Eksploatacja i Niezawodnosc – Maintenance and Reliability
Volume 23 (2021), Issue 2
journal homepage: http://www.ein.org.pl

Article citation info:
Hryciów Z, Rybak P, Gieleta R. The influence of temperature on the damping characteristic of hydraulic shock absorbers. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2021; 23 (2): 346–351, http://doi.org/10.17531/ein.2021.2.14.

The influence of temperature on the damping characteristic of hydraulic shock absorbers

Indexed by: Web of Science Group

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Highlights

- Shock absorber performance-temperature characteristic curves were determined.
- A method for determining the continuous use damper for ambient temperatures was proposed.
- Measurements over a wide temperature range showed profound changes in the damping factor.
- Energy dissipated during one cycle decreased linearly with the increase of the temperature.

Abstract

This paper presents the results of bench-tests and calculations assessing the influence of temperature on the performance of a two-pipe hydraulic shock absorber. The shock absorber prepared for the tests was cooled with dry ice to a temperature corresponding to that associated with the average winter conditions in a temperate climate. The temperature range of the shock absorber during testing was ensured via equipping it with a thermocouple and monitoring it with a thermal imaging camera. During testing, the shock absorber was subjected to kinematic forces of a selected frequency with two different, fixed displacement amplitudes. The results of the tests showed a direct correlation between the decrease of component resistance at lower temperatures. The rate of change in resistance was higher at lower temperatures. It was also found that the energy dissipated in one shock cycle decreased linearly with an increasing temperature. Finally, a method for determining the ideal use temperature of the shock absorber for the assumed operating conditions was also presented.

Keywords

hydraulic shock absorber, performance, damping factor, temperature, dissipation energy.

1. Introduction

Nowadays, in order to obtain the required damping values and the desired vibration response of car bodies, and the controlled response on its unsprung mass, double-acting hydraulic shock absorbers are usually implemented in unison with suspension spring elements. These shock absorbers are characterized by their different, two-way resistive forces during their compression stroke and their expansion stroke (the approach and distancing of the wheel to the body, respectively). The magnitude of these resistance forces depends on the parameters of the throttling valves used to decrease the flow of liquid between the chambers in the damper. The shock absorber functions via the conversion of the mechanical energy, generated by the transfer of liquid through the throttling valves, into the thermal energy.

Due to being a fundamental component for the comfort and safety of vehicle users, hydraulic shock absorbers are expected to meet high design, technical and operational requirements. These can be summarized as follows:

- stability of the damping characteristic curves over the assumed service life (or mileage),
- high operational efficiency under expected use conditions,
- as long a shock length as possible,
- low sensitivity to environmental factors (e.g., temperature, humidity),
- high mechanical strength and shock resistance,
- high durability, low weight and compact dimensions.

The correct functioning of shock absorbers is of particular importance for truck and off-road special-purpose vehicles. This is due to these vehicles travelling on poor quality or unpaved roads (where pits, thresholds, bumps and other irregularities appear), in various climatic and meteorological conditions, for a significant part of their service life. Under these conditions, the shock absorbers are then subjected to intense and complex loads with large displacement amplitudes and velocities. This intensive service life accelerates the wear of the shock absorbers components, and in turn, decreases their performance. As a result, the deterioration of the chassis and the vehicle steering are greatly expedited, in turn, affecting both the user comfort and safety.

Malfunctions of the shock absorber can be caused by, among other things, the following reasons: failure of the seals; too low level of the working fluid; valve leaks and vibrations; wear of the working elements; improper fastening (due to the loosening of the fixing elements); wear or loss of the rubber sleeve properties. From the development of these impairments, it is then possible to notice a progressive increase in the operating temperature of the shock absorber, significantly exceeding any recommended operating temperatures.

These permissible operating temperature ranges are specified by the shock absorber manufacturers. In most cases, they are in the range of −40 to 130°C [3], although for special applications (e.g., off-road vehicles) the maximum permissible temperature can reach up to

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180°C. This value is related to, among other characteristics, the type of seals used and their resistance to high temperatures. Temperature also affects the viscosity of the oil, and thus affects the damping characteristic curve of the shock absorber (i.e. the force-temperature relationship of the component). Reducing the viscosity of the oil when the temperature of the shock absorbers increases, as well as the pressure inside its chambers, in extreme cases can lead to the oil leakage. As a result, this causes the deterioration of the shock absorber's operation, or even irreversible damage. In conventional shock absorber designs, mineral oils are used as the working fluid. Whereas, in heavy-duty shock absorbers, synthetic oils are used, which are characterized by their greater resistance and decreased temperature-related viscosity changes. The viscosity of the oil used must not be too high, since this leads to problems at low operating temperatures (generating excessive force values that can lead to damage of the shock absorber). On the other hand, too low a viscosity increases the foaming tendency of the oil, reducing the damping forces and the lubricating properties. The typical dynamic viscosity of the mineral oils is around 40 MPa·s at 15°C [3].

In order to better identify the response of shock absorbers over time, a number of scientific publications have been focused on bench-tests and numerical calculations for the shock absorbers. These studies referred to the determination of the damping characteristic curves, the effect of the damping values on the vehicle dynamics [4, 19], and issues related to their mathematical modelling. In [16], for example, the authors presented a method for modelling a shock absorber (in particular, for its valves), and then confirmed their results based on the experimental results.

In previous scientific research, shock absorber tests results could be found that take into account temperature [5, 10, 14, 18] and their impact on the driving comfort of the user [13]. Studies of the shock absorbers filled with numerous types of fluids were also presented in [12], where the authors presented their heating characteristics during operation with a constant amplitude and frequency. This type of test determined the amount of heat exchanged between the shock absorber and the environment, and can be considered important for preventing the shock absorbers from overheating and the unfavorable changing of the damping characteristic curves. In [6] an attempt was made to assess the technical condition of vehicle-mounted shock absorbers based on their temperature changes during the vehicle movement. The temperature effect on the damping performance of the shock absorber, by implementing the Eusam method, was presented in [8]. The tests were carried out for two temperatures (−5°C and 20°C) and five different types of cars. The tests performed showed a decrease in the effectiveness of the shock absorbers in the range 5 to 25% at warmer temperatures. Changes in performance due to temperature changes were also analyzed for aircraft shock absorbers. Where, in [15], the authors presented the results of their experimental studies conducted at temperatures of −25°C, 0°C, 25°C and 50°C. Measurements of the shock absorber's damping characteristic curves were performed, as well as viscosity tests for hydraulic aviation oil. In this study, for positive temperatures (Celsius), a close to linear characteristic curve was observed for the viscosity decrease with temperature. At negative temperatures, the viscosity increased rapidly. As a result, the damping factor of the shock absorber was directly affected. These tests were also supplemented by calculations based on the CFD method.

The influence of the temperature on the basic characteristic curves was also evaluated for shock absorbers with variable damping characteristic curves. In [7], the influence of the temperature on the characteristic curves of a magnetorheological fluid shock absorber was described. In addition to the working fluid itself, the temperature influence on the resistance of the coils used in the control track were also studied, which was found to affect the resistance values of the shock absorber. Similar considerations were presented in [11], where a temperature range of 25 - 70°C was studied. Furthermore, examples of analytical studies were found in [1, 2, 10]. In [2], the authors presented a thermodynamic model of the shock absorber. This was used to simulate the change in the temperature of the shock absorber during its operation (for different movement speeds), until the vehicle's continuous use temperature was reached. Thus, determining the thermal energy dissipation capabilities of the shock absorber, where these results were also compared with experimental results. In another study [1], a mathematical model of the shock absorber and the heat flow between its elements was explored. This approach made it possible to determine the values of the damping forces, as well as the thermal effects caused by the changes in the geometry of the shock absorber and the properties of its components. Based on these calculations, it was determined that the highest temperature during the operation depends on the working fluid and the elements in direct contact with it, in particular the seals of the component.

In most of the literature found, results were presented for the shock absorbers at temperatures above 20°C; due to typical vehicle operating conditions. However, no results could be found in the literature for lower testing temperatures, such as the working temperature range, as declared by the manufacturers. Therefore, the main aim of the present study was to determine the influence of the working temperature range on the hydraulic shock absorber and its damping characteristic curves and energy dissipation capabilities. In addition, the possibility of heat dissipation to the environment was also explored.

2. Methodology

For the determination of the influence of the working temperature range on the hydraulic shock absorbers, a hydraulic shock absorber designed for installation in the rear suspension of a Renault D280 truck (with a custom bodywork) was tested. For this study, a telescopic Monroe E532080 shock absorber was used for the suspension of the vehicle.

The vehicle's shock absorber tests were carried out on the Instron 8802 electromechanical apparatus, which enables both static and dynamic tests. During the tests, the forces applied were controlled via the displacement signal.

The test program, as explained in further detail below, included the determination of the force-displacement characteristic curves of the rear shock absorber (without a rubber bushing and without a metal-rubber bushing) for different force frequencies at the fixed shock absorber strokes and for the different shock absorber strokes at a fixed force frequency. Ten load loops were recorded for all tests to determine the basic characteristic curves of the shock absorber, measuring both stroke and force frequency. In the case of testing the influence of the temperature on the damping characteristic curves of the shock absorber, the force and displacement were measured continuously from the initial temperature until the temperature value stabilized (or until it reached the maximum permissible value of 100°C). During the tests, the temperature of the shock absorber's surface (in its central part) was recorded using a J-type thermocouple. Thermal images were also taken using a FLIR model 6000 camera every 30 seconds. A view of the stand with the mounted shock absorber was shown in Fig. 1.

3. Results

3.1. Basic characteristic curves of the shock absorber

In the first stage of the experimental testing, the damping characteristic curves of the shock absorber were determined at a constant ambient temperature of 26°C. During these tests, the amplitude of the displacement was changed from 20 to 100 mm, while maintaining a constant frequency of 0.1 Hz. For each variant, the force value and shock absorber's piston displacement were recorded accordingly. Fig. 2 summarizes the force-displacement and damping characteristics of the shock absorber. When the shock absorber was stretched, its resistance was around 10 to 15 times greater than during compression. The characteristic curves provided show the limit force values of the pressure valve (from around 4.7 kN). This corresponded to a relative

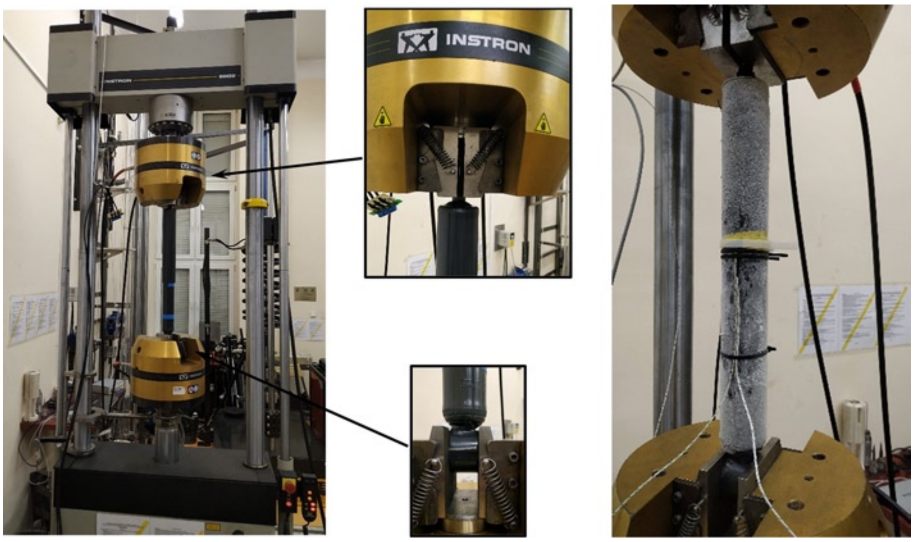

Fig. 1. The testing stand

piston speed of around 30 mm/s. For higher piston speeds, the force changed relative to the speed changes, and were smaller than in the initial force range. For the range of low speeds, the damping factor was 167 kNs/m, while at high speeds it was around 13 times lower reaching 12.9 kNs/m.

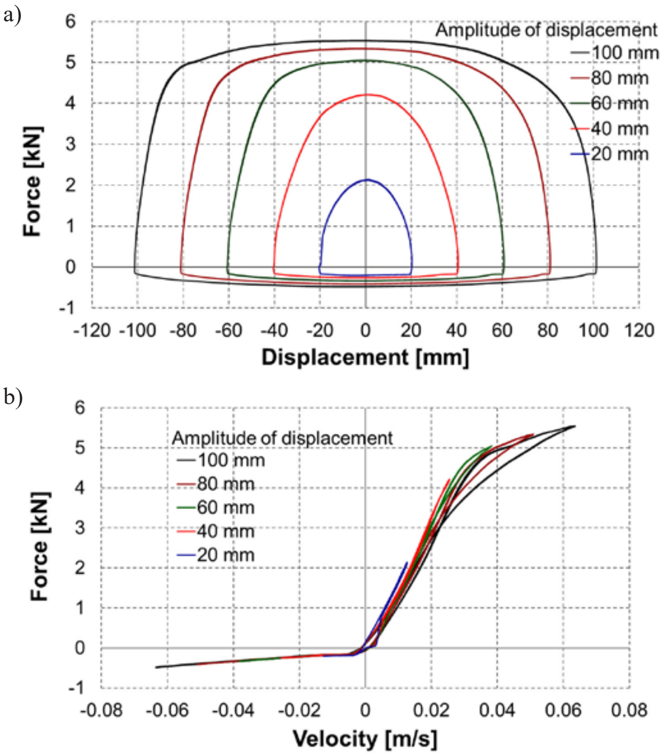

Fig. 2. Force-displacement and force-velocity characteristics of the shock absorber

3.2. Analysis of the heating process

An important issue for identifying the energy dissipation ability of the shock absorber was to study its heating and cooling processes. For this purpose, tests from the initial temperature to the operating temperature (state temps) were carried out for a fixed value of a displacement amplitude of 100 mm and a frequency of movement of 0.1 Hz. This temperature was measured on the outer surface of the shock absorber cylinder, thus being lower than the temperature of the oil inside the shock absorber. In addition, thermographic photographs were taken at fixed intervals (every 30 seconds). Fig. 3 shows the selected temperature distributions characterizing the process of heating the walls of the shock absorber. From this figure, it could be concluded that the cylinder heats up stronger in its upper part. The temperature difference between the upper and middle parts was around 5.1°C at the end of the measurements, and between the upper and lower parts as much as 16.3°C. Greater heating of the upper part was associated with, among other factors, the friction of the piston rod during its movement relative to the damper seal.

Fig. 4 displays the temperature changes found in the upper, middle and lower parts of the shock absorber (at points P1, P2 and P3 – Fig. 3, respectively). At the final stage of testing, the temperature on the surface of the shock absorber stabilized itself. Its increments were small and did not change by more than 0.1°C after an additional 60 s of the shock absorber's operation. Therefore, at this point, the study was terminated. The ability of the shock absorber to dissipate heat was characterized by, among others aspects, its geometry, the types of materials used or paint coatings applied. This process was described by the shock absorber cooling curve. In order to determine the shock absorber's cooling curve, the temperature changes of the heated shock absorber were measured after placing the subject in an environment with a constant temperature. The resulting curve was consistent with the examples found in the literature [14], and it should be emphasized that it depends on, among other things, the type of shock absorber and the prevailing environmental conditions (e.g., air temperature and humidity or relative air vlocity).

The change in temperature T(t) was described by the equation (1), expressing Newton's law of cooling [17]:

$$\frac{dT}{dt} = -k \cdot \left(T_p - T_{ot}\right) \tag{1}$$

where:

T_{ot} – ambient temperature [°C],
T_p – initial temperature [°C],
t – time [s],
k – decay constant [1/s].

Integration of equation (1) and rearrangement of terms leads to the expression in the form (2):

$$T(t) = T_{ot} + \left(T_p - T_{ot}\right) \cdot \exp(-k \cdot t) \tag{2}$$

Based on the approximation of the cooling results by function (2), the value of the decay constant k was determined to be around 0.034 s-1. The constant k can be described by the following relation (3):

$$k = \frac{\lambda \cdot S}{m \cdot c} \tag{3}$$

where:

λ – heat transfer coefficient [$W/(m^2 \cdot K)$],
S – heat exchange area [m^2],
m– mass [kg],
c – specific heat (J/(kg·K)).

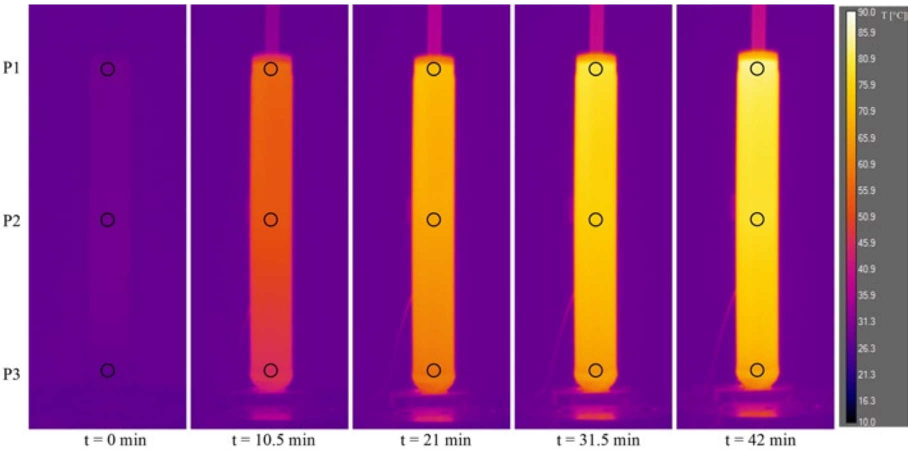

Fig. 3. Selected temperature distributions on the walls of the shock absorber

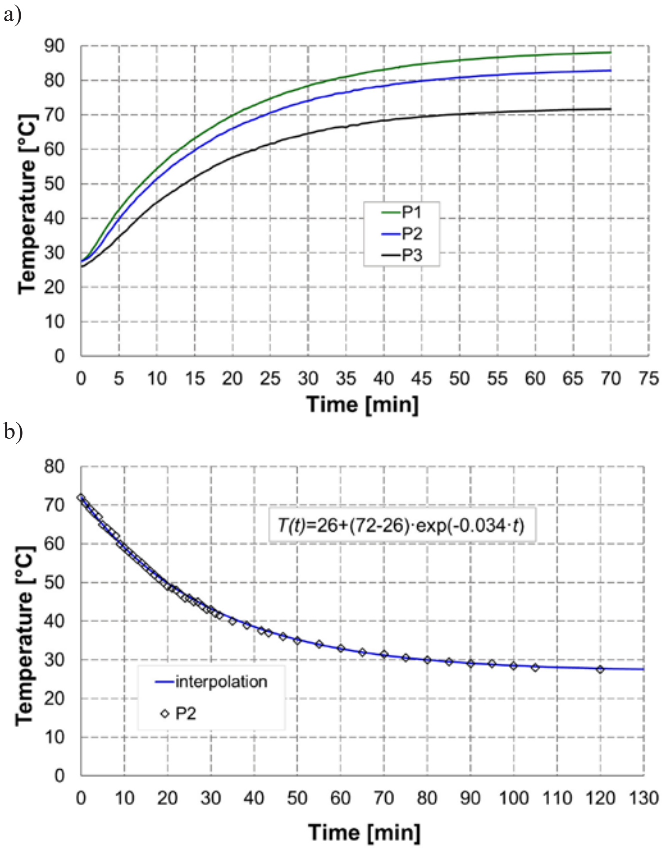

Fig. 4. Temperature changes on the surface of the shock absorber (left – heating, right – cooling)

Assuming the above-mentioned coefficients remain constant with respect to the temperature, it is possible (using Fourier's law for fixed heat flow conditions) to estimate the value of the continuous use temperature for other ambient temperatures. For this purpose, one should use the working conditions of the external force (energy dissipated in the shock absorber during one cycle) with the energy transferred to the external environment (4):

$$\dot{Q} = \frac{E_c}{t_c} = S \cdot \lambda \cdot \left(T - T_{ot}\right) \tag{4}$$

where:

$\dot{Q}$ – heat flux [W],
E_c – energy dissipated during one cycle [J],
t_c – duration of one operating cycle [s],

Transforming (4) yields relation (5):

$$S \cdot \lambda = \frac{E_c}{t_c \cdot \left(T - T_{ot}\right)} = const \tag{5}$$

For example, at an ambient temperature of 26°C, the tested shock absorber reached a continuous use temperature (in the middle part – point P2) of 83.71°C, dissipating an energy of 972 J during one cycle (lasting 10 s). If the amount of energy dissipated varies with temperature according to the dependence $E_c(T) = -2.15 \cdot T + 1152$ (fig. 7) at ambient temperature T_{ot2}, thus, the continuous use temperature T_2 is (6):

$$T_2 = \frac{S \cdot \lambda \cdot t_{c2} \cdot T_{ot2} + 1152}{S \cdot \lambda \cdot t_{c2} + 2.15} \tag{6}$$

At $T_{ot2} = -10$°C, after working with the same amplitude and frequency, the continuous use temperature of the shock absorber would reach $T_2 = 51.8$ ° C (dissipating an energy of 1040 J in one cycle). The presented method enables the evaluation of how appropriate the selected shock absorber for a specific car is for operation in the desired climatic conditions. According to literature, the increase in operating temperature in relation to the ambient temperature should not exceed 40-70°C [3].

3.3. Temperature influence on the damping characteristic curves

Given the final aim of the study was to determine the characteristic curves of the shock absorber at different operating temperatures. The tests previously described were carried out for two further displacement amplitudes of the shock absorber piston, while maintaining a constant frequency value of 0.1 Hz. The low value of the movement frequency permitted the minimization of the temperature difference between the oil and the walls of the shock absorber. In addition, the high speeds applied to the shock absorber lead to the generation of significant forces, exceeding the limit of opening the pressure limiting valve. Thus, causing a disturbance in the observation of the effect of temperature on the damping factor values. To reduce the heat exchange with the environment, the shock absorber cylinder was covered with a 20 mm thick layer of an insulating foam. This protected the cylinder walls against the intense heat exchange with the surroundings of the cooled shock absorber and against the heat transfer through the heated shock absorber. The insulation accelerated the heating process and enabled higher continuous use temperatures to be reached. For an amplitude of 50 mm, the tests were carried out in the temperature range from −40°C to 53°C (the established temperature value for the asserted conditions), and for 100 mm from −8°C to 100°C. Analyzing the results for the determination of the characteristic curves of the shock absorber at the different operating temperatures, it could be concluded that larger force differences in the shock absorber occur for smaller displacements (speeds), as seen in Fig. 5. For an amplitude of 100 mm the operation (i.e. opening) of the pressure limiting valve (and thus the force values) was observed for all temperatures. This was evidenced by the flattening of the upper part of the characteristic curves.

Fig. 6 provides a summary of the damping characteristics obtained in the temperature range from −40°C to 100°C. As previously mentioned, due to the rapid build-up of forces at −40°C and −20°C, the tests were carried out only for a displacement amplitude of 50 mm. Basing on these characteristics, the values of the damping factor were determined when the shock absorber was stretched in the low-speed range (before the pressure valve was opened).The results were summarized in Table 1. In addition, it shows the percentage changes in the

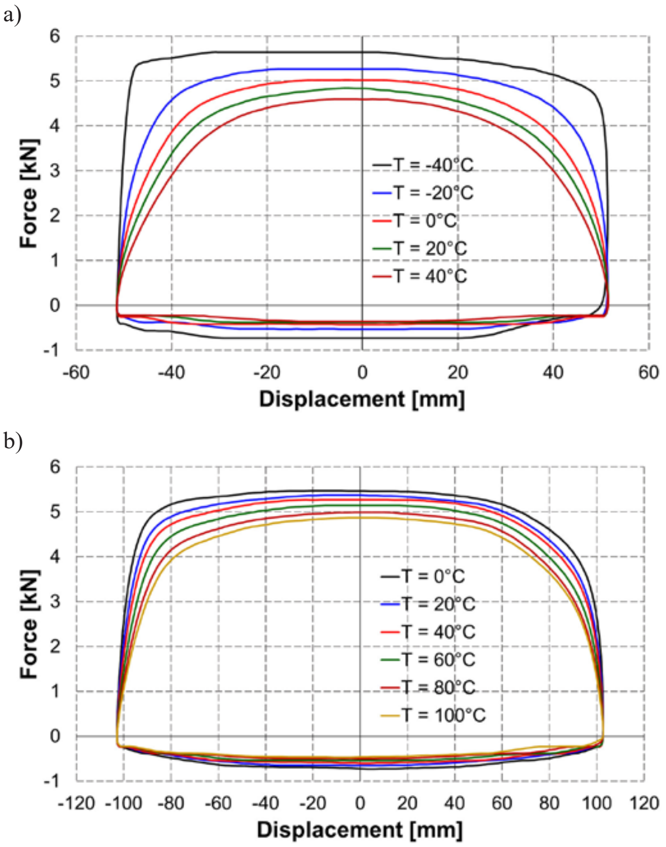

Fig. 5. Influence of the temperature on the force-displacement characteristics of the shock absorber (left – amplitude 50 mm, right – amplitude 100 mm)

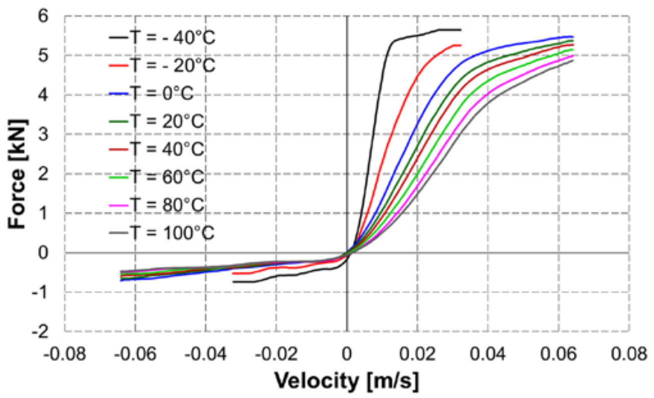

Fig. 6. Temperature influence on the damping characteristic curves of the shock absorber

Table 1. The changes of the damping coefficient in relation to a temperature

	Temperature [°C]							
	−40	−20	0	20	40	60	80	100
Damping coefficient c [kNs/m]	613.6	290.1	190.5	162.9	149.9	139.5	130.6	121.8
Relative difference $\delta c_{20°C}$ [%]	276.6%	78.1%	16.9%	0.0%	−8.0%	−14.4%	−19.8%	− 25.3%

value of the damping coefficient in relation to the value obtained at a temperature of 20°C.

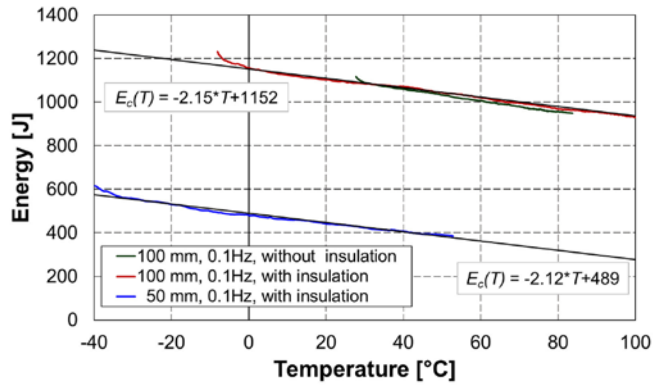

Fig. 7. Energy dissipated in one cycle

For the obtained changes in the damping force, as a function of temperature, the value of the dissipated energy was calculated for each full operating cycle as determined from the dependence (7):

$$E_c = \oint F dx \,, \tag{7}$$

For the initial part of the obtained characteristics curves, the curvature is well pronounced, as presented in Fig. 7. This was related to the time it took to transfer heat from the oil to the outer surface of the cylinder. After a short time, the heat transfer process was stopped. As a result, there was an almost linear decrease in the energy dissipated in one operating cycle with the increasing temperature.

For a force amplitude of 100 mm, the test was terminated when the temperature reached 100°C. For a force amplitude of 50 mm, only a temperature of 53°C was obtained. At this temperature, the amount of energy supplied to the system through the work of the external force evened the energy released to the environment. In addition, it could be stated that the rate of change in the amount of energy dissipated as a function of the temperature did not depend significantly on the displacement amplitude of the shock absorber piston. In both variants, a similar value was obtained (−2.15 J/°C for 100 mm and −2.12 J/°C for 50 mm). It also did not depend on the insulation used. For a shock absorber without insulation and covered with a layer of foam, a similar decrease in dissipated energy was observed with an increase in temperature.

4. Conclusions

This paper presents the results for laboratory bench-tests and calculations for determining the influence of temperature on the performance-based characteristic curves of a two-pipe hydraulic shock absorber installed on the rear suspension of a truck. Based on the results obtained, it was possible to conclude that the shock absorber's temperature had a significant influence on the damping factor values. This effect was particularly evident as the temperature decreased. Compared to the value obtained at 20°C, at 100°C the value of the damping coefficient decreased by around 25%, while at −40 ° C its value increased by around 280%.

Larger changes in the damping forces, due to temperature changes, were observed for smaller displacements of the shock absorber piston (lower movement speeds). For higher speeds, a pressure limiting valve was used.

Over a wide range of temperatures, the amount of energy dissipated during one cycle changed almost linearly with temperature. For the tested shock absorber, the specified rate of change was around −2.1 J/°C.

At low temperatures the relative motion of the elements of the shock absorber rapidly generated large resistance forces even at low speeds; with their value being limited by the pressure valve. High damping forces reduced the susceptibility of the suspension, increased the dynamic loads acting on the body and increased the likelihood of wheels tearing off the ground while driving.

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