Theoretical Characteristics of Fluid Flow within a Pneumatic System

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Abstract: *There are numerous applications in industry branches that use pneumatic drive to achieve various imposed movements for the working body. Here the working fluid is represented by a gaseous medium that is influenced by the temperature, humidity and pressure values. With regard to the flow pattern, a clear distinction must be made between the fluid volume at inlet and the discharge volume due to air compressibility properties. Specific parameters regarding the state of the working fluid are given by volume, pressure and temperature and any momentary modification of these specific values depends on the transformation mode to which the fluid is subjected at a given time. Theoretical flow aspects of the working fluid through a pneumatic installation model as well as the transformations to which the working fluid is subjected during operation are presented. Numerical flow analysis on a virtual model is used in order to highlight the primary flow parameters values for the pattern model containing distinct flow orifices paths used usually in pneumatic drive systems.*

Keywords*: Pneumatic system, air flow, circulation orifices, three-dimensional modelling, CFD*

1. Introduction

It is known that the bonds between the fluid molecules are weaker than the solids causing the flow, but in the case of gases the molecular bonds action has a virtually non-existent effect, causing rather a rejection between the molecules within the free space so that the distances between them become larger. This creates an environment that, unlike liquids, has a strong compressibility property at varying external pressure forces and at different temperature values.
The compressed air gaseous medium is used in pneumatically operated low pressure and force transmission systems as compared to hydraulic systems. General laws of fluid flow can be applied also to pneumatic drive with the particularity that the gaseous medium is directly influenced by temperature, humidity and pressure. Air density values decrease with temperature and humidity affects directly the transformations that occur in the gaseous fluid volume so that specific state parameters which can modify the working process based on energy transmission through pneumatic drive are influenced.
The pneumatic system is based on the compressed air circulation through the working equipment components with specific velocity and pressure values. This continuous fluid movement is inevitably accompanied by pressure losses and variations in the air flow rate due to the crossing of different network sections at a given time. Friction forces of the gaseous medium with different installation elements are encountered so that a part of the mechanical work produced for the fluid circulation is consumed to overcome these resistances. Energy consumption values results as a heat amount that is taken up by the gaseous medium. The flow pattern is considered to be in permanent mode with the same features as hydrostatic drive systems.

2. Specific transformations to the air mass within the pneumatic drive system

- Isocorous transformation or air conversion to a constant volume $\left(V_a = ct;\ dV_a = 0\right)$.
It is the case that the air mass is retained in an enclosure and receives or dissipates an amount of heat, in which case the mechanical work is zero and consequently the variation of the energy value is given by the amount of heat ceded or received by the air amount.
For two states of the gaseous medium (I and II) it can be write the state relation for the isocorous transformation in which the pressure variation is proportional to the absolute temperature: 0

$$\frac{p_I}{p_{II}} = \frac{T_I}{T_{II}} \tag{1}$$

$$\frac{p}{T} = ct. \tag{2}$$

- isobar transformation is specific to the case where a mass of air enclosed in a piston or membrane enclosure upon which a constant load is applied. At constant pressure values heat exchange with the external environment is achieved.

The thermal equation for two states of the gaseous medium corresponding to the isobar transformation shows that the volume variation is directly proportional to the absolute temperature: 0

$$\frac{V_I}{V_{II}} = \frac{T_I}{T_{II}} \tag{3}$$

$$\frac{V}{T} = ct. \tag{4}$$

- isothermal transformation is obtained when the temperature of the gaseous medium remains constant following the mechanical and heat exchange.

The internal energy of the fluid environment is constant and the heat amount is fully transformed into mechanical work. The state equation for two states of the gaseous medium (I and II) is: 0

$$p_I V_I = p_{II} V_{II} \tag{5}$$

$$pV = ct. \tag{6}$$

- adiabatic transformation describes where the mass of air receives and shares mechanically work but without exchanging heat with the outside environment.

$$pV^{x} = ct;\ T \cdot V^{x-1} = ct. \tag{7}$$

This is the case for pneumatic drives in which the working process takes place in a very short time so that heat exchange is not recorded.

- polytropic transformation is the general case where the specific heat is constant.

$$pV^{\kappa} = ct. \tag{8}$$

$$\kappa = \frac{C_p}{C_V} \tag{9}$$

3. Theoretical aspects for a fluid flow within a pneumatic installation

The pneumatic actuations practice involves the use of variable compressed air masses in order to achieve the proper work process. This change within the fluid mass used in the actuation determines changes in the state of specific parameters based on the thermodynamic process taking place within the pneumatic installation.
The use of a pneumatically-actuated linear motor involves considering the status of the gaseous medium at the inlet, inside the cylinder and at the device outlet.
The air flow through the installation takes place with pressure losses and changes in flow rates due to the resistance encountered inside the installation network. These losses need to be considered when designing and dimensioning the network elements by the design engineer.
For two flow sections considered on the network (I and II) the energy conservation equation for an M mass of air can be written: 0

$$E_{II} - E_I = Q_{I,II} - A\left(p_{II}V_{II} - p_I V_I\right) - \frac{AM}{2g}\left(\omega_{II}^2 - \omega_I^2\right) - AL_{fr\,I,II} - L_{ex} \tag{10}$$

Where:
E_I, E_{II} - internal energy values for section I and II;
ω_I, ω_{II} - medium values of air velocity for section I and II;
L_{ex} - mechanical work for exterior produced by kinetic energy of air for pneumo-dynamic actuation;
Taking into account the enthalpy of the gas used in the drive system, the state equation can be written as follows: 0

$$I_{II} - I_I = Q_{I,II} - \frac{AM}{2g}\left(\omega_{II}^2 - \omega_I^2\right) - AL_{fr\,I,II} - AL_{ex} \tag{11}$$

where:
I_I, I_{II} - air enthalpy for section I and II;
For a 1 kg air mass unit used in a pneumatic drive system, the conservation equation can be written as follows: 0

$$dE = dQ - Ad\left(pV\right) - Ad\left(\frac{\omega^2}{2g}\right) - AL_{fr} \tag{12}$$

Where considering the relation for fluid volume with specific weight $\left(V = \frac{1}{\gamma}\right)$ it can be written:

$$d\left(\frac{\omega^2}{2g}\right)+\frac{dp}{\gamma}+dL_{fr}=0 \tag{13}$$

Relationship that describes the possibility of changing the air kinetic energy and the mechanical workload in order to overcome the friction forces in the network together with the change in system pressure values.
By integrating into various types of transformations considered for the gaseous medium can be obtained the following relations:
- For adiabatic transformation: 0

$$\frac{\omega_{II}^2-\omega_I^2}{2g}+\frac{\kappa}{\kappa-1}\cdot\frac{p_I}{\gamma}\left[\left(\frac{p_{II}}{p_I}\right)^{\frac{\kappa-1}{\kappa}}-1\right]+L_{fr}=0 \tag{14}$$

- For isothermal transformation: 0

$$\frac{\omega_{II}^2-\omega_I^2}{2g}+\frac{p_I}{\gamma}\cdot\ln\frac{p_{II}}{p_I}+L_{fr}=0 \tag{15}$$

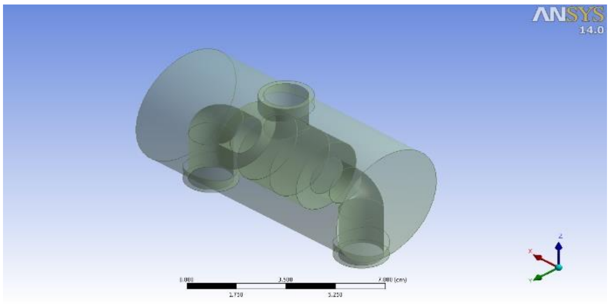
- For polytropic transformation: 0

$$\frac{\omega_{II}^2-\omega_I^2}{2g}+\frac{n}{n-1}\cdot\frac{p_I}{\gamma}\left[\left(\frac{p_{II}}{p_I}\right)^{\frac{n-1}{n}}-1\right]+L_{fr}=0 \tag{16}$$

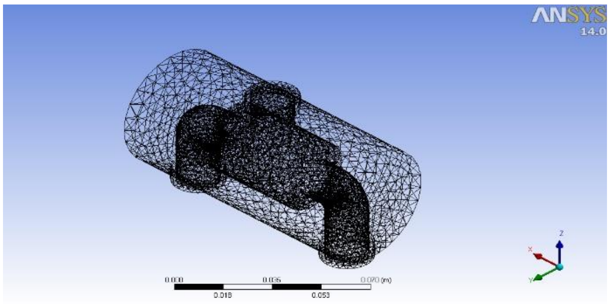
Particular flow characteristics occur in the air flow through the conduits of the pneumatic drive system and through different diameters orifices necessary to make the couplings between the pipes or with various appliances used in the installation assembly.

4. Air flow inside a circuit selector device virtual model

By analyzing the flow of the working fluid on the virtual model (figure 1), important details can be obtained regarding the occurrence of the fluid flow resistance and the areas in which it occurs, whether we are talking about pipes of different diameters, orifices or component devices used for adjusting the pressure or fluid flow rate values.
The use of fluid flow analysis methods provides the possibility to improve the fluid region shape inside the device model so as to minimize the losses due to the resistances occurring in the flow paths so as to manage and optimize the pumping needs and overall the costs of installation using.
The three-dimensional model of a circuit selector device is chosen to perform the flow analysis, as shown in figure 1 along with the mesh network model.



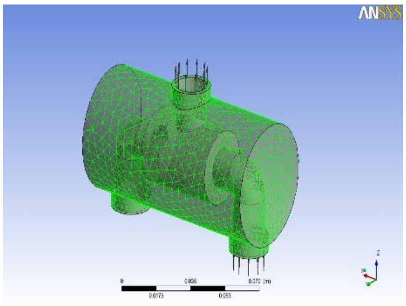
a) imported model



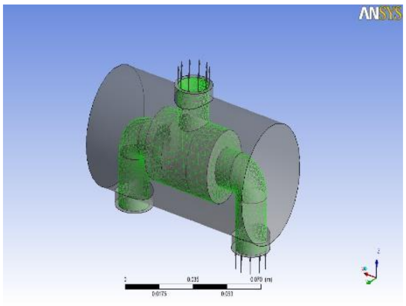
b) mesh network of triangular elements

Fig. 1. Three-dimensional assembly model taken into consideration for flow analysis

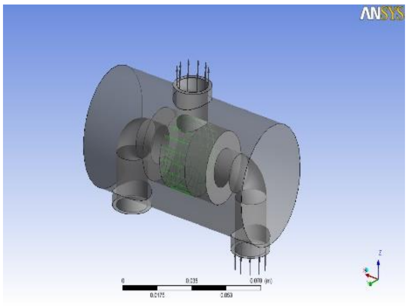
It is highlighted the operating principle for this particular device used to select a higher-pressure signal value within the working fluid that circulates from the inlet orifice that to the device outlet.
The analysis is based on the declared fluid velocity values at the inlet port and the axial displacement of the adjusting element positioned inside the model, which has the possibility of moving in one direction or another in order to provide the momentary connection of two orifices function of the higher fluid pressure value.
The main domains of the analysis are represented by the solid model or the device casing declared as outer walls, the fluid region positioned inside the device and the regulating element being declared as immersed solid within the fluid region.
The meshing network was made with triangular shape elements, with 42533 nodes and 221592 elements.
The working fluid is represented by air at 25 degrees Celsius with the k-Epsilon turbulence option for the fluid region.
The analyzed model has two inlet ports for the working fluid and one outlet. The adjusting element is represented by a centrally positioned cylindrical drawer that has the ability to perform translational movement within the selector device body.
In the set of initial values, the air inlet velocity is declared with a value of 3 m/s for the first case and then with a value of 5 m/s for the second case.
Also, for the immersed solid regulator element an axial directional movement is declared at a velocity value of 1 cm/s.
This device performs the selection of the high-pressure values, the fluid signal being sent further to the circuit by choosing the branch with the highest pressure at the two inlet ports.
Figure 2 shows the main domains of the analysis on the imported virtual model.



a) Device body



b) Fluid region



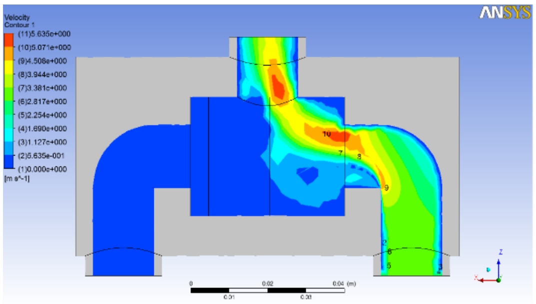
c) Immersed solid

Fig. 2. Flow analysis main domains

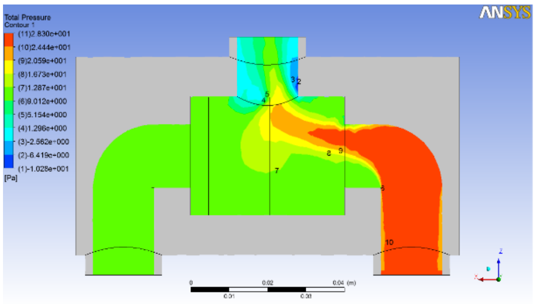
Thus, when the pressure value at one of the two inlet orifices is greater, the locking element is forced in translational motion opening the outlet, connecting in this way the two orifices and allowing the fluid to circulate along this new created path. The other branch is automatically blocked due to the position of the adjustment element.

The airflow analysis is performed with the Ansys CFX program.
The results are presented in terms of total pressure and fluid velocity values recorded for both analysed cases, (figure 3).

Case 1

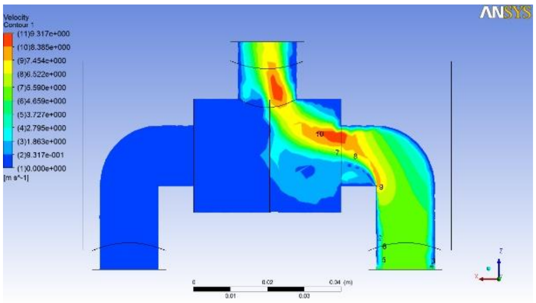


a) Fluid velocity values

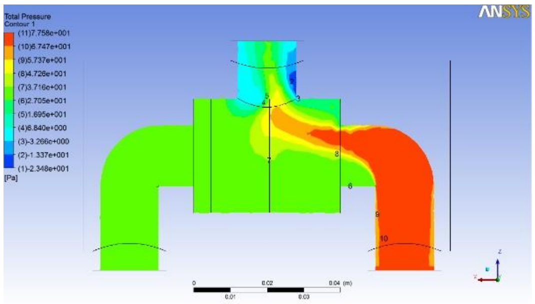


b) Total pressure values

Case 2



c) Fluid velocity values

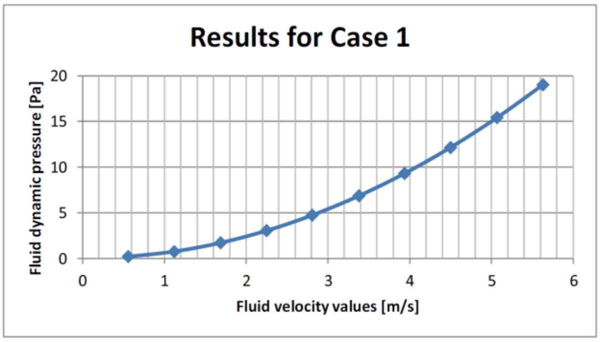


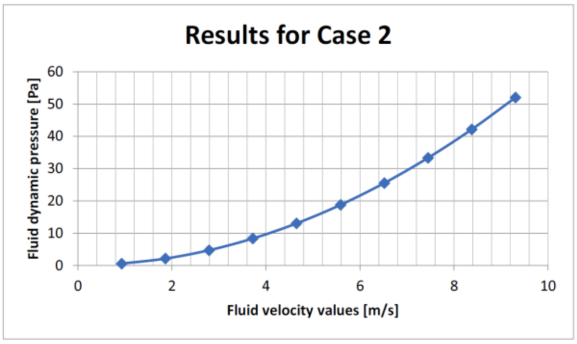
d) Total pressure values

Fig. 3. The flow analysis obtained result values

On the obtained results, can be observed the trajectory described by the working fluid inside the selection chamber, which due to the movement of the adjusting element (immersed solid) to the left direction has the possibility to circulate between the inlet and outlet orifice.
The distribution of velocity values and total pressure values on the active branch of the device model are presented.
Table 1 shows the variation diagrams for the total pressure component represented by the dynamic pressure. The exponential growth model for dynamic pressure is shown based on the operating fluid velocity values recorded for the fluid region in the two analysed cases.

Table 1





5. Conclusions

Pneumatic actuator drives are used in industry for a much lower range of pressures and powers compared to hydraulic drives.
For pneumatic drive, the compressor is used as a primary energy source in order to provide the compressed air demand for transport in the working circuit.
Specific industrial applications are using pneumatic drive and the required compressed air flow rate necessary to be supplied by the compressor can be estimated.
The air flow rate value supplied by the energy source must also take into account the losses within the installation that need to be defeated. These losses are due to the friction forces of the fluid with the crossed pipes walls, but also the various devices that are interposed on the circuit.
Such a device is also the selection valve whose model is presented and analyzed in the paper.
It represents a constructive solution for a device that is able to send forward in the circuit a signal of higher-pressure value.
Analysis of the air flow as working fluid is achieved on the valve virtual model.
The velocity distribution and pressure values recorded at the fluid region level are presented for the two analysed cases.
High fluid velocity values are noted in areas where the fluid is forced to circulate (reduced section), and the total pressure values are higher on the device inlet area to the adjustment drawer area. On the diagrams made for the total pressure component represented by the dynamic pressure in relation to the fluid velocity it can be noticed an exponential increase for both analyzed cases. Based on the results obtained from fluid flow analysis on the virtual model of the selection valve, are created the premises of optimizing the constructive shape of the apparatus in order to allow uniformity of the velocity and pressure values during operation, thus improving the values for the operating efficiency of the entire actuation drive.

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