N} \sum_{k=1}^N [q_k - \alpha(T_k - T_0)]^2}$$

which is the generally accepted error estimation [8, 9].

| Sensor | I   | II  | III | IV  | V   | VI  | PKO |
|--------|-----|-----|-----|-----|-----|-----|-----|
| $\alpha$, W/(m$^2$·K) | 9.51 | 10.28 | 11.48 | 8.59 | 8.76 | 9.90 | 8.76 |
| $\sigma_q$, W/m$^2$      | 0.23 | 0.30 | 0.22 | 0.11 | 0.14 | 0.16 | 0.17 |

5. Results discussion
Visually the experimental data description accuracy degree by formula (1) with the obtained values of the heat transfer coefficient (table 2) can be qualitatively assessed according to figure 8 for every sensor separately. As can be seen, the agreement is quite acceptable. However, the small values of the heat flux mean values standard deviation $\sigma_q$ (table 2) are mainly caused by the fact that the total number of test points $N$ is sufficiently high. The given reason mitigates the presence of the experimental data high frequency pulsation on the heat flux in each particular measurement (figure 5-figure 7, b). The mentioned pulsations are not observed in the experimental temperature data (figure 5 figure 7, a). This is resulted from the heat flux sensor high sensitivity and its appropriate response even to the ambient air weak flows caused by the accidental factors. The internal temperature sensor with a higher response time does not have such a reaction.
Figure 8. The heat flux calculated according to the formula (1) (the solid line) and the experimental data on the heat flux sensors (dotted line).

6. Conclusions
The data of table 2 lead to the conclusion that when carrying out the calculations by using the heat exchangers technical theory methods it is acceptable to consider in the first approximation that the heat transfer coefficient is constant and identical in magnitude on all outer surfaces limiting the pneumatic element.
7. References

[1] Burian Yu A and Silkov M V 2017 J. Phys.: Conf. Ser. 858 012007 URL: https://doi.org/10.1088/1742-6596/858/1/012007 (Date of the application 14.01.18)

[2] Tesfay A H and Goel V K 2015 IOP Conf. Ser.: Mater. Sci. Eng. 100 012020 URL: https://doi.org/10.1088/1757-899X/100/1/012020 (Date of the application 14.01.18)

[3] Gavriloski V and Jovanova J 2010 Dynamic behaviour of an air spring element (Machines & industrial design engineering vol 4-5) pp 24–7

[4] Presthus M 2002 Derivation of Air Spring Model Parameters for Train Simulation (Master Thesis: Lulea University of Technology) p 74

[5] Pevzner Ya M, Gorelik A M 1963 Pneumatic and hydropneumatic suspension (Moscow: GNTIML) p 319

[6] Korneyev S A, Korneev V S, Zubarev A V, Klimentyev E V 2016 Fundamentals of the technical theory of pneumatic shock absorbers (Omsk: OmGTU) p. 148

[7] The Engineering ToolBox, available at URL: https://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html (Date of the application 14.01.18)

[8] Squires G L 1968 Practical Physics (London: McGraw-Hill) p 246

[9] Hudson D J 1964 Statistics. Lectures on Elementary Statistics and Probability (Geneva: CERN) p 296