

Article

Experimental Analysis of Air Temperature Variation in Pneumatic Flexible Elements Connected by Multiple Flow Openings

Jozef Krajňák * , Robert Grega , Matej Urbanský, Lucia Žul'ová and Marianna Tomašková

Faculty of Mechanical Engineering, Technical University of Kosice, 04200 Kosice, Slovakia; robert.grega@tuke.sk (R.G.); matej.urbansky@tuke.sk (M.U.); lucia.zulova@tuke.sk (L.Ž.); marianna.tomaskova@tuke.sk (M.T.)

* Correspondence: jozef.krajnak@tuke.sk; Tel.: +42-1-556-022-373

Abstract

Pneumatic flexible elements are widely used in mechanical systems for vibration damping, noise reduction, and improvement of dynamic properties. During cyclic loading, periodic compression and expansion of the enclosed air cause pressure fluctuations, airflow between interconnected chambers, pressure losses, and the conversion of mechanical energy into heat. This thermal loading may influence the stiffness, damping properties, durability, and operational reliability of elastomeric pneumatic elements. This study investigates the influence of the number of connecting openings on the thermal behaviour of two pneumatically coupled flexible elements under dynamic loading. Experimental measurements were carried out using a specially designed test rig at different charging pressures and with different numbers of active connecting openings. Three temperatures were monitored: the air temperature inside the pneumatic element T_{air} , the inner surface temperature T_{in} , and the outer surface temperature T_{out} . The results showed that increasing the number of connecting openings reduced all monitored temperatures and led to a more uniform temperature distribution within the pneumatic system. The thermal response also depended on the charging pressure, with a gradual transition from air-dominated heating at lower pressures to inner-surface-dominated heating at higher pressures. A simplified theoretical model was used to identify the main physical quantities influencing temperature development, including pressure, volume variation, airflow resistance, heat transfer, and energy dissipation. In addition, the interpretation of the observed temperature reduction was supported by a simplified analytical assessment based on the orifice-flow relationship, which showed that increasing the total flow area reduces the pressure difference required for cyclic airflow and consequently decreases pressure-loss-related heat generation. The findings demonstrate that the number of connecting openings is an important design parameter for controlling the thermal response of pneumatic flexible elements.



Academic Editors: Hugo Filipe Diniz Polcarpo and Tiago Silva

Received: 11 June 2026

Revised: 7 July 2026

Accepted: 7 July 2026

Published: 9 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: flexible elements; dynamic loading; air heating; pressure losses; airflow; flexible shaft couplings

1. Introduction

Pneumatic systems are widely used in mechanical engineering, vehicle suspension, vibration isolation, transport mechanisms, machine tools, and flexible drive systems because they combine a relatively simple structure with good reliability and favourable dynamic properties. Their ability to transmit energy by means of compressed air and simultaneously

absorb part of the mechanical energy generated during dynamic loading makes them suitable for applications in which vibration reduction, noise mitigation, and compensation of dynamic shocks are required [1,2].

In pneumatic flexible elements, the dynamic response is governed by the coupled behaviour of compressed air and the elastomeric structure. During cyclic loading, periodic compression and expansion of the working medium occur, which causes pressure fluctuations, airflow between chambers, pressure losses, and dissipation of mechanical energy into heat. These phenomena influence not only the temperature of the enclosed air but also the temperature of the elastomeric wall, and consequently the stiffness, damping capability, durability, and operational reliability of the element. From the design point of view, sealing, airflow control, and the structural arrangement of pneumatic components are therefore important factors affecting the overall performance of such systems [3–5].

Elastomeric materials, especially rubber and rubber-cord composites, are commonly used in pneumatic flexible elements because of their favourable elastic, damping, and deformation properties [6,7]. However, their mechanical and dynamic properties are temperature-dependent. Prolonged exposure to elevated temperatures may accelerate thermo-oxidative ageing, change stiffness, reduce fatigue resistance, and shorten the service life of elastomeric components. Previous studies have shown that thermal ageing at temperatures around 70 °C can already affect the mechanical and dynamic behaviour of rubber compounds [8,9]. For this reason, the thermal behaviour of pneumatic flexible elements under dynamic loading should be considered together with their mechanical and vibration characteristics.

Previous studies have investigated the thermodynamic and dynamic behaviour of air springs and pneumatic flexible elements from several viewpoints. Existing research has mainly focused on air spring modelling, pressure-volume relationships, heat transfer, airflow through orifices, auxiliary reservoir effects, dynamic stiffness, damping, hysteresis behaviour, and experimental validation of theoretical models [10–13]. These works provide an important basis for understanding the interaction between compressed air, airflow resistance, heat exchange, and elastomeric structures. In the field of flexible shaft couplings and vibration control, several studies have also addressed the dynamic behaviour of mechanical systems with flexible couplings, their influence on torsional vibrations, noise generation, vibration stability, and failure prevention [14–20].

Although these studies provide valuable knowledge about pneumatic elements and dynamically loaded mechanical systems, the influence of the number of connecting ports between two pneumatically coupled flexible elements has not been sufficiently analysed. Most previous works have focused on pressure level, volume change, excitation frequency, auxiliary reservoir volume, orifice area, stiffness, damping, or general dynamic behaviour. However, the number of connecting ports represents a specific design parameter that directly affects the effective flow area, pressure equalization between chambers, airflow resistance, energy dissipation, and heat generation during cyclic loading.

This represents the main research gap addressed in the present study. While it may be physically expected that increasing the total flow area reduces pressure losses and temperature rise, the magnitude of this effect, its dependence on operating pressure, and the resulting temperature distribution between the air, the inner rubber surface, and the outer rubber surface have not been systematically quantified. In particular, the transition from air-dominated heating at lower pressure to material-dominated heating at higher pressure has not been sufficiently explained for pneumatically coupled flexible elements.

The aim of this study is therefore to experimentally analyse the influence of the number of connecting ports on the thermal behaviour of two pneumatically coupled flexible elements subjected to dynamic loading. The investigated system is based on pneumatic

flexible elements used in flexible shaft couplings, where the connecting openings can be modified and thus used as a design parameter affecting airflow and heat generation. The study evaluates the air temperature inside the element, the temperature of the inner rubber surface, and the temperature of the outer surface for different numbers of connecting ports and operating pressures.

The novelty of the paper lies in the experimental quantification of the effect of the number of connecting ports on the thermal response of pneumatically coupled flexible elements, as well as in the identification of different dominant heating mechanisms at lower and higher operating pressures. The obtained results contribute to a better understanding of the relationship between airflow, pressure losses, energy dissipation, temperature development, and dynamic performance of pneumatic vibration isolation systems and flexible shaft couplings.

2. Pneumatic Elastic Elements

Pneumatic elastic elements are used in mechanical systems in which vibration isolation, dynamic load compensation, damping, and flexible support are required. Their function is based on the combination of compressed air and an elastomeric shell, which enables them to absorb dynamic loads while maintaining suitable flexibility and damping properties.

In engineering practice, pneumatic elastic elements are manufactured in various structural configurations. They differ mainly in their geometric shape, number of bellows, flange design, mounting method, permissible stroke, operating pressure range, and dynamic stiffness [21,22]. Typical designs include single-bellows, double-bellows, and triple-bellows elements, which are selected according to the required deformation range, load capacity, and vibration isolation properties [23,24]. Examples of commonly used pneumatic elastic elements are shown in Figure 1. This figure is included only to illustrate the variety of available designs and flange arrangements. The present study, however, is focused exclusively on the pneumatic elastic elements used in the experimental measurements, which are shown in Figure 2.



Figure 1. Different types of elastic elements.

The experimental investigation was carried out using two single-bellows pneumatic elastic elements PE-130. These elements are commonly applied in pneumatic flexible shaft couplings and vibration isolation systems. They consist of a reinforced rubber-cord elastomeric body, which provides flexibility, strength, and resistance to repeated cyclic deformation. During operation, the elements are subjected to periodic compression and expansion of the enclosed air. This process causes pressure fluctuations, airflow between interconnected chambers, pressure losses, and the conversion of part of the mechanical energy into heat.

The tested pneumatic elements were mounted in the experimental test rig and interconnected by a specially designed connecting flange. The flange allowed the number of active

connecting openings between the two pneumatic chambers to be varied. This arrangement made it possible to investigate how the number of connecting openings affects airflow conditions, pressure equalization, energy dissipation, and temperature development in the pneumatic system.



Figure 2. Elastic elements used for experimental measurements.

The experimental samples used in the study are shown in Figure 2. During the measurements, the number of active connecting openings on the measuring device shown in Figures 3 and 4 was varied from one to six. The air temperature inside the pneumatic element, the temperature of the inner rubber surface, and the temperature of the outer surface were monitored under dynamic loading. The detailed design of the connecting flange and the method of closing selected openings are presented later in Figures 5 and 6.

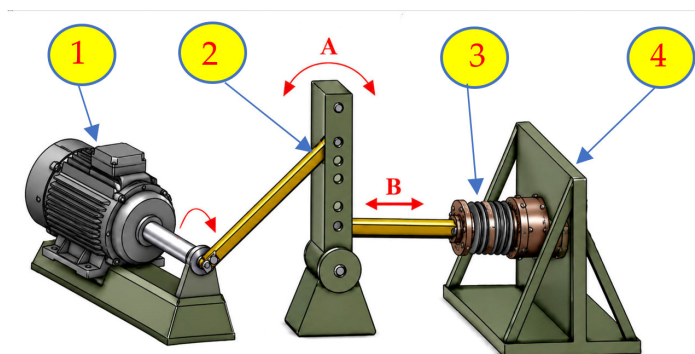


Figure 3. 3D Model of the Proposed Experimental Test Device.

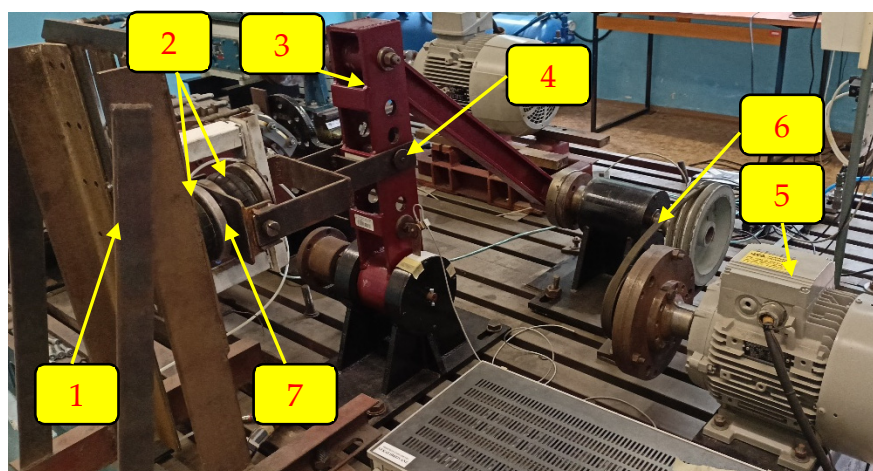


Figure 4. Real experimental test device for dynamic oscillatory loading of two interconnected flexible pneumatic elements.

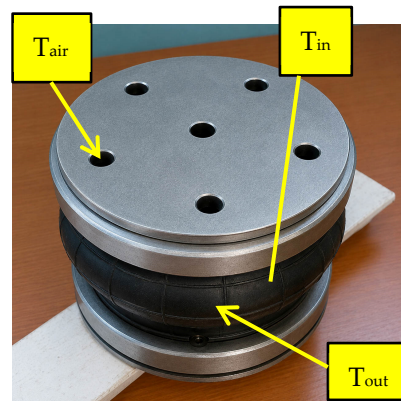


Figure 5. Connecting flange with temperature measurement points.

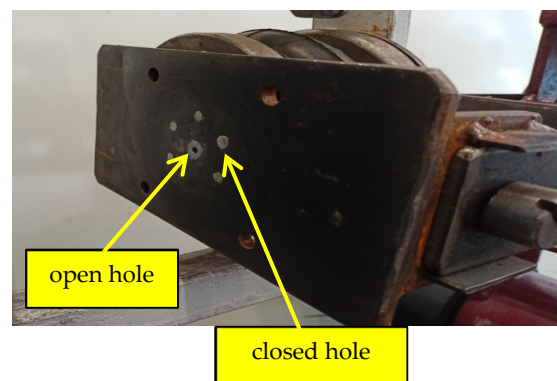


Figure 6. Fixing the flexible element in the connecting flange.

Elevated temperature is an important factor affecting the behaviour of pneumatic elastic elements. It may influence the mechanical properties of the rubber-cord material, increase thermal ageing, change stiffness and damping characteristics, and reduce the long-term reliability of the element. For this reason, the thermal response of the tested pneumatic elements was analysed in relation to the number of connecting openings and selected operating conditions.

3. Simplified Theoretical Model of Temperature Evolution in Pneumatic Flexible Elements

Due to the complexity of the airflow processes occurring inside interconnected pneumatic flexible elements, including unsteady compressible flow, pressure equalization between chambers, turbulence effects, heat transfer, and material deformation, the development of a comprehensive mathematical model would require advanced numerical methods and extensive experimental validation. Therefore, a simplified theoretical model was developed in this study. The purpose of the model is not to provide an exact prediction of the temperature evolution but rather to identify the dominant parameters and physical quantities affecting the thermal behavior of pneumatic flexible elements during dynamic loading. The model enables a qualitative assessment of the influence of operating pressure, volume variation, airflow, and thermodynamic processes on the resulting temperature changes and serves as a theoretical basis for the interpretation of the experimental results presented in this paper.

This theoretical model describes the heating of air in two pneumatically coupled flexible elements subjected to dynamic harmonic loading. The elements are interconnected by circular holes with a diameter of 5 mm. During operation, one element is compressed

while the other expands, causing periodic airflow between them. Due to pressure losses, turbulent flow, and compression-expansion processes, the air temperature increases.

The time-dependent volumes of the two elements are described by harmonic Functions (1) and (2):

$$V_1(t) = V_0 - \Delta V \sin(\omega t) \quad (1)$$

$$V_2(t) = V_0 + \Delta V \sin(\omega t) \quad (2)$$

where the angular frequency is calculated according to Equation (3), and the amplitude of volume change depends on the effective area as shown in Equation (4), where x_a represents the displacement amplitude, which in this case was 7.7 mm.

$$\omega = 2\pi f \quad (3)$$

$$\Delta V = A_{\text{eff}} \cdot x_a \quad (4)$$

The air inside the elements is considered an ideal gas:

$$pV = mRT \quad (5)$$

The airflow between the elements is described by the orifice flow Equation (6):

$$\dot{m} = C_d \cdot A \cdot \sqrt{2\rho\Delta p} \quad (6)$$

where

C_d —discharge coefficient, A —total hole area, ρ —air density, Δp —pressure difference.

The total flow area is:

$$A = N \frac{\pi d^2}{4} \quad (7)$$

The thermal behavior of the air is described by the energy balance equation:

$$mc_v \frac{dT}{dt} = -p \frac{dV}{dt} + \dot{Q}_{\text{loss}} - hA_s(T - T_{\text{ambient}}) \quad (8)$$

where the first term represents the compression work, the second term represents the thermal energy generated by dissipation, and the third term represents heat transfer to the surroundings [25,26]. A smaller number of holes increases flow resistance and pressure losses, which leads to higher thermal energy dissipation and consequently higher air temperature. The proposed model can be further extended using CFD simulations and advanced thermodynamic analysis.

4. Description of the Measuring Device

First, a preliminary 3D model of the experimental test device, shown in Figure 3, was designed in order to demonstrate the operating principle of the system. This device is intended for dynamic loading of various flexible elements and serves as the basis for the subsequent construction of a real experimental measuring setup.

The proposed 3D model was designed so that the electric motor, marked as position 1, generates rotational motion characterized by rotational speed n , which can be continuously adjusted according to experimental requirements. Using a crank mechanism, the rotational motion is transformed into an oscillating motion denoted by the letter A . This oscillating motion is subsequently converted into a reciprocating linear motion B , which dynamically loads the flexible elements marked as position 3.

The flexible elements are firmly mounted in a supporting frame identified as position 4. The crank mechanism contains several adjustment holes, allowing modification of the

loading amplitude according to the required experimental conditions. Based on this proposed 3D model, a real experimental measuring device was subsequently designed and constructed, which is shown in Figure 4.

Based on the proposed 3D model, a functional experimental test rig was designed and constructed in the laboratory of measurement and tuning of torsional vibrations at our department. The experimental setup used for the performed measurements is shown in Figure 4.

The test rig consists of a supporting frame structure (1), in which two pneumatic flexible elements PE-130 (2) are mounted and interconnected by means of a connecting flange (7), shown in detail in Figure 5. These elements are single-bellows pneumatic elements commonly used in flexible pneumatic shaft couplings developed at our department. The elements are manufactured from rubber-cord composite material and are capable of operating at working pressures ranging from 100 to 700 kPa. The mechanism used for converting rotary motion into reciprocating linear motion (3) was also developed at our department. By changing the position of the connecting arm in different mounting holes (4), it is possible to modify the amplitude of dynamic loading according to the required experimental conditions. The entire experimental setup is driven by a DC electric motor (5) type SM 160L with an output power of 16 kW. The motor is equipped with an additional thyristor speed controller type IRO, enabling continuous speed regulation in the range from 0 to 2000 min⁻¹.

The measurements were carried out at three different rotational speeds: 400, 600 and 800 min⁻¹.

Figure 5 shows a detailed view of the connecting flange equipped with six flow openings. Figure 6 presents the flange mounted in the experimental measuring device, where the method used to regulate the number of openings can be clearly observed. This configuration allowed controlled airflow between the two pneumatic flexible elements during dynamic loading. By adjusting the number of active openings, it was possible to modify the airflow conditions and investigate their influence on the thermal behavior of the interconnected pneumatic system.

The oscillating motion generated by the crank mechanism depends directly on the rotational speed of the electric motor. Torque transmission from the motor to the mechanism is realized through a belt transmission (6), which simultaneously reduces dynamic shocks and partially dampens vibrations due to its elastic properties. Temperature measurements were carried out using M-3870D METEX digital multimeters (Metex Corporation, Seoul, South Korea) equipped with ETP-003 thermal probes, providing a measurement range of −50 °C to +250 °C and an accuracy of ±0.5 °C. Using these measuring devices, the air temperature inside the pneumatic element T_{air} , the temperature of the inner surface T_{in} , and the temperature of the outer surface T_{out} of the flexible element were monitored. The ambient temperature was maintained at a constant value using an air-conditioning system $T_0 = 22$ °C. The measured temperatures were recorded at time intervals: $t = 1, 2, 3, 4, 5, \dots, 29, 30$ min. for selected rotational speeds, air pressures, and deformation amplitudes. Based on previous experimental experience, it was observed that the temperature of the pneumatic elements stabilized after approximately 20–27 min of operation. The developed experimental device enables dynamic loading of pneumatic flexible elements at various rotational speeds while simultaneously allowing adjustment of the loading amplitude within a specified range. By changing the position of the connecting holes on the crank mechanism (3), the oscillation amplitude can be modified. During the presented measurements, the deformation amplitude was set to a value of 7.7 mm.

The experimental measurements were carried out over a period of 20 days under laboratory conditions. Before each measurement, the prescribed initial conditions were

ensured, including the required charging pressure, the selected number of active connecting openings, the deformation amplitude, and the ambient temperature. The ambient temperature was maintained at approximately 22 °C using an air-conditioning system.

Each measurement configuration was repeated three times in order to evaluate the repeatability of the measured temperature values. For a given number of active connecting openings, the pneumatic system was first set to the selected charging pressure and the measurement was repeated three times under the same conditions. After completing these repetitions, the charging pressure was changed and the same procedure was repeated. The measurements were gradually performed at charging pressures of 200, 300, 400, and 500 kPa. Although the investigated pneumatic elastic elements are designed for a maximum operating pressure of 700 kPa, the maximum pressure used in the present experimental study was limited to 500 kPa. This pressure limit was selected for safety reasons and to ensure reliable sealing of the pneumatic system during repeated dynamic loading.

After completing the full pressure sequence for a given configuration of connecting openings, the connecting flange was modified to change the number of active openings. The entire measurement procedure was then repeated for the new configuration. This process continued until all configurations with different numbers of connecting openings were measured.

The temperature measurements were performed using M-3870D METEX digital multi-meters equipped with ETP-003 thermal probes, with a measurement accuracy of ± 0.5 °C. During repeated measurements under identical operating conditions, the observed deviations between repeated temperature readings were lower than the sensor accuracy of ± 0.5 °C. This indicates good repeatability of the measurements and confirms that the measured temperature trends were not significantly affected by random measurement variations.

5. Experimental Measurement Results

Figures 7 and 8 present the measured temperature values obtained at an oscillation frequency 800 min^{-1} with a single connecting port. Distinct temperature profiles were observed depending on the charging pressure. At $p_0 = 200 \text{ kPa}$, the air temperature T_{air} reached the highest value of 57 °C after 30 min of operation, while the inner surface temperature T_{in} reached 53 °C and the outer surface temperature T_{out} reached 37 °C. At $p_0 = 500 \text{ kPa}$, the temperature distribution changed. The highest temperature was recorded on the inner surface T_{in} , which reached 54 °C, whereas T_{air} reached 41 °C and T_{out} remained 37 °C. These results indicate that, at lower charging pressure, the air temperature is the dominant thermal parameter, while at higher charging pressure heat accumulation near the inner surface becomes more significant.

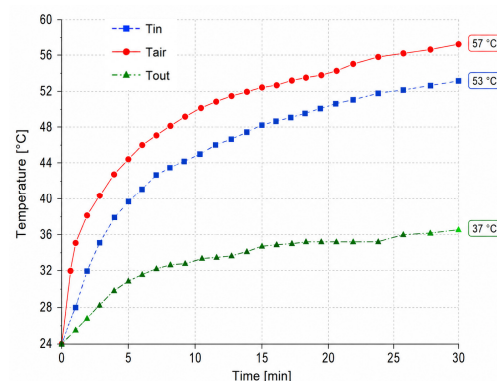


Figure 7. Measured temperature values at $p_0 = 200 \text{ kPa}$ and 1 connecting port.

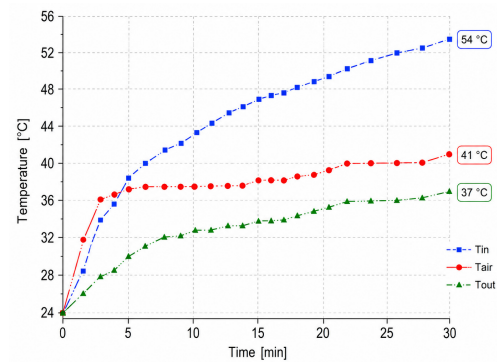


Figure 8. Measured temperature values at $p_0 = 500$ kPa and 1 connecting port.

Figures 9 and 10 show the temperature development for two connecting ports at $p_0 = 200$ kPa and $p_0 = 500$ kPa. In both cases, the temperatures increased rapidly during the initial stage of the experiment and then gradually approached a stabilized state. At $p_0 = 200$ kPa, T_{air} reached approximately 45 °C, T_{in} reached 43 °C, and T_{out} reached 30 °C after 30 min. At $p_0 = 500$ kPa, the highest temperature was recorded on the inner surface, where T_{in} reached approximately 43 °C, while T_{air} reached 36 °C and T_{out} reached 31 °C. This confirms that the charging pressure influences not only the final temperature level but also the dominant location of heat accumulation.

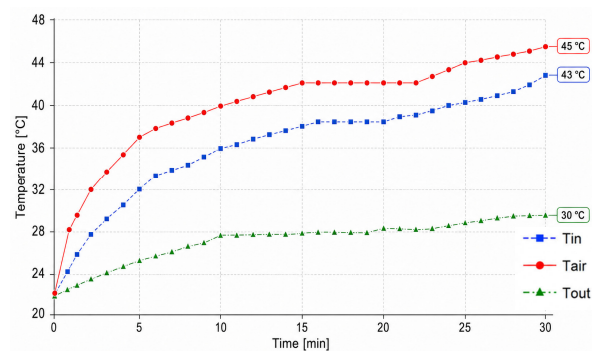


Figure 9. Measured temperature values at $p_0 = 200$ kPa and 2 connecting ports.

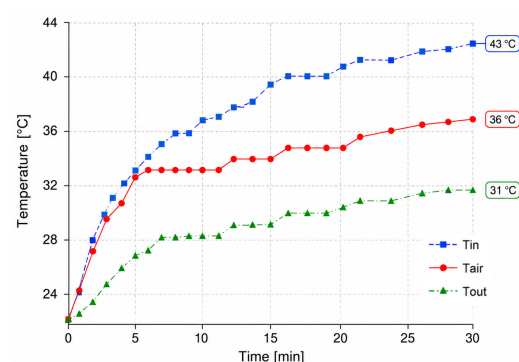


Figure 10. Measured temperature values at $p_0 = 500$ kPa and 2 connecting ports.

The measurements were also performed for higher numbers of connecting ports. Figures 11 and 12 present the results for three connecting ports, while Figures 13 and 14 show the temperature development for six connecting ports. Increasing the number of connecting ports reduced the temperature levels and led to a more uniform temperature distribution within the pneumatic element. For six connecting ports at $p_0 = 200$ kPa, both T_{air} and T_{in} reached approximately 33 °C after 30 min, while T_{out} reached 27 °C. Compared

with the configuration with one connecting port, the air temperature decreased by 24 °C, the inner surface temperature by 20 °C, and the outer surface temperature by 10 °C.

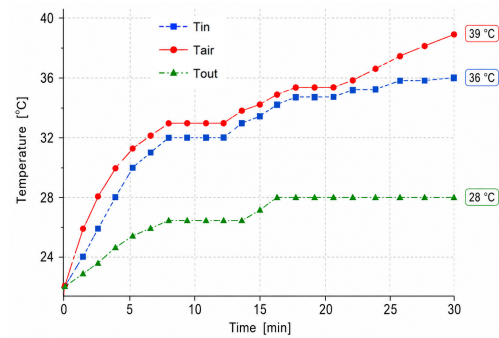


Figure 11. Measured temperature values at $p_0 = 200$ kPa and 3 connecting ports.

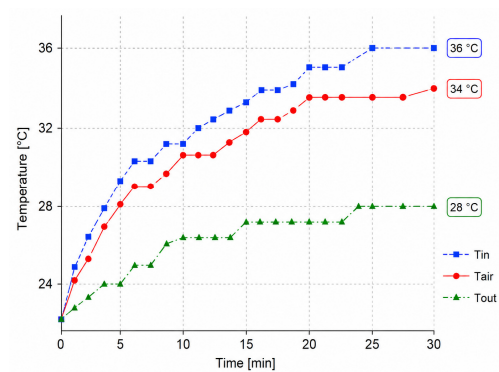


Figure 12. Measured temperature values at $p_0 = 500$ kPa and 3 connecting ports.

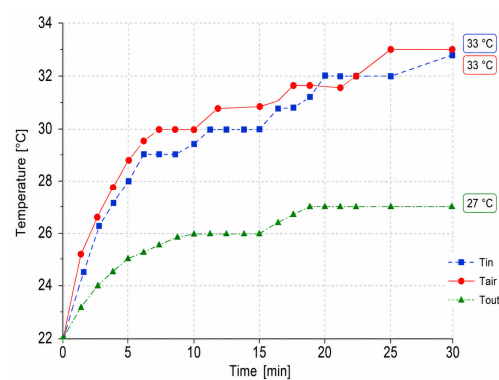


Figure 13. Measured temperature values at $p_0 = 200$ kPa and 6 connecting ports.

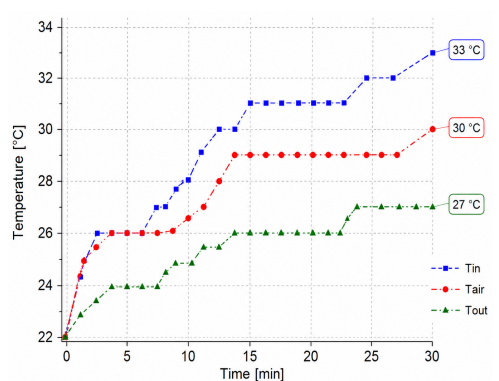


Figure 14. Measured temperature values at $p_0 = 500$ kPa and 6 connecting ports.

A similar reduction was observed at $p_0 = 500$ kPa. With six connecting ports, T_{in} reached 33 °C, T_{air} reached 30 °C, and T_{out} reached 27 °C. Compared with one connecting port, the inner surface temperature decreased by 21 °C, the air temperature by 11 °C, and the outer surface temperature by 10 °C. The temperature difference between the maximum and minimum measured values was reduced to only 6 °C for both investigated pressure levels, indicating improved pressure equalization and reduced heat generation in the system.

Based on the experimental measurements, summary relationships were developed to evaluate the effect of the number of connecting ports on the measured temperatures.

Figures 15 and 16 present the limiting cases for charging pressures of $p_0 = 200$ kPa and $p_0 = 500$ kPa. These results show a consistent decrease in all monitored temperatures with an increasing number of connecting ports. At $p_0 = 200$ kPa, the dominant temperature was the air temperature T_{air} , whereas at $p_0 = 500$ kPa the highest values were recorded for the inner surface temperature T_{in} . For six connecting ports, the temperatures converged considerably, confirming that a larger number of connecting ports improves airflow conditions and reduces thermal gradients within the pneumatic element.

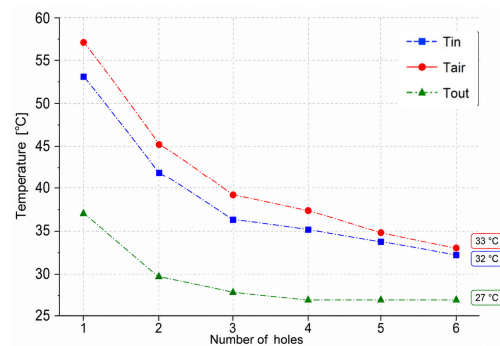


Figure 15. Effect of the number of ports on temperature at a constant pressure of $p_0 = 200$ kPa.

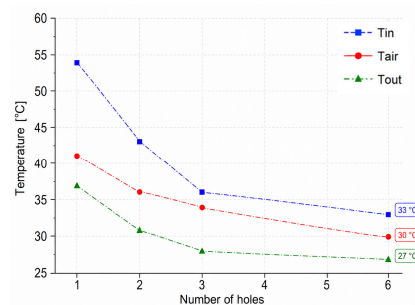


Figure 16. Effect of the number of ports on temperature at a constant pressure of $p_0 = 500$ kPa.

Figures 17–19 present the influence of the number of connecting ports and charging pressure on the measured temperatures after 30 min of dynamic loading. Figure 17 shows the development of the inner surface temperature T_{in} , Figure 18 presents the outer surface temperature T_{out} , and Figure 19 shows the air temperature inside the pneumatic flexible element T_{air} . Since the air temperature exhibited the most pronounced dependence on charging pressure, Figure 18 is presented in an enlarged form to improve the readability of the temperature differences between individual pressure levels.

As shown in Figure 17, the inner surface temperature T_{in} decreased systematically with an increasing number of connecting ports. For one connecting port, T_{in} reached 53 °C at 200 and 300 kPa, 53.5 °C at 400 kPa, and 54 °C at 500 kPa. When the number of connecting ports increased to six, T_{in} decreased to 33 °C for all investigated pressure levels. The total reduction in T_{in} was therefore approximately 20 – 21 °C. The most significant decrease occurred between one and three connecting ports, where T_{in} dropped from approximately

53–54 °C to 36 °C. Further increases in the number of ports caused only a gradual decrease, indicating that the heat generation near the inner rubber surface becomes less sensitive to additional flow area after three connecting ports.

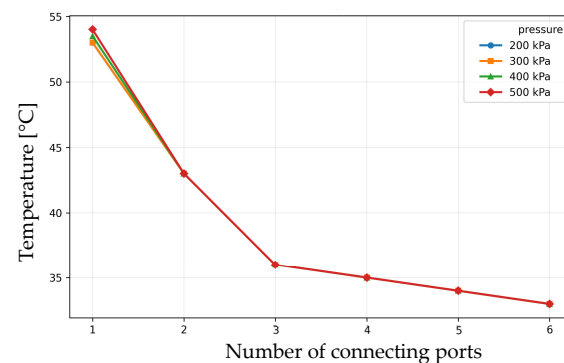


Figure 17. Dependence of the inner surface temperature T_{in} on the number of connecting ports at different charging pressures in the pneumatic flexible element.

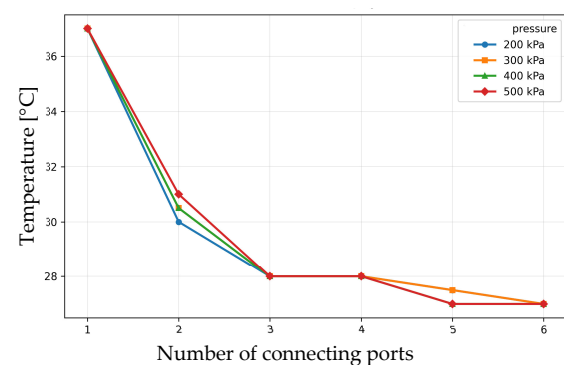


Figure 18. Dependence of the outer surface temperature T_{out} on the number of connecting ports at different charging pressures in the pneumatic flexible element.

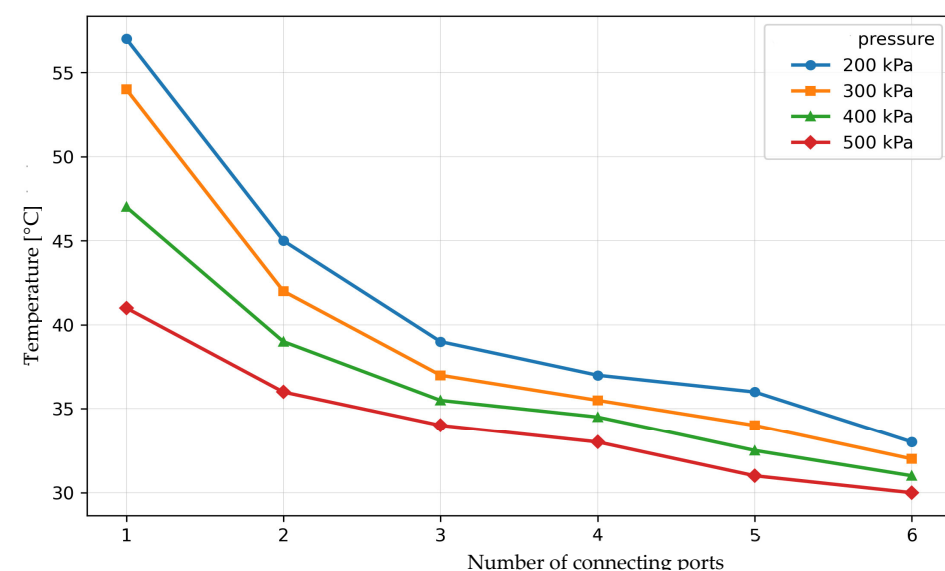


Figure 19. Dependence of the air temperature T_{air} on the number of connecting ports at different charging pressures in the pneumatic flexible element.

Figure 18 shows that the outer surface temperature T_{out} was less affected by charging pressure than T_{in} and T_{air} . For one connecting port, T_{out} reached 37 °C for all investigated pressure levels. With an increasing number of connecting ports, T_{out} decreased to approxi-

mately 27 °C for six ports. The total reduction in T_{out} was therefore about 10 °C. The most visible decrease again occurred between one and three connecting ports, while for four to six ports the values changed only slightly. This confirms that the outer surface temperature is mainly affected by the heat transferred through the rubber-cord wall and is less sensitive to direct pressure changes inside the pneumatic element.

The most pronounced pressure dependence was observed for the air temperature T_{air} , shown in Figure 19. With one connecting port, T_{air} reached 57 °C at 200 kPa, 54 °C at 300 kPa, 47 °C at 400 kPa, and 41 °C at 500 kPa. This means that, for the most restricted flow configuration, the difference in T_{air} between 200 kPa and 500 kPa was 16 °C. With six connecting ports, T_{air} decreased to 33 °C at 200 kPa, 32 °C at 300 kPa, 31 °C at 400 kPa, and 30 °C at 500 kPa. The pressure-related difference was therefore reduced to only 3 °C. These results indicate that additional connecting ports improve pressure equalization between the chambers and reduce pressure-loss-related air heating.

Table 1 presents the measured values of the inner surface temperature T_{in} , the air temperature inside the pneumatic element T_{air} , and the outer surface temperature T_{out} after 30 min of dynamic loading. The values are given for different numbers of active connecting ports and different charging pressures. The table complements the graphical results and enables a direct comparison of the influence of the number of ports and pressure on the resulting thermal response of the pneumatic system.

Table 1. Measured temperatures after 30 min of dynamic loading for different numbers of connecting ports and charging pressures.

Connecting Ports	T_{in} [°C]	T_{air} [°C]	T_{out} [°C]	Pressure [kPa]
1	53	57	37	200
1	53	54	37	300
1	53.5	47	37	400
1	54	41	37	500
2	43	45	30	200
2	43	42	30.5	300
2	43	39	30.5	400
2	43	36	31	500
3	36	39	28	200
3	36	37	28	300
3	36	35.5	28	400
3	36	34	28	500
4	35	37	28	200
4	35	35.5	28	300
4	35	34.5	28	400
4	35	33	28	500
5	34	36	27.5	200
5	34	34	27.5	300
5	34	32.5	27	400
5	34	31	27	500
6	33	33	27	200
6	33	32	27	300
6	33	31	27	400
6	33	30	27	500

Overall, the results show that the number of connecting ports has a strong influence on all measured temperatures. The highest temperature reduction was observed when the number of connecting ports increased from one to three. At higher numbers of ports, the temperature decrease became more gradual, which indicates that the effective airflow area was already sufficient for improved pressure equalization. Among the three measured temperatures, T_{air} showed the highest sensitivity to charging pressure, while T_{out} was the least sensitive. These results confirm that the thermal behaviour of the pneumatic flexible element is governed by the combined effects of airflow resistance, pressure equalization, heat transfer through the elastomeric wall, and hysteresis losses in the rubber-cord material.

6. Discussion

The experimental results confirmed that the thermal behaviour of pneumatically coupled flexible elements is significantly influenced by both the number of active connecting openings and the operating pressure. In the original version of the manuscript, the discussion was mainly based on the limiting pressure levels of 200 kPa and 500 kPa. In the revised study, additional measurements at 300 kPa and 400 kPa were included, which enabled a more continuous evaluation of the temperature development over the investigated pressure range. These additional results showed that the influence of pressure on the thermal response is gradual and that the transition between the dominant heating mechanisms does not occur abruptly, but develops progressively with increasing pressure.

All monitored temperatures decreased systematically as the number of active connecting openings increased. This trend was observed for the air temperature inside the pneumatic element, the inner rubber surface temperature, and the outer surface temperature. From a physical point of view, this behaviour is associated with the increase in the effective flow area between the interconnected chambers. For a hole diameter of $d = 5 \text{ mm}$, the area of one opening is $1.96 \times 10^{-5} \text{ m}^2$. Therefore, increasing the number of active openings from one to six increases the total flow area from $1.96 \times 10^{-5} \text{ m}^2$ to $1.18 \times 10^{-4} \text{ m}^2$, i.e., by a factor of six. According to the orifice–flow relation used in Equation (6), for a given cyclic mass-flow requirement, the pressure difference required to drive the flow decreases as the total flow area increases. As a result, flow resistance, pressure losses, and pressure-loss-related energy dissipation are reduced.

This analytical interpretation is directly supported by the experimental results. The highest temperatures were measured for the most restricted configuration with one connecting opening, while the lowest temperatures were obtained for six connecting openings. At $p = 200 \text{ kPa}$, the air temperature decreased from $57 \text{ }^\circ\text{C}$ for one connecting opening to $33 \text{ }^\circ\text{C}$ for six connecting openings. At $p = 500 \text{ kPa}$, the inner surface temperature decreased from $54 \text{ }^\circ\text{C}$ to $33 \text{ }^\circ\text{C}$. These reductions confirm that the decrease in temperature was not random, but was directly related to the reduction in flow restriction and improved pressure equalization between the chambers. Thus, the experimental data, the orifice–flow relationship, and the energy-balance formulation provide a consistent basis for explaining the observed temperature reduction.

Although the general trend of decreasing temperature with increasing flow area can be expected from physical principles, the experimental contribution of this study lies in the quantification of this effect for pneumatically coupled flexible elements under dynamic loading. The measurements showed not only the direction of the trend, but also the magnitude of the temperature reduction for different operating pressures and different numbers of connecting openings. This is important because the thermal response of pneumatic flexible elements affects their stiffness, damping capability, material ageing, and long-term operational reliability.

The extended pressure range also confirmed that the charging pressure has a significant influence on the temperature distribution within the system. At lower pressures, the highest temperature was generally observed in the enclosed air. This indicates that, under these conditions, the dominant heat generation mechanism is mainly associated with cyclic compression and expansion of the air and with pressure losses during airflow through the connecting openings. Since the air mass and thermal capacity are lower at lower pressure levels, the temperature of the enclosed air responds more sensitively to periodic compression, expansion, and energy dissipation.

With increasing pressure, the thermal behaviour of the system changed. At higher pressures, the temperature of the inner rubber surface became more significant and, in some cases, exceeded the air temperature. This behaviour can be explained by several coupled mechanisms. Higher pressure increases the amount of stored energy in the compressed air and enhances heat transfer from the air to the elastomeric wall. At the same time, the rubber-cord structure is subjected to higher deformation resistance during cyclic loading, which increases internal friction and hysteresis losses in the material. Consequently, part of the mechanical energy is converted directly into heat within the elastomeric structure, leading to heat accumulation near the inner surface of the pneumatic element.

The added measurements at 300 kPa and 400 kPa support this interpretation. They show that the thermal response gradually changes between the lower-pressure and higher-pressure regimes. At intermediate pressure levels, the difference between air-dominated heating and material-dominated heating becomes less pronounced, indicating that both mechanisms contribute to the resulting temperature field. This confirms that the thermal behaviour of pneumatic flexible elements cannot be evaluated only from the viewpoint of airflow, but must also include heat transfer and material hysteresis effects.

The outer surface temperature remained the lowest monitored temperature in all investigated configurations. This indicates that the heat generated inside the pneumatic element is transferred gradually through the elastomeric wall to the surrounding environment. The lower outer surface temperature also confirms that the rubber-cord wall acts as a thermal barrier, causing part of the heat to accumulate near the inner surface, especially at higher pressure levels. This effect is important from the viewpoint of long-term operation, because thermal loading of the inner surface may influence material ageing even when the outer surface temperature remains relatively low.

The repeatability of the measurements further supports the reliability of the observed trends. Each configuration was measured repeatedly under identical operating conditions, and the deviations between repeated temperature readings were lower than the accuracy of the temperature probe, which was ± 0.5 °C. This indicates that the differences observed between individual configurations were mainly caused by changes in the number of connecting openings and operating pressure, rather than by random measurement variations.

The simplified theoretical model presented in the manuscript should be interpreted as a supporting tool for identifying the main physical quantities influencing temperature development, not as a fully predictive numerical model. The model indicates that temperature changes are affected by pressure, volume variation, airflow through the connecting openings, pressure losses, heat transfer, and energy dissipation. The experimental results confirmed the importance of these quantities. However, the model does not fully describe local turbulent flow, spatial temperature gradients, time-dependent heat transfer coefficients, or the complete viscoelastic behaviour of the rubber-cord material. Therefore, a more detailed numerical analysis, for example using CFD or coupled thermo-fluid–structure modelling, may be the subject of future research.

From a practical point of view, the results show that the number of connecting openings can be used as a simple design parameter for controlling the thermal behaviour of

pneumatically coupled flexible elements. Increasing the number of active openings reduces temperature rise and leads to a more uniform temperature distribution. This may contribute to improved durability, slower thermal ageing of the elastomeric material, and more stable dynamic properties during long-term operation. The findings are relevant for pneumatic vibration isolation systems, flexible shaft couplings, suspension systems, and other mechanical systems in which pneumatic flexible elements are exposed to repeated dynamic loading.

Overall, the results demonstrate that the thermal behaviour of pneumatic flexible elements is governed by the combined effects of airflow, pressure equalization, energy dissipation, heat transfer, and material hysteresis. The study therefore extends the experimental understanding of pneumatically coupled flexible elements and shows that their thermal state should be considered together with their dynamic properties during design and optimization.

7. Conclusions

In this study, the thermal behaviour of pneumatic flexible elements connected by different numbers of flow openings was experimentally investigated. The measurements were carried out under laboratory conditions using a specially designed test rig under dynamic loading. Three temperatures were monitored: the air temperature inside the pneumatic element T_{air} , the inner surface temperature of the rubber element T_{in} , and the outer surface temperature T_{out} .

The experimental programme was extended to include four charging pressures, namely 200, 300, 400, and 500 kPa, and different numbers of active connecting openings. Each configuration was measured repeatedly under the same initial conditions. The deviations observed during repeated measurements were lower than the accuracy of the temperature probe, which was ± 0.5 °C. This confirms good repeatability of the measured trends. Although the tested pneumatic flexible elements are designed for operation up to 700 kPa, the maximum experimental pressure was limited to 500 kPa for safety reasons and to ensure reliable sealing during dynamic loading.

The results confirmed that the number of connecting openings has a significant influence on all monitored temperatures. Increasing the number of openings from one to six caused a systematic decrease in T_{air} , T_{in} , and T_{out} . The greatest temperature reduction was observed when the number of openings increased from one to three, while further increases resulted in a more gradual decrease. This indicates that, after a certain effective flow area is reached, the influence of additional openings on temperature reduction becomes less pronounced.

The most significant change was observed for the air temperature T_{air} . At a pressure of 200 kPa, T_{air} decreased from 57 °C with one connecting opening to 33 °C with six openings, corresponding to a reduction of 24 °C. The inner surface temperature T_{in} decreased by approximately 20–21 °C, while the outer surface temperature T_{out} decreased by approximately 10 °C. These results demonstrate that a larger number of connecting openings improves pressure equalization between the chambers, reduces flow resistance, and limits heat generation and accumulation within the pneumatic system.

The additional measurements at 300 and 400 kPa made it possible to describe the influence of charging pressure on the thermal response in more detail. The results showed that the transition between air-dominated heating and inner-surface-dominated heating is gradual. At the lower pressure of 200 kPa, the highest temperature was generally recorded in the air inside the element. At the higher pressure of 500 kPa, the dominant temperature shifted to the inner surface temperature T_{in} . This behaviour is consistent with increased heat transfer from the compressed air to the elastomeric wall and with the

possible contribution of hysteresis losses in the rubber-cord material under higher pressure and deformation loading.

From a practical point of view, the results show that the number of connecting openings can be considered a simple but important design parameter for controlling the thermal response of pneumatic flexible elements. By selecting an appropriate number of openings, it is possible to reduce thermal loading, promote a more uniform temperature distribution, and contribute to more stable dynamic properties, lower thermal stress, and improved operational reliability of the element.

The simplified theoretical model used in this study served mainly to identify the principal physical quantities influencing temperature development, particularly pressure, volume variation, airflow through the connecting openings, pressure losses, heat transfer, and energy dissipation. The model was intended to serve as a qualitative interpretative framework and a supporting tool for explaining the experimental results, rather than as a fully predictive numerical model.

A limitation of the present study is that the measurements were performed for one specific type of pneumatic flexible element, a selected pressure range, a defined deformation amplitude, and laboratory operating conditions. Future research should extend the experimental programme to include additional excitation frequencies, deformation amplitudes, different types of pneumatic elements, and long-term durability tests. Further development of a more detailed numerical model, for example using CFD or coupled thermo-mechanical modelling, would also be useful for analysing local airflow, heat transfer, and temperature gradients within the material.

Overall, the study extends the experimental understanding of the thermal behaviour of pneumatic flexible elements under dynamic loading. The results confirm that the thermal state of these elements is closely related to their structural configuration and operating pressure. Therefore, the temperature behaviour should be considered together with dynamic properties when designing pneumatic vibration isolation systems and flexible couplings.

Author Contributions: R.G. and M.U. performed the experimental analyses and prepared the manuscript. J.K. supervised and coordinated the research, managed the manuscript preparation process, revised previous versions of the manuscript, and approved its final version. M.T. and L.Ž. collected and processed the experimental data. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by KEGA-Cultural and Educational Grant Agency of the Ministry of Education, Culture and Sports of the Slovak Republic (KEGA) 037 TUKE-4/2024 and (KEGA) 044 TUKE-4/2024; the Slovak Grant Agency under the grant VEGA 1/0573/25.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

KKaDI	Department of Design, Automotive and Transport Engineering
CFD	Computational Fluid Dynamics
3D	Three-Dimensional
DC	Direct Current

References

1. Ali, H.I.; Noor, S.B.B.M.; Bashi, S.M.; Marhaban, M.H. A Review of Pneumatic Actuators (Modeling and Control). *Aust. J. Basic Appl. Sci.* **2009**, *3*, 440–454.
2. Wróbel, A. Pneumatic Elements of Machine Tools. *Int. J. Mod. Manuf. Technol.* **2020**, *12*, 137–142.
3. Calvert, C.; Tirovic, M.; Stolarski, T. Design and Development of an Elastomer-Based Pneumatic Seal Using Finite Element Analysis. *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **2002**, *216*, 127–138. [[CrossRef](#)]
4. Miatluk, M.; Kamiński, Z.; Czaban, J. Characteristic Features of the Airflow of Pneumatic Elements of Agricultural Vehicles. *Comm. Mot. Power Ind. Agric.* **2003**, *3*, 174–181.
5. Galati, R.; Mantriota, G.; Reina, G. Analytical Modelling of Pneumatic Tyre Deformation during Sharp-Edge Obstacle Negotiation with Eccentric Contact Loading. *Mech. Mach. Theory* **2026**, *225*, 106458. [[CrossRef](#)]
6. Medvecká-Beňová, S.; Miková, L.; Kaššay, P. Material Properties of Rubber-Cord Flexible Element of Pneumatic Flexible Coupling. *Metalurgija* **2015**, *54*, 194–196.
7. Ramadhani, Z.S.; Akbar, H.I.; Pramudi, G.; Kayne, F.N. Design of a Flexible Flange Coupling with Pin Bush for a Rubber Crushing Machine. *Eng. Sustain. Dev.* **2025**, *1*, 22–32.
8. Dolui, T.; Chanda, J.; Ghosh, P.; Mukhopadhyay, R. Why the Fracture Resistance of Natural Rubber Compound Reduced When Subjected to Thermal Ageing? *Polym. Bull.* **2024**, *81*, 14353–14369. [[CrossRef](#)]
9. Cui, Z.; Liu, W.; Tan, L.; Sun, G.; Hu, X. Evidence for Non-Arrhenius Behavior of EPDM Rubber by Combining Arrhenius and Time-Temperature Superposition (TTS) Extrapolations. *RSC Adv.* **2024**, *14*, 5216–5221. [[CrossRef](#)] [[PubMed](#)]
10. Lee, S.J. Development and Analysis of an Air Spring Model. *Int. J. Automot. Technol.* **2010**, *11*, 471–479. [[CrossRef](#)]
11. Liu, H.; Lee, J.C. Model Development and Experimental Research on an Air Spring with Auxiliary Reservoir. *Int. J. Automot. Technol.* **2011**, *12*, 839–847. [[CrossRef](#)]
12. Löcken, F.; Welsch, M. The Dynamic Characteristic and Hysteresis Effect of an Air Spring. *Int. J. Appl. Mech. Eng.* **2015**, *20*, 127–145. [[CrossRef](#)]
13. Luo, X.; Li, D.; Liu, J.; Zhang, H.; Yang, X. Theoretical Modeling and Experimental Test for Dynamic Characteristics of an Air-Spring Vibration Isolation System. *J. Braz. Soc. Mech. Sci. Eng.* **2023**, *45*, 489. [[CrossRef](#)]
14. Wittenburg, J. Shaft Couplings. In *Kinematics: Theory and Applications*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 387–410.
15. Nemchinov, S.; Khristenko, A. Stress-Strain State of Pneumatic Flexible Shaft Coupling for Ball Mill Drives. *Sci. J. Silesian Univ. Technol. Ser. Transp.* **2018**, *99*, 125–134. [[CrossRef](#)]
16. Tadeo, A.T.; Cavalca, K.L.; Brennan, M.J. Dynamic Characterization of a Mechanical Coupling for a Rotating Shaft. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2011**, *225*, 604–616.
17. Khoshravan, M.R.; Paykani, A. Design of a Composite Drive Shaft and Its Coupling for Automotive Application. *J. Appl. Res. Technol.* **2012**, *10*, 826–834. [[CrossRef](#)]
18. Kiss, T.; Ng, W.-F.; Mitchell, L.D. A New Shaft Coupling Design for a High-Speed Rotor Wheel. In Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Boston, MA, USA, 17–20 September 1995; pp. 55–60.
19. Homišin, J.; Grega, R.; Kaššay, P.; Fedorko, G.; Molnár, V. Removal of Systematic Failure of Belt Conveyor Drive by Reducing Vibrations. *Eng. Fail. Anal.* **2019**, *99*, 192–202. [[CrossRef](#)]
20. Khanlo, H.M.; Ghayour, M.; Ziaei-Rad, S. The Effects of Lateral-Torsional Coupling on the Nonlinear Dynamic Behavior of a Rotating Continuous Flexible Shaft-Disk System with Rub-Impact. *Commun. Nonlinear Sci. Numer. Simul.* **2013**, *18*, 1524–1538. [[CrossRef](#)]
21. Moseley, P.; Florez, J.M.; Sonar, H.A.; Agarwal, G.; Curtin, W.; Paik, J. Modeling, Design, and Development of Soft Pneumatic Actuators with Finite Element Method. *Adv. Eng. Mater.* **2016**, *18*, 978–988. [[CrossRef](#)]
22. Reynolds, D.B.; Repperger, D.W.; Phillips, C.A.; Bandry, G. Modeling the Dynamic Characteristics of Pneumatic Muscle. *Ann. Biomed. Eng.* **2003**, *31*, 310–317. [[CrossRef](#)] [[PubMed](#)]
23. Liptai, P.; Moravec, M.; Badida, M. Research of Possibilities of Using the Recycled Materials Based on Rubber and Textiles Combined with Vermiculite Material in the Area of Noise Reduction. *Adv. Mater. Res.* **2014**, *1001*, 171–176. [[CrossRef](#)]

24. Tawk, C.; Alici, G. Finite Element Modeling in the Design Process of 3D Printed Pneumatic Soft Actuators and Sensors. *Robotics* **2020**, *9*, 52. [[CrossRef](#)]
25. Kurpaska, S.; Slipek, Z. Mathematical Model of Heat and Mass Transfer in a Horticultural Substrate during Heating by a Warm Air Stream. *J. Agric. Eng. Res.* **1996**, *65*, 305–311. [[CrossRef](#)]
26. Serageldin, A.A.; Abdelrahman, A.K.; Ookawara, S. Earth-Air Heat Exchanger Thermal Performance in Egyptian Conditions: Experimental Results, Mathematical Model, and Computational Fluid Dynamics Simulation. *Energy Convers. Manag.* **2016**, *122*, 25–38. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.