Analysis of the Possibility of Using Compressed Air to Drive Vehicles

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Abstract: The aim of the research described in this article, is to analyze the possibility of using compressed air to drive vehicles. In pneumatic vehicles, the energy is stored in a tank of compressed air, which is later converted into the movement of the vehicle. This article provides calculations for the amount of energy, which is contained in 1 liter of compressed air, for various values of air pressure. Then, the efficiency of the drive system and the resistances to motion, are calculated for various deviations of the mass of passenger cars. Later, based on previously calculated parameters, the theoretical range of compressed air vehicles is calculated, in relation to the pressure in the pressure tank, its capacity and the weights of the vehicles. In this article, a simulation verification, of analytical calculations is carried out, using an example of a light pneumatic vehicle, designed at the Wroclaw University of Technology.

Keywords: compressed air vehicles; pneumatics; energy density

1 Introduction

Nowadays, there are attempts to produce cars that will pollute the environment as little as possible [1]. Electric and hydrogen cars are becoming more and more popular [2]. Another possible type of energy used to propel vehicles is compressed air [3]. This type of drive was already used in the 19th century to drive locomotives [4] [5] and trams in cities, and then it was replaced by gasoline and electric drive [6]. For several decades, several companies have returned to this type of drive and are trying to produce pneumatic cars [7]. Currently, passenger cars powered by compressed air are produced by the Indian company TATA MOTORS in cooperation with the French company MDI [8].

Table 1 shows the various parameters of compressed air vehicles. I believe that producers' information about their vehicles should be approached with a certain amount of distrust, because they try to advertise their product as much as possible.

Table 1

Vehicle's parameters. Markings: - no data, [I] manufacturer of locomotives for Polish mines, [II] team name at the XII. International Aventics Pneumobile Competition, [III] university, where the vehicle was constructed, [IV] eight tanks with a diameter of 300 - 400 mm, [V] several tanks with a volume of 1.5 m^3 to 2.5 m^3, [VI] constructor's prediction, no testes on the road, [VII] speed, at which the maximum range was reached

vehicle model \ vehicle parameter	vehicle weight [kg]	engine power [kW]	pressure tanks volume [dm^3]	pressure tank initial pressure [bar]	maximum speed [km/h]	range [km]	year or age of production	another source of energy
Tata Nano (air powered) [9]	-	-	-	-	-	200	XXI	none
Tata AIRPod 2.0 [10]	350	7	300	-	80	up to 120	XXI	none
Test car for the Di Pietro engine [11]	400	-	-	-	60	-	XXI	none
Trams in Nantes [5]	7000	-	eight tanks[IV]	25	9	6	1876	steam (170 °C)
Locomotive BVD-35 [4,5]	9000	35	1380	-	11	-	XIX	none
Arnold Jung Lokomotivfabrik[I] [4,5]	-	up to 70	several tanks[V]	200	14	-	1956-1987	none
Motorcycle O2 Pursuit [12]	-	-	-	-	140[VI]	100[VI]	XXI	none
Toyota Ku:Rin [13]	-	-	-	-	129	3.2	XXI	none
Riga Fresh[II] [14]	-	-	10	200	50	10.6	XXI	none
Zhejiang University[III] [6]	1820	-	200	120	30[VII]	1.87	2004	none

The construction of a vehicle powered by compressed air has two big problems. Firstly, compressed air has a low specific energy (about 90 times less than gasoline) [15]. Secondly, the efficiency of pneumatic systems built of typical pneumatic components ranges from 5% to 20% [16] [17].

Constructors of pneumatic vehicles often choose to build their own motors to propel the vehicle to increase efficiency. The cars produced by TATA MOTORS company have a piston engine designed by the former owner of the company, Mr. Guy Negre. The vehicles designed by EngineAir company are equipped with a rotary engine designed by the owner of the company, Mr. Angelo Di Pietro. This constructor declares the efficiency of its engine at the level of 95% [18].

Table 2 shows the energy density and specific energy of the different types of energy used to propel vehicles. From the table, we can see that compressed air has a much lower energy density than other commonly used energy sources used to drive machines.

Table 2
Energy density and specific energy of the different types of energy [19] [20]

No.	Type of energy	Specific energy [MJ/kg]	Energy density [MJ/l]
1	Gasoline	46.4	34.2
2	LPG	46.4	26.0
3	Diesel	45.6	38.6
4	Liquid hydrogen	141.9	8.45
5	Lithium-ion batteries [21]	0.4 - 1	0.9 - 2.5
6	Compressed air (300 bar) [15, 20, 22]	0.5	0.2

2 Calculation of Air Energy Density for Different Values of Air Pressure

The energy stored in compressed air can be defined as the work that the gas can do during expansion. The work done by the gas during expansion is equal to the area under the pressure-volume curve.

Figure 1 shows the gas expansion diagram. The work done by the gas during expansion is indicated by the blue lines. The work done by the gas during expansion, considering the atmospheric pressure outside the cylinder, is shown in green lines.

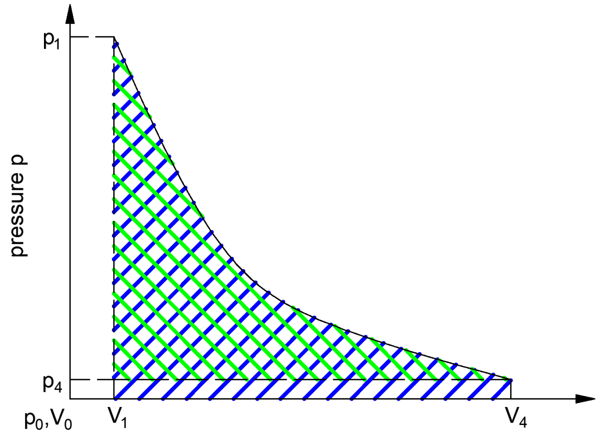

Figure 1

The gas expansion diagram. The work done by the gas during expansion is indicated by the blue lines. The work done by the gas during expansion, considering the atmospheric pressure outside the cylinder, is shown in green lines, p_1 – initial pressure, p_4 – atmospheric pressure, V_1 – initial volume, V_4 – final volume

In the further part of the paper, the work marked with green lines will be called useful work, and the work marked with blue lines will be called absolute work.

In the calculations, I will assume that compressed air is an ideal gas.

2.1 Work Done by Compressed Air in an Isothermal Process

Assuming ideal heat exchange, the energy stored in 1 liter of compressed air can be calculated as the work that the gas can do in an isothermal process.

The isothermal process is represented by the equation:

$$p_1 V_1 = p_4 V_4 \tag{1}$$

The absolute work done by the gas can be written as:

$$L = \int_{V_1}^{V_4} p \, dV \tag{2}$$

From equation (1) we can obtain the function p(V):

$$p = V_1 * p_1 * \frac{1}{V} \tag{3}$$

After substituting formula (3) into formula (2), we obtain the formula for absolute work:

$$L_{absolute\ isothermal} = V_1 * p_1 * \ln\left(\frac{V_4}{V_1}\right) \tag{4}$$

The absolute work done by the gas can also be calculated from the initial and final pressures:

$$L_{absolute\ isothermal} = V_1 * p_1 * \ln\left(\frac{p_1}{p_4}\right) \quad (5)$$

The equation of useful work can be written as the following equation:

$$L_{useful} = L_{absolute} - p_4(V_4 - V_1) \quad (6)$$

If the final pressure is equal to the atmospheric pressure, the useful work in an isothermal process can be written by the equation:

$$L_{useful\ isothermal} = V_1 * p_1 * \ln\left(\frac{p_1}{p_4}\right) - p_4(V_4 - V_1) \quad (7)$$

2.4 Specific Energy and Energy Density of Compressed Air - Calculation Results

Table 3 shows the maximum work done by one liter of compressed air during expansion in an isothermal process. The work values are shown for several pressures.

Table 3
Maximum work done by one liter of compressed air during expansion in isothermal processes

initial pressure of compressed air [bar]	100	150	200	300	350	700	1000
absolute work in isothermal process [kJ]	46.6	75.8	106.6	171.8	205.7	459.3	691.6
useful work in isothermal process [kJ]	36.6	60.8	86.6	141.8	170.7	389.3	591.6

Exergy is the maximum work that a gas can do when it comes into equilibrium with its surroundings. For compressed air, exergy is useful work in an isothermal process. The exergy values are marked in green in Table 3. The value of exergy best corresponds to the term: *the amount of energy stored in compressed air.*

Table 4 presents the specific energy and energy density values of compressed air.

Table 4
Specific energy and energy density values of compressed air

pressure of compressed air p_1 [bar]	100	150	200	300	350	700	1000
density [kg/liter]	0.12	0.18	0.24	0.36	0.42	0.83	1.2
energy density (kJ/liter)	36.6	60.8	86.6	141.8	170.7	389.3	591.6
specific energy (kJ/kg)	305.0	338.5	362.5	396.3	409.2	467.3	497.2

The energy density and specific energy values presented in Table 4 are different from those given in some articles [9][14]. The difference may be due to the adoption of a different type of work in the calculation - absolute work rather than useful work.

3 Calculation of the Work done by Expanding Air in a Typical Pneumatic System

In a typical pneumatic drive system powered from a compressed air tank, there is a reducing valve that reduces the pressure to the required pressure value. Next, through the valve system and the buffer tank, the air goes to the executive element, which converts the expanding air into mechanical work.

Figure 2 shows a simplified diagram of a pneumatic drive system that includes a pressure tank, a pressure reducing valve, a buffer tank, a diverting valve and an actuator. Pressure drops are also marked on the diagram.

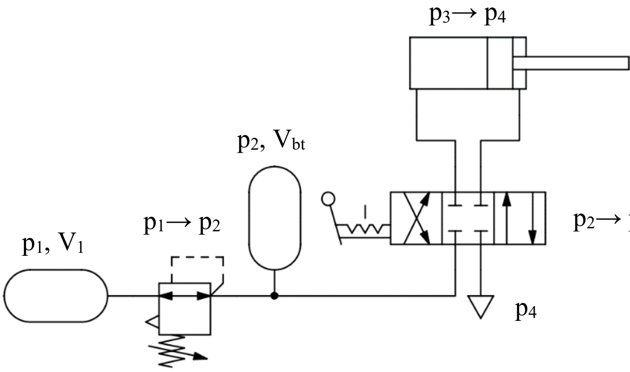

Figure 2

Simplified diagram of a pneumatic drive system that includes a pressure tank, a pressure reducing valve, a buffer tank, a diverting valve and an actuator, p_1 – pressure in the pressure tank, V_1 – pressure cylinder volume, p_2 – pressure downstream of the pressure reducer, V_{bt} – buffer tank volume, p_3 – pressure entering the actuator, p_4 – atmospheric pressure

In practice, it is impossible to use all the energy stored in compressed air. Losses are mainly caused by:

- Throttling on the reducing valve. The reduction is required, because the engine is running at a lower pressure than the pressure stored in the pressure tank
- Filling the dead volume
- Pressure losses on diverting valves

Figure 3 shows a proposal for a graphical interpretation of the work done by the gas during expansion and the losses in the pneumatic system in Figure 2.

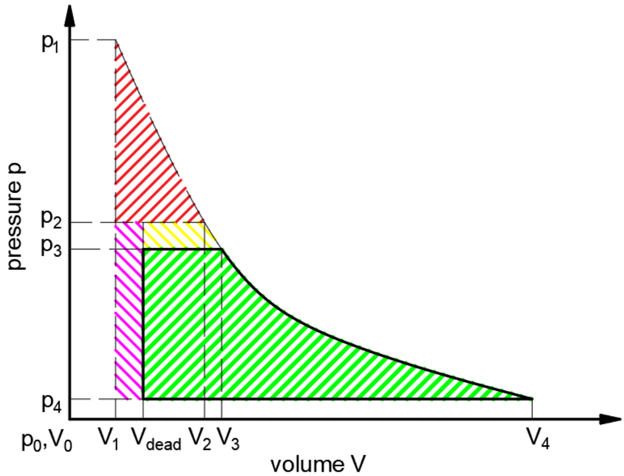

Figure 3

Proposal for a graphical interpretation of the work done by the gas during expansion and the losses in the pneumatic system, p_1 – pressure in the pressure tank, V_1 – pressure cylinder volume, p_2 – pressure downstream of the pressure reducer, V_{bt} – buffer tank volume, p_3 – pressure entering the actuator, p_4 – atmospheric pressure

Let's assume a hypothetical pneumatic system according to the diagram in Figure 2, in which the actuator has an infinitely long stroke, and the diverting valve will be switched all the time to its right position. In such a system, the work done by the gas will initially result from filling the actuator with air at pressure p_3. Then, the work of the gas will result from the expansion of the gas accumulated in the actuator and in the dead volume. In the graph in Figure 3, the work done by the gas is marked in green. The entire field marked in Figure 3 (red field, pink field, yellow field, and green field) is the maximum useful work that can be done by a gas with initial pressure p_1 and initial volume V_1. The red field shows the pressure losses on the reducing valve. The pink field represents dead volume losses. The yellow field indicates pressure losses on the diverting valves. The work marked in green is spent on overcoming friction losses in the actuator and performing the task entrusted to the actuator.

The work that the can be done by the gas in the actuator of such a pneumatic system can be calculated as the green field.

Assuming an isothermal process, the green area can be calculated as follows:

$$L_{green\ field} = V_1 * p_1 * \ln\left(\frac{p_3}{p_4}\right) - V_{dead} * (p_3 - p_4) \tag{8}$$

In order to estimate the work that can be done in the system in Figure 2, I make the following assumptions:

- The dead volume V_{dead} is 10% the volume V_2
- Pressure loss on the control valves (p2→ p3) is 10%
- The pressure value is reduced 20 times, on the reducing valve (p1→ p2), but the pressure value p_2 is not lower than 11 bar
- Compressed air in the actuator can expand to atmospheric pressure

Table 5 shows the values of the useful work that can be done by 1 liter of compressed air in the isothermal process for the adopted assumptions (green field). The work values are given for different initial pressures.

Table 5
The values of the useful work done by 1 liter of compressed air in the isothermal process for the adopted assumptions. The work values are given for different initial pressures.

initial pressure of compressed air p_1 [bar]	100	150	200	300	350	700	1000
useful work done by 1 liter of compressed air in an isothermal process for the adopted assumptions [kJ]	22.2	33.3	44.3	77.5	95.4	237.0	373.2

4 Estimation of the Theoretical Maximum Range of Pneumatic Vehicles

The theoretical range can be estimated on the basis of the energy stored in the pressure tank and the resistance to motion of the vehicle, the drivetrain efficiency and the efficiency of the pneumatic system.

4.2 Vehicle Motion Resistance when Driving at a Constant Speed

Vehicle motion resistance is calculated as the sum of aerodynamic drag and wheel rolling resistance:

$$F_{vehicle\ motion\ resistance} = F_{aerodynamic\ drag} + F_{rolling\ resistance} \quad (9)$$

Wheel toe-in resistance and damping resistance were omitted due to their small values.

Table 6 shows the driving resistance of vehicles for various values of vehicle weight. The resistances are presented for the vehicle speed equal to $v = 50\frac{km}{h}$.

Table 6
The driving resistance of vehicles for various values of vehicle weight. The resistances are presented for the vehicle speed equal to $v = 50\frac{km}{h}$.

vehicle weight [kg]	200	500	1000	1500	2000
rolling resistance [N]	19.6	49.5	99.0	148.4	197.9
aerodynamic drag [N]	80	80	80	80	80
total resistance to motion [N]	99.6	129.5	179.0	228.4	277.9

4.2 Theoretical Range of Pneumatic Vehicles

The range of the compressed air vehicle can be calculated using the formula below:

$$s = \frac{L}{F_{vehicle\ motion\ resistance}} * \eta_1 * \eta_2 \qquad (10)$$

where:

s Vehicle range

L Work, that can be done in a pneumatic drive system by expansion of compressed air stored in a pressure tank

η_1 Drivetrain efficiency, I assume $\eta_1 = 0.9$

η_2 Efficiency of the air motor, I assume $\eta_2 = 0.9$

Table 7 shows the theoretical range of compressed air vehicles moving uniformly at a speed of $v = \frac{50\ km}{h}$. The range values are given for different values of the initial pressure stored in the pressure tank and for different vehicle weights. The range value is based on 1 liter of compressed air. The values of the ranges were calculated from the formula (10) and based on data from Table 5 and Table 6.

Table 7
The theoretical range of compressed air vehicles moving uniformly at a speed of $v = 50\frac{km}{h}$. The range values are given for different values of the initial pressure stored in the pressure tank and for different vehicle weights. The range value is based on 1 liter of compressed air

Initial pressure of pressure tank p_1 [bar] / Vehicle mass [kg]	100	150	200	300	350	700	1000
200	181 m	270 m	360 m	630 m	776 m	1928 m	3035 m
500	139 m	208 m	277 m	485 m	597 m	1483 m	2335 m
1000	101 m	151 m	200 m	351 m	432 m	1073 m	1689 m
1500	79 m	118 m	157 m	275 m	338 m	841 m	1324 m

2000	65 m	97 m	129 m	226 m	278 m	691 m	1088 m

5 Presentation of the Simulated Vehicle

Table 8 shows the basic parameters of the tested vehicle.

Table 8
The basic parameters of the tested vehicle

No.	Parameter	Value
1	mass of the vehicle with the driver	200 kg
2	aerodynamic drag coefficient	0.5
3	efficiency of the drive system	0.9
4	efficiency of the pneumatic system	0.9
5	length	2350 mm
6	width	1400 mm
7	height	1100 mm
8	front surface	1 m^2

The diagram of the pneumatic system of the vehicle is shown in Figure 4.

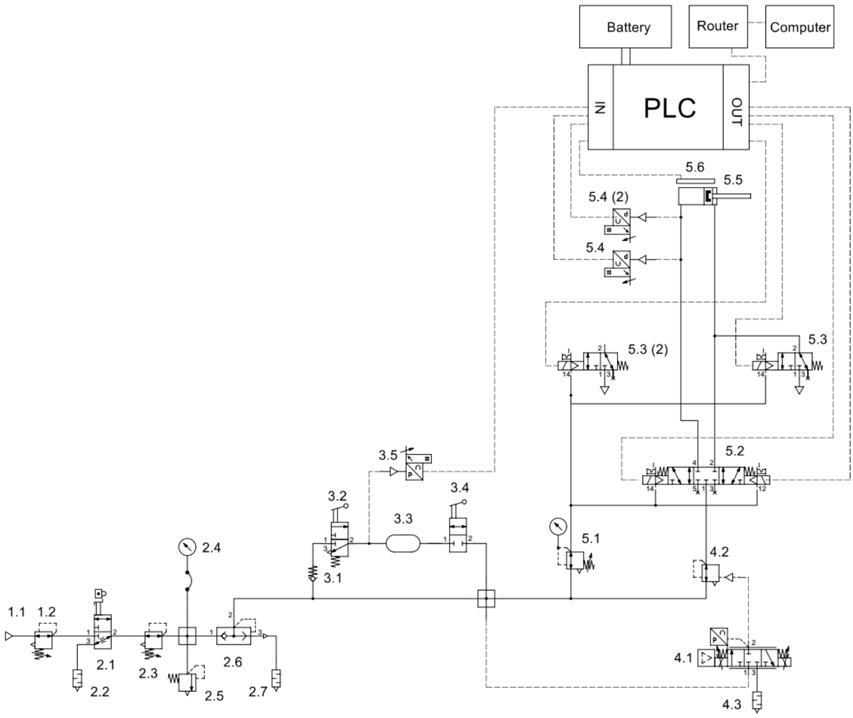

Figure 4
Scheme of the pneumatic system in the vehicle [23]

6 Analytical Calculations of Vehicle Range

The range of the vehicle is calculated from the formula (10).

6.1 The Work of Compressed Air, that can be Performed by the Pneumatic System

The work of compressed air that can be done by the pneumatic system in the presented vehicle is calculated from formula (8).

I make the following assumptions for the calculations:

- Dead volume is the volume of the buffer tank
- The air, in the actuator, can expand to a pressure of 1 bar

- When driving at a speed of 15 km/h, the pressure fed to the actuator will be equal to the reduced pressure. I assume no pressure loss due to the small flow required
- When driving at maximum speed, the pressure supplied to the actuator will be equal to 90% of the reduced pressure. I assume pressure loss due to high flow

6.2 Movement Resistance

Vehicle motion resistance is calculated as the sum of aerodynamic drag and wheel rolling resistance. Wheel toe-in resistance and damping resistance were omitted due to their small value.

6.2.1 Rolling Resistance

I assume that rolling resistance is constant. Rolling resistance can be described by the formula:

$$F_{rolling\ resistance} = m * g * \frac{f_t}{r_d} \tag{11}$$

where:

m mass of the vehicle with the driver, I assume m =200 kg
f_t coefficient of rolling friction for a bicycle tire, I assume = 4.5 mm [24]
r_d tire dynamic radius, r_d = 250 mm

6.2.2 Aerodynamic Drag

Data for aerodynamic drag calculations are given in Table 8.

7 Simulation Model

In the Simcenter Amesim program, a block model was built containing all pneumatic and mechanical elements of the system. The block model is shown in Figures 5 and 6.

Figure 5 shows a block model of the pneumatic system.

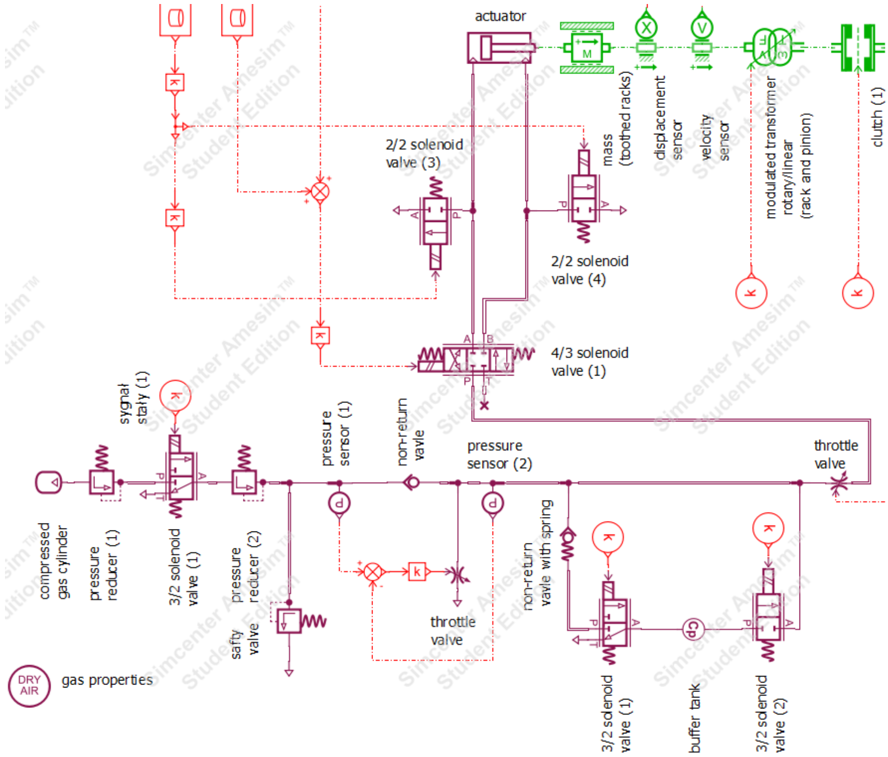

Figure 5

Simulation model of the pneumatic system made in Simcenter Amesim [23]

Figure 6 shows a block model of the mechanical system.

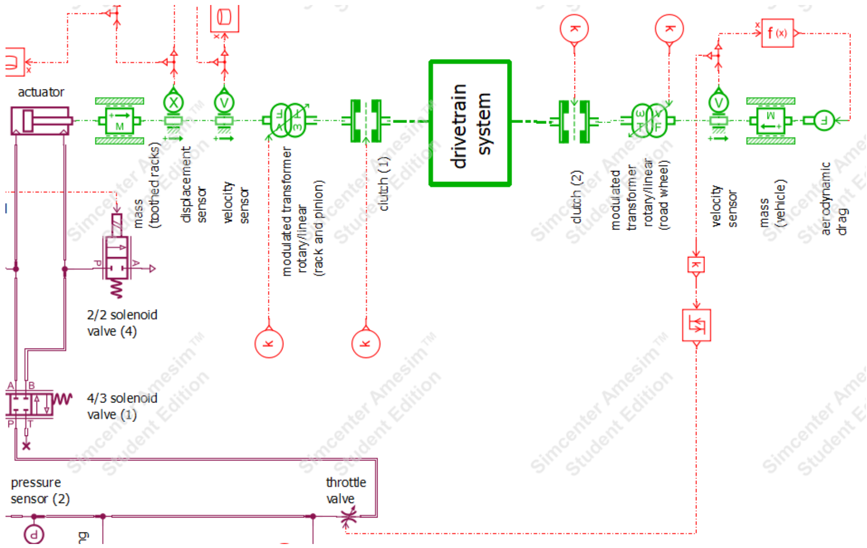

Figure 6
Simulation model of the mechanical system made in Simcenter Amesim. Only the start and end of the propulsion system are shown.

Table 8 shows the boundary conditions of selected block elements of the Simcenter Amesim model.

Table 8
The boundary conditions of selected block elements of the Simcenter Amesim model

No.	The name of the component or components in the pneumatic system	Boundary condition
1	pressure cylinder	Volume: 10 liters, initial pressure: 201 bar
2	actuator	stroke: 50 cm, piston diameter: 80 mm, piston rod diameter: 25 mm, thermal conductivity: 60 000 W/K*m^2.
3	buffer tank	volume: 10 l, thermal conductivity: 29 000 W/K*m^2
4	pneumatic hose	internal diameter of wires: 10 mm, thermal conductivity: 420 W/K*m^2,
5	solenoid valves	orifice area:120 mm^2
6	vehicle	rolling resistance (constant): 35.3 N, weight: 200 kg
7	aerodynamic drag	drag coefficient: 0.5

8 Results of Simulations and Analytical Calculations

8.1 Vehicle Range Calculations for a Speed of 15 km/h

Table 9 presents the vehicle range values for simulations and analytical calculations. Calculations and simulations were carried out for the average vehicle speed of 15 km/h for four values of the reduction pressure on the reducing valve. For each value of the reduction pressure, the amount of air dose was calculated. After delivering a dose of compressed air, the valve supplying compressed air was closed. The further movement of the actuator was caused by the expansion of the air.

For the purpose of elaborating the results, I define three terms:

- $$\text{calculation accuracy} = 100 * \frac{\text{range (simulation)}}{\text{range (calculations)}} \quad (12)$$
- $$\text{theoretical efficiency} = 100 * \frac{\text{compressed air exergy}}{\text{range (calculations)} * \text{movement resistance}} \quad (13)$$
- $$\text{actual efficiency} = 100 * \frac{\text{compressed air exergy}}{\text{range (simulations)} * \text{movement resistance}} \quad (14)$$

Table 9

Vehicle range according to simulation and analytical calculations for an average vehicle speed of 15 km/h with partial filling of the chamber

reduced pressure p_2 [bar]	11	9	6	4
range according to simulation [m]	7641	7435	6484	5093
range according to analytical calculations [m]	9235	8507	6998	5449
calculation accuracy [%]	82.7	87.4	92.7	93.5
theoretical vehicle efficiency [%]	43.2	39.8	32.7	25.5
actual vehicle efficiency [%]	35.8	34.8	30.3	23.8

Table 9 shows that the calculation accuracy is in the range of 83% to 94%, and the value of the actual efficiency of the vehicle is in the range of 24% to 36%.

Figure 7 shows the course of pressure and temperature in both cylinder chambers as a function of time and the position of the piston as a function of time. The pressure reduction value on the reducing valve is 11 bar.

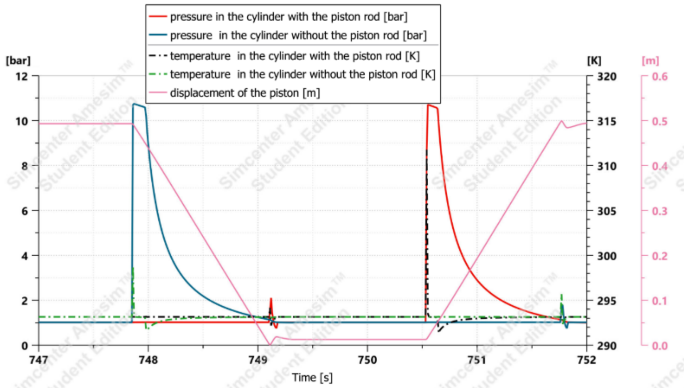

Figure 7

The course of pressure and temperature in both cylinder chambers and the position of the piston in the function of time

In Figure 7 in the diagram, it can be seen that the pressure supplied to the engine is about 10.6 bar (the pressure drop is only 0.4 bar). When opening the inlet valves to the actuator chamber, the air temperature in the actuator chamber temporarily dynamically increases by about 20 K. After closing the intake valves, the air begins to expand, and its temperature temporarily decreases by about 1.5 K. Fluctuations in the air temperature inside the actuator during its actuator do not exceed 20 K. It can be seen that the temperature fluctuations are much smaller, than they would be during adiabatic expansion.

Figure 8 shows the pressure and temperature in both cylinder chambers as a function of time and the shows the piston position in the time function. The pressure reduction value on the reducing valve is 4 bar.

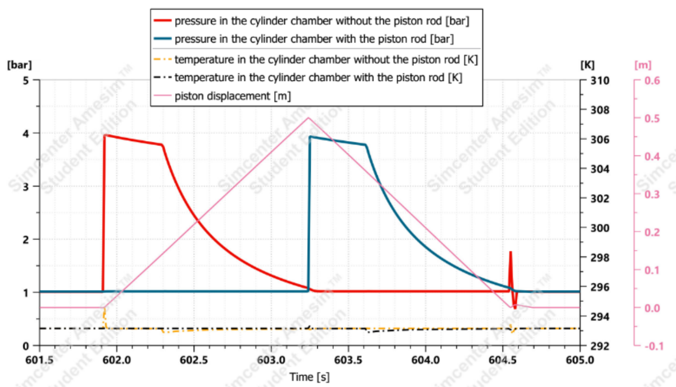

Figure 8

The course of pressure and temperature in both cylinder chambers as a function of time and the position of the piston in a function of time

In Figure 8 on the diagram, it can be seen that the pressure supplied to the engine is about 3.9 bar (the pressure drop is only 0.1 bar). When opening the intake valves to the actuator chamber, the air temperature in the actuator chamber temporarily increases dynamically by about 1.5 K. When the intake valves are closed, the air temperature value does not change. Fluctuations in air temperature inside the actuator during its actuator do not exceed 1.5 K. It can be seen that the temperature fluctuations are much smaller than they would be during adiabatic expansion.

8.2 Vehicle Range Calculations for your Maximum Speeds

Table 10 shows the vehicle range values for simulation and analytical calculations. Analytical calculations of the range were carried out only on the basis of the values of the average resistance of movement of the simulated vehicle.

Table 10
The range of the vehicle according to simulation and analytical calculations for the maximum average speed achieved during the simulation

reduced pressure p_2 [bar]	11	9	6	4
average speed during simulation [km/h]	34.27	32.23	24.5	20.01
maximum speed during simulation [km/h]	45.27	39.63	28.24	22.4
average value of motion resistance during simulation [N]	69.1	63.4	50.8	45.5
range according to simulation [m]	4198	4502	4816	4344
range according to analytical calculations [m]	5415	5541	5585	4858
calculation accuracy [%]	77.5	81.2	86.2	89.4
theoretical vehicle efficiency [%]	43.2	40.6	32.8	25.5
actual vehicle efficiency [%]	33.5	33.0	28.3	22.8

Table 10 shows that the accuracy of the calculation is in the range of 78% to 89%, and the value of the actual efficiency of the vehicle is in the range of 23% to 34%.

Figure 9 shows the pressure course just after the reducing valve, in the buffer tank and in the rodless chamber of the actuator in the time function. The pressure reduction value on the reducing valve is 11 bar. During a constant vehicle speed, the pressure supplied to the actuator is approximately 9.9 bar (pressure drop is 1.1 bar).

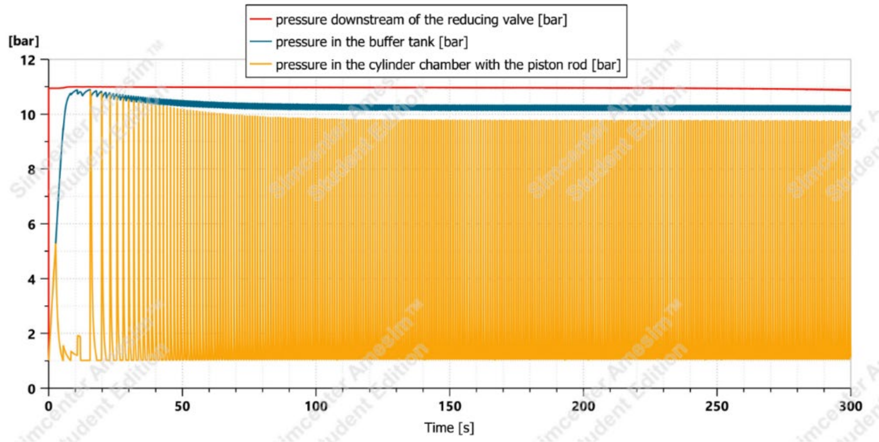

Figure 9

Pressure course downstream the reducing valve, in the buffer tank and in the rodless chamber of the actuator as a function of time

Figure 10 shows the pressure and temperature in both cylinder chambers as a function of time and the piston position as a function of time. The pressure reduction value on the reducing valve is 11 bar.

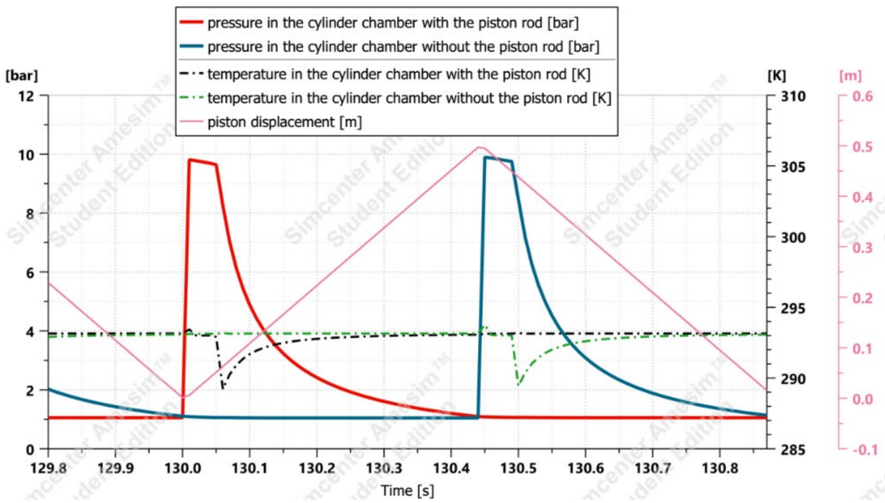

Figure 10

The course of pressure and temperature in both cylinder chambers as a function of time and the position of the piston in a function of time

In Figure 10, the diagram shows that the pressure supplied to the actuator is approximately 9.9 bar (the pressure drop is only 1.1 bar). When opening the inlet valves to the actuator chamber, the air temperature in the actuator chamber temporarily dynamically increases by about 11 K. After closing the intake valves, the air begins to expand and its temperature temporarily decreases by about 5 K. It can be seen that the temperature fluctuations are much smaller than they would be during adiabatic expansion.

Conclusions

This article calculates the energy of compressed air, depending on the pressure. The resistance to motion of typical passenger cars depending on the mass and speed has also been calculated. On the basis of this information and the assumed efficiencies, it was possible to estimate the vehicles range and consumption of compressed air in a theoretical compressed air vehicle.

The article also describes the simulation tests in the Simcenter Amesim program, which allows determination of the range of a compressed air vehicle designed at the Wrocław University of Technology. The simulations confirmed the results of analytical tests with satisfactory accuracy of 78% to 94%, depending on the particular case examined. According to simulation calculations, a pneumatic vehicle built at the Wrocław University of Technology uses from 23% to 36% of compressed air energy stored in a compressed air tank, to overcome resistance to motion. The rest of the energy is lost in the pneumatic system on the reducing valve, to fill the dead volume, to pressure losses during the flow and to friction losses in the actuator and drivetrain. This paper also shows the calculation methods, which can enable the initial selection of the pressure tank for the pneumatic vehicle.

Due to the low energy density of compressed air (about 90 times lower, than the energy density of gasoline), compressed air vehicles seem to be only suitable for urban transport. Urban vehicles can be small and light, which will ensure low resistance to motion. In addition, a cities infrastructure, could provide the possibility of frequent charging of the compressed air tank. If compressed air vehicles are used in transport, they will need much larger compressed air tanks, than those used for gasoline combustion cars.

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