CHARACTERISTIC FEATURES OF THE AIRFLOW OF PNEUMATIC ELEMENTS OF AGRICULTURAL VEHICLES

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INTRODUCTION

Various elements, which are used in pneumatic systems, such as valves, regulators, connecting pieces, air pipes, and nozzles, are characterised by internal volume (capacity) and resistance. The air-stream, flowing successively through the elements of the system, changes its shape, direction, density, pressure and temperature. The complexity of the processes, which are connected with the air flowing through the pneumatic devices, complicates the dynamics of the modelling of the multi-element pneumatic systems, where it is practically impossible, via calculation, to define the characteristics of the airflow, i.e. the dependence of the mass air-stream, which flows through the resistance element, on the factors which cause the flow. Consequently, the characteristics of the airflow for most of the pneumatic elements should be determined experimentally.

The paper aims to evaluate the suitability of the typical models of characteristics of the airflow for the description of the dynamics of airflow through the elements used in the pneumatic systems of agricultural vehicles. The analysis is based on the experimental investigations carried out in accordance with the method devised by the authors.

A METHOD OF DEFINING THE PARAMETERS OF THE CHARACTERISTICS OF THE AIRFLOW

For the calculation of the intensity of the airflow in the pneumatic resistance element a range of theoretical and empirical formulas, determined for the most typical pneumatic elements such as nozzles, local resistance elements (orifice, gland) and linear resistance elements (air pipes, long pipelines) is used. In order to unify the mathematical description of the mass of the air flowing through various resistance elements the selected dependencies are brought to the form used for the adiabatic flow through the nozzles [4]:

$$Q = (\mu A) \cdot v_m \frac{p_1}{R \cdot T_1} \varphi_{\max}(\sigma) \cdot \varphi(\sigma) \tag{1}$$

where:

(μA) – is conductance (the effective field of the flow) (m^2),
T_1 – is the temperature of the air before the resistance element (K),
σ – is the ratio of the pressure p_2 (Pa) after the resistance element to the pressure p_1 (Pa) before it,
$\varphi(\sigma)$ – is the nondimensional function of the airflow,
R – is the gas constant, for air R = 287.14 [J/(kg·K)],
v_m – is the velocity of sound propagation in the immovable gas $v_m = \sqrt{\kappa \cdot R \cdot T_1}$,
κ – is the adiabate coefficient,
$\varphi_{\max}(\sigma)$ – is the maximal value of the Saint Venant and Wantzel's theoretical function:

$$\varphi_{\max}(\sigma) = \sqrt{\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}} = 0{,}578 \cdot$$

On the basis of the dependence (1) it is possible to confirm the fact that the determination of the characteristic of the airflow of a tested element comes to the identification of the parameters of the selected form of the function of the airflow $\varphi(\sigma)$ and the parameter (μA), which defines the abilities of the airflow.

Here the method of the process identification is used in 2 stages: the first stage is a physical experiment based on the air-stream flowing through the tested element; the second one is a numeric experiment, where numeric values of the unknown parameters are determined.

A test bed for the realisation of the experimental stage was installed at the Agricultural Machines and Vehicles Department of the Bialystok Institute of Technology. The test bed is shown schematically in Fig. l.

With a sudden opening of the electromagnetic valve (4) the compressed air from the air-holder (3) flows through the tested element (5) to the air-holder (6). The air pressure is registered in the emptied air-holder (3) and the filled air-holder (6) as well as directly before the tested element (5). It should be noticed that another measuring system is also possible: the air-holder (6) comes off and the air flows from the tested element directly to the atmosphere. In order to simplify the measuring position the method of intermediate measurement of the intensity of the airflow on the basis of the registered pressure changes in the process of filling a constant volume chamber through the given resistance element was accepted. Assuming the adiabatic character of the process, the change of the air mass in a capacity can be performed by the formula:

$$Q = \frac{dm}{dt} = \frac{V}{\kappa RT} \cdot \frac{dp}{dt} \tag{2}$$

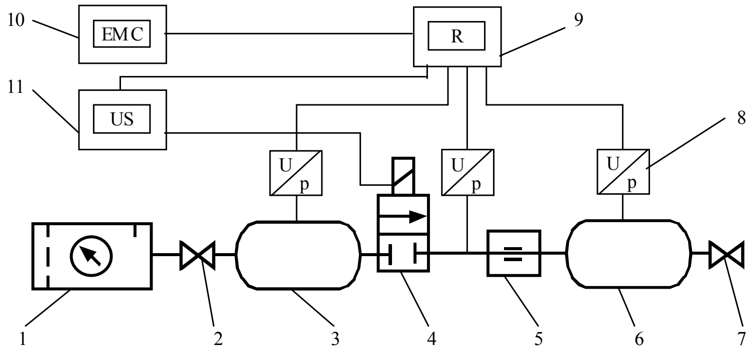

Fig. 1. The scheme of the test bed: l – air preparation station; 2, 7 – blocking ball valve QH 1/4; 3 – air-holder (emptied); 4 – electromagnetic valve MV1H-2- 11/2; 5 – the tested element; 6 – air-holder (filled); 8 – pressure converter P15RVA1/10B; 9 – registrar MC201 A; 10 – computer; 11 – controlling device

For the development of the mathematical model of the measurement system the formula is substituted by the analytical diagram (Fig. 2).

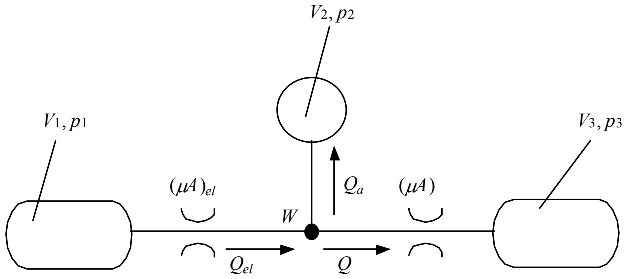

Fig. 2. Analytical diagram of the capacity: V_1 = 40.23·10-4 (m^3) is the volume of the emptied air-holder; V_2 = 0.308·10-4 (m^3) is the volume of the intermediate chamber (the air-pipe which connects the electromagnetic valve with the tested element); V_3 = 40·10^{-4} (m^3) is the volume of the filled air-holder; Q_{el}. is the total air-stream which flows through the electromagnetic valve; Q_a is the total air-stream accumulated in the intermediate volume; Q is the total air-stream which flows through the tested element; $(\mu A)_{el}$ is the conductivity of the electromagnetic valve; (μA) is the conductivity of the tested element

Taking advantage of the node method for pneumatic networks [3], the equation of balance of the mass air-streams in node W was achieved:

$$Q_{el} - Q_a - Q = 0$$

where the separate air-streams are defined according to the equating of the gas state in a given volume:

$$Q_{el} = -\frac{V_1}{\kappa RT} \cdot \frac{dp_1}{dt} \quad Q_a = \frac{V_2}{\kappa RT} \cdot \frac{dp_2}{dt} \quad Q = \frac{V_3}{\kappa RT} \cdot \frac{dp_3}{dt}$$

Two separate resistance elements are presented in Fig. 2: the first one is the resistance element of an electromagnetic valve and the second one is the resistance of the tested element. According to the dependence (1) the equations of air-stream flow through the resistance elements are presented in the following form:

$$Q = (\mu A) \cdot v_m \cdot \frac{p_2}{RT} \cdot \varphi(\sigma_{kr}) \cdot \varphi\left(\frac{p_3}{p_2}\right)$$
$$Q_{el} = (\mu A)_{el} \cdot v_m \cdot \frac{p_1}{RT} \cdot \varphi(\sigma_{kr}) \cdot \varphi\left(\frac{p_2}{p_1}\right) \tag{4}$$

The described analytical diagram has been used at the second stage of the conducted research for the development of the numerical method for the identification of the parameters of the characteristic of the airflow. In the following iterations the theoretical change of pressure p_{3t} is being searched for on the basis of the registered changes of pressure p_{1d}, p_{2d}, p_{3d} in volumes V_1, V_2, V_3 through solving numerically the following differential equation according to the Fehlberg method:

$$\frac{dp_{3t}}{dt} = \frac{\kappa RT}{V_3}\left((\mu A) \cdot v_m \cdot \frac{p_{2d}}{RT} \cdot \varphi_{\max}(\sigma) \cdot \varphi\left(\frac{p_{3t}}{p_{2d}}\right)\right) \tag{5}$$

The conductance (μA) and the parameters of the function of the airflow are numerically identified by the Hook-Jeevs nongradient method of linear search in the process of minimisation of the expression:

$$\sum_{i=1}^{m} (p_{3di} - p_{3ti})^2$$

till the achievement of the required accuracy of the calculations. The matching degree of the registered change of pressure p_{3d} and the theoretical change of pressure p_{3t} is evaluated on the basis of the corrected value of the non-linear coefficient, improved on the degree of freedom:

$$R^2 = 1 - \frac{m-l}{m-1} \cdot \frac{\sum_{i=1}^{m} (p_{3d} - p_{3t})^2}{\sum_{i=1}^{m} (p_{3d} - \bar{p}_{3t})^2}$$

where:

l – is the number of significant coefficients of the regression equations,
m – is the number of the experimental points of the registered curve.

For the measurements data canvassing the standard software of the registrar MC201A was used; for the numeric parameters identification a special computer programme written in Delphi was used. Procedures published in article [1] were used in the solving of the differential non-linear equations and in the process of minimisation.

THE RESULTS OF THE CONDUCTED RESEARCH

For the identification of the characteristics of the airflow of the tested pneumatic elements used in tractors and agricultural trailers the function of the airflow, well known from the scientific literature, was used (Tab. 1). Function N 8 was achieved on the basis of the Dary and Weisbach's dependence for the adiabatic flow of the air through the air pipes [5]. For the isothermal flow $\kappa = 1$ its simplified version is achieved, which forms the basis of the method applied by L. Kaminski [2].

Table 1. The functions of the airflow

Nr	The function of the airflow	Mathematical form
1	Saint Venant and Wantzel's	$\varphi(\sigma)=\begin{cases}\frac{1}{\varphi_{\max}(\sigma)}\sqrt{\frac{2}{\kappa-1}\left(\sigma^{\frac{2}{\kappa}}-\sigma^{\frac{\kappa+1}{\kappa}}\right)} & \text{for } 0{,}53\le\sigma\le 1\\ 1 & \text{for } 0\le\sigma<0.53\end{cases}$
2	ISO 8778	$\varphi(\sigma)=\begin{cases}2\sqrt{\sigma(1-\sigma)} & \text{for } 0{,}5\le\sigma\le 1\\ 1 & \text{for } 0\le\sigma<0{,}5\end{cases}$
3	Sanville's [6] ISO 6358	$\varphi(\sigma)=\begin{cases}\sqrt{1-\left(\frac{\sigma-\sigma_L}{1-\sigma_L}\right)^2} & \text{for } \sigma_L\le\sigma\le 1\\ 1 & \text{for } 0\le\sigma<\sigma_L\end{cases}$
4	Miatliuk and Autushko's [4]	$\varphi(\sigma)=b\frac{1-\sigma}{b-\sigma}$
5	Miatliuk and Autushko's [4] B = const = 1.13	$\varphi(\sigma)=1.13\frac{1-\sigma}{1.13-\sigma}$
6	Woelke's [7]	$\varphi(\sigma)=\sqrt{1-\sigma^{a\exp\left(-b\cdot\sigma^2\right)}}$
7	Woelke's [7]	$\varphi(\sigma)=\begin{cases}\sqrt{\frac{1-\sigma^{a\cdot\exp(-b\sigma^2)}}{1-\sigma_L^{a\cdot\exp(-b\sigma^2)}}} & \text{for } \sigma_L\le\sigma\le 1\\ 1 & \text{for } 0\le\sigma<\sigma_L\end{cases}$
8		$\varphi(\sigma)=\sqrt{1-\sigma^{\frac{\kappa+1}{\kappa}}}$

For every element the testing is repeated at least 20 times, with the registration of periodical pressure changes in the filled (emptied) volumes of 2000 measuring points on each curve. Moreover, the curve segments which comply with the transient process (several hundred measuring points) were used for the identification. The examples of the experimental changes of absolute pressure p_{1d}, p_{2d}, p_{3d} in separate chambers and the theoretical change of pressure p_{3t} (continuous line) for pipe filter 8110 are shown in Figure 3.

The results of the identification of the characteristics of the airflow of the tested element, i.e. the value of conductance (μA) and of the coefficient of the function of the airflow $\varphi(\sigma)$ are presented in Table 2. Fig. 4 shows the diagram of the identified functions of the airflow for oil separator 42 480 141.

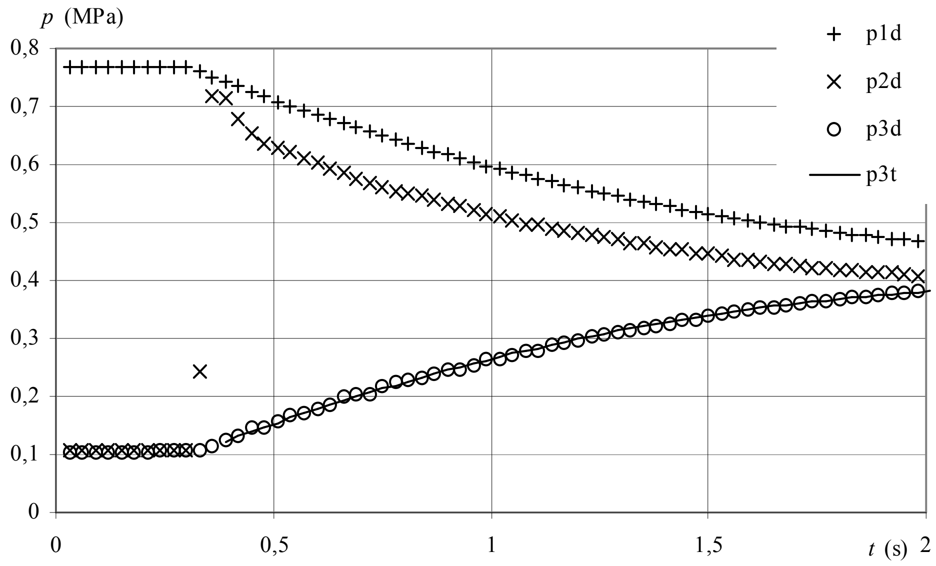

Fig. 3. Registered experimental changes of pressure p_{1d}, p_{2d}, p_{3d} and theoretical change of pressure p_{3t} deter mined by the differential equation (5) (every 10th measuring point is shown)

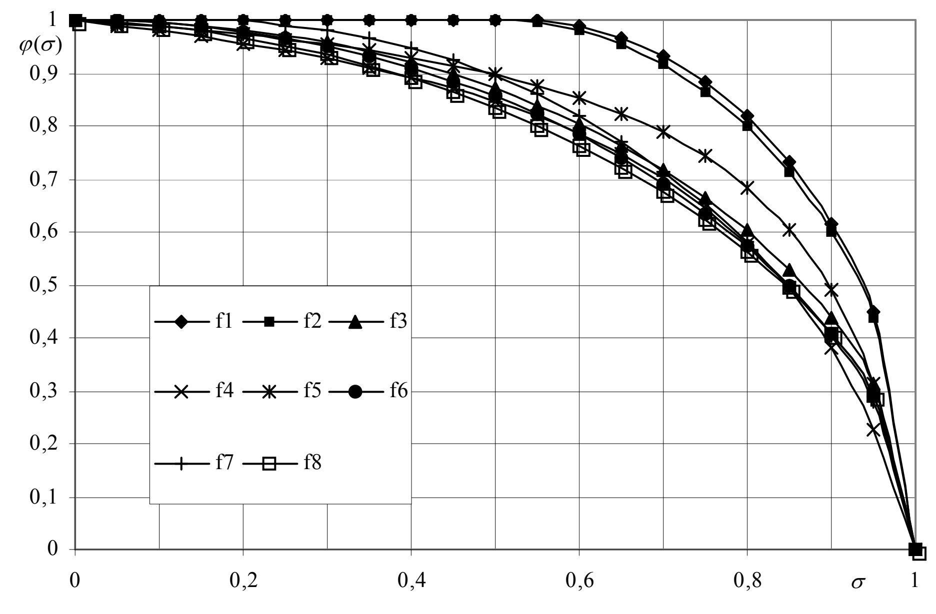

Fig. 4. The diagram of the function of the airflow $\varphi(\sigma)$ for oil separator 42 480 141

Table 2. Parameters of the characteristics of the airflow of selected elements for different directions of the flow [values $(\mu A) \cdot 10^{-5} m^2$]

Function	Pipe joint X50 13 00		Pipe filter 8110 (HF01)		Oil separator 42 480 141
	1-2	2-1	1-2	2-1	1-2
1	$(\mu A) = 4.08751$	$(\mu A) = 4.64707$	$(\mu A) = 5.40599$	$(\mu A) = 4.70456$	$(\mu A) = 3.47928$
2	$(\mu A) = 4.10443$	$(\mu A) = 4.65809$	$(\mu A) = 5.41581$	$(\mu A) = 4.72591$	$(\mu A) = 3.49232$
3	$(\mu A) = 4.52247$ $\sigma_L = 0.017$	$(\mu A) = 5.12201$ $\sigma_L = 0.037$	$(\mu A) = 5.97868$ $\sigma_L = 0.025$	$(\mu A) = 5.23623$ $\sigma_L = 0.023$	$(\mu A) = 3.87339$ $\sigma_L = 0.013$
4	$(\mu A) = 4.72335$ $b = 1.237$	$(\mu A) = 5.33197$ $b = 1.225$	$(\mu A) = 6.14112$ $b = 1.207$	$(\mu A) = 5.44301$ $b = 1.228$	$(\mu A) = 4.00485$ $b = 1.222$
5	$(\mu A) = 4.43674$	$(\mu A) = 5.04228$	$(\mu A) = 5.86443$	$(\mu A) = 5.12616$	$(\mu A) = 3.79226$
6	$(\mu A) = 4.74091$ $A = 1.644$ $b = 0.046$	$(\mu A) = 5.23326$ $A = 2.038$ $b = 0.231$	$(\mu A) = 6.04930$ $A = 1.983$ $b = 0.048$	$(\mu A) = 5.35552$ $A = 1.916$ $b = 0.110$	$(\mu A) = 3.95215$ $A = 1.976$ $b = 0.167$
7	$(\mu A) = 4.59112$ $A = 1.648$ $b = 0.048$ $\sigma_L = 0.188$	$(\mu A) = 5.22881$ $A = 1.693$ $b = 0.067$ $\sigma_L = 0.165$	$(\mu A) = 5.96534$ $A = 2.046$ $b = 0.106$ $\sigma_L = 0.145$	$(\mu A) = 5.22737$ $A = 2.025$ $b = 0.179$ $\sigma_L = 0.169$	$(\mu A) = 3.83044$ $A = 2.592$ $b = 0.626$ $\sigma_L = 0.166$
8	$(\mu A) = 4.69070$	$(\mu A) = 5.33696$	$(\mu A) = 6.20692$	$(\mu A) = 5.43752$	$(\mu A) = 4.01744$

For all the functions the values of the squared coefficients of non-linear regression, bigger than 0.99, were found. The numbers of separate functions on the diagram correspond to the numeration accepted in Tables 1 and 2.

CONCLUSIONS

High accuracy and repeatability of the parameters of the characteristics of the airflow of the tested elements were achieved owing to the application of the numeric method of identification. It results from using (during the process of identification) the whole diagram of the measured pressure changes in contradistinction to other methods [4] [2], which base mainly on several selected measuring points.

The analysis of the received results gives us the right to claim that for most of the tested pneumatic elements part of the function of the airflow forms a pencil of curves, which are very similar to each other. But then, the curves, which correspond to the theoretical function of Saint Venant and Wantzel (N l) and to its simplified formula (N 2) lie much above the level of the others and are characterised by the minimal values of coefficients of non-linear regression (Figure 4). The values of the effective surface of the flow (μA), determined on the basis of various models differ the less, the more the curves of the airflow are closer to each other. It should be stressed that the determined values of conductivity are to be used together with the model of the function of the airflow by which it was achieved.

For practical application functions N 3, 4 and 8 (Table 1) are advised because of their high accuracy and low time consumption of their computer identification. Sometimes, in the case of complicated multiparametral functions of the airflow (N 6) the process of computer identification of separate coefficients is very difficult or even impossible.

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SUMMARY

The article presents the method of the computer identification of the characteristics of the airflow of the pneumatic resistance elements. The results of the carried out researches for the selected pneumatic elements used in agricultural vehicles (oil separator, air-pipe filter and the joint of the air pipes) are applied. On the basis of the researches the verification of the basic models of the function of the airflow used in the simulation researches of pneumatic systems was performed.

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