

**Budapest University of Technology and
Economics
Faculty of Mechanical Engineering**

**Fluid mechanical properties of
pneumatic fluid power systems**

Thesis booklet

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1. Introduction

Work on numerical modeling of complex electro-pneumatic (EP) systems had been started in 1999 in the Department of Fluid Mechanics. The capabilities of computers in that time have allowed analyzing whole systems in the time domain, and not just some parts of it. This R&D topic has been based on the cooperation with Knorr-Bremse. The company is the leading supplier of braking systems for commercial vehicles of more than 6 tonne vehicle weight as well as railway vehicles. The Knorr-Bremse Research and Development Centre had been opened in 1999 in Budapest, and although the R&D activity in Hungary had already been started in 1995, the opening of the dedicated R&D centre provided a new boost in this area, and it has been a major motive of this work.

The capabilities of computers in that time were already quite acceptable; however, it still had several shortcomings. It was a major problem to create a software environment necessary to model complex EP systems. The resources of the Department were too restricted to develop such an environment. The logical choice was therefore to purchase such an environment. This was the new edition of the AMESim software from Imagine. This new edition has already possessed the capabilities necessary to model complex EP systems. However, it was perplexing that even this new version, which included more than 1000 different components in more than 10 libraries, still unable to provide a model which is able to accurately describe one of the key components of an EP system – the EP valve. Based on this fact, in my work I have concentrated to develop a new model of an EP valve, which is capable of predict the flow characteristics with an accuracy deemed acceptable from engineering point of view.

The development of computers means that experiments are increasingly substituted by numerical modeling. This can only be appropriate, if numerical models with acceptable accuracy are available. As nowadays the importance of the automotive safety systems are higher than ever and still growing, the analysis and design of better EP systems is still an important topic. Since I have unable to find an appropriate EP valve model in the literature, it seemed reasonable to develop one. This motivation has been boosted by the fact that these safety systems can prevent accidents and environmental disasters.

2. Results

The object of my investigation was a specific EP valve family which can be found in a number of EP systems, especially in the EP brake systems of commercial vehicles [1]. The aim was to analyze valves which are frequently used in systems where quick, reliable and accurate operation is essential, and which are used in systems under development. These valves – due to their low maximum flow rate – are often used as a control valve in pneumatic relay valves providing high flow rate and short response time [2][3]. The most important properties of these valves can be found in the list below, and the layout is displayed on **Fig. 1**.

- Small size and weight for quick response and low current demand.
- Switching time is typically in the millisecond range.
- Low flow rate because of the small orifice diameter (1-2 mm range).
- As it is usually a control valve, the knowledge of the flow characteristics is paramount for reliable system modeling.
- Bistable, which means it can hold two stable states (open/closed).
- Pressure range is typically 1-13 bar.
- The air enters through a circular envelope, almost radially. After an approximately 90° turn, the air exits via a short (approx. 5-10 mm), cylindrical tube axially.

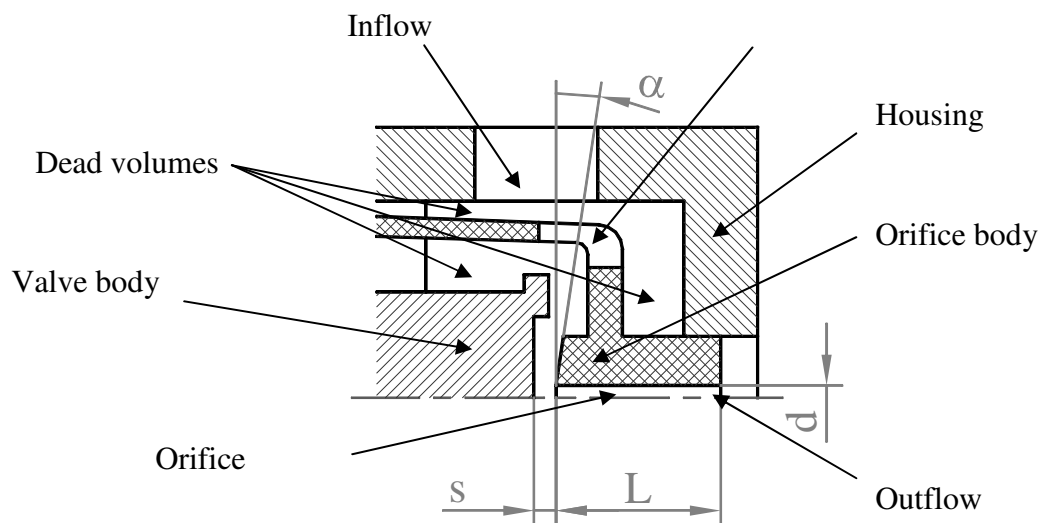


Fig. 1.: Flow geometry

During modeling of EP valves the important parameters from fluid mechanic point of view are the pressure, temperature, mass flow rate and enthalpy flow rate. By concentrating the analysis further, it can be said that the most important flow parameter of an EP valve is the mass flow rate, which depends on a number of other parameters. Usually, however, in a production system the mass flow rate depends mainly on the valve pressure ratio and the properties of gas entering to the valve, because the geometry of the valve is given, and the usual EP valves are either opened or closed. Proportional valves are quite rarely used in EP systems of commercial vehicles, because they are much more expensive than a simple bistable EP valve, they are larger, have more weight and need more energy to operate for a given flow rate. In simple bistable EP valves the valve body is located in one of the two end positions during the majority of operation, therefore the valve geometry can be considered

constant. To model an isentropic, stationary flow, the mass flow rate can be calculated using the following equation [4][5][6]:

$$q_m = A \cdot C_m \cdot \frac{P_u}{\sqrt{T_u}} \quad (1)$$

As in real gases there will always be some kind of loss and contraction, it is modeled using the flow coefficient (C_q):

$$q_m = A \cdot C_q \cdot C_m \cdot \frac{P_u}{\sqrt{T_u}} \quad (2)$$

Where the mass flow rate (q_m) is the function of the upstream pressure (p_u) and temperature (T_u), the smallest geometric cross-section (A), the mass flow parameter (C_m), and the flow coefficient (C_q). The flow coefficient is necessary to describe real flows better than the analytically derived equation. Therefore to describe the flow characteristics of an EP valve, the flow coefficient has to be determined.

It was the aim of a number of investigations during the last decades to determine the flow coefficient of different orifices and valves in the function of pressure ratio and geometry [7][8][9][10][11][12][13][14][15][16][17][18]. However, they all share at least one common property – the restricted applicability for the EP valve under investigation. Some of these models suggest a constant flow coefficient, some of them analyze only part of the pressure ratio domain, and there are differences in the geometry in most of the cases. Therefore it was necessary to create an EP valve model which is able to accurately predict the flow coefficient through the whole pressure ratio domain

The flow characteristics of an EP valve are affected by a number of parameters. During my investigations the following parameters were taken into account: the upstream and downstream pressure (p_u, p_d), the upstream temperature (T_u), the orifice diameter (d), the length of the orifice (L), the roughness of the orifice wall (k), the distance of the valve body (s), the gas properties (R, κ, ν), the valve seat angle (α) and the average flow velocity in the orifice (v).

As this list presents quite a number of parameters, and investigating all of them would require a considerable amount of time, I have attempted to decrease the number of parameters using dimensional analysis [19]. The resulting dimensionless parameters are as follows: valve seat

angle (α), isentropic exponent (κ), pressure ratio $\left(\frac{p_d}{p_u}\right)$, Reynolds number $\left(\frac{v \cdot d}{\nu}\right)$, relative

roughness $\left(\frac{k}{d}\right)$, the length-diameter ratio of the orifice $\left(\frac{L}{d}\right)$, the ratio of the valve body

distance and the orifice diameter $\left(\frac{s}{d}\right)$, and the flow coefficient $\left(\frac{q_m}{A \cdot C_m} \cdot \frac{\sqrt{T_u}}{p_u}\right)$. The most

important statements of the dimensional analysis can be found at the end of this booklet, in **Thesis 1**.

During the literature research and the dimensional analysis I have concluded that in order to develop a widely applicable valve model, it is reasonable to create an analytical model of a simplified geometry first. This analytical model contains the description of the physical processes; therefore it serves as a foundation for modeling more complicated geometries. The analytical model of the valve uses the fluid momentum law applied onto a Borda-type orifice, and it can describe the flow characteristics within the entire pressure ratio domain. The most important statements of the analytical model can be found in **Thesis 2**.

In modern, highly integrated EP systems the pressurized air usually flows from one chamber to another via an EP valve. Moreover, these systems are already equipped with integrated high-speed pressure transducers to supply the control system with pressure values, and incorporate interfaces to connect to external diagnostic and data-logging devices [20]. This gave me the idea that this integrated system can be used somehow to determine the flow characteristics of the valve. It means that using an appropriate measurement procedure, the flow characteristics of the EP valve can be measured without disassembling the system or incorporating additional devices which is advantageous compared to existing measurement methods [21][22][23][24]. But because usually there is no temperature transducers integrated in EP systems, such a measurement method should be developed which does not take the temperature change into account. The theoretical layout of a from-chamber-to-chamber system can be seen on **Fig. 2**. and the mass flow rate can be calculated using **Eq. (3)**. The most important statements of the new measurement method can be found in **Thesis 3**.

$$q_m = \frac{V \cdot \frac{dp}{dt}}{R \cdot T \cdot \kappa} \quad (3)$$

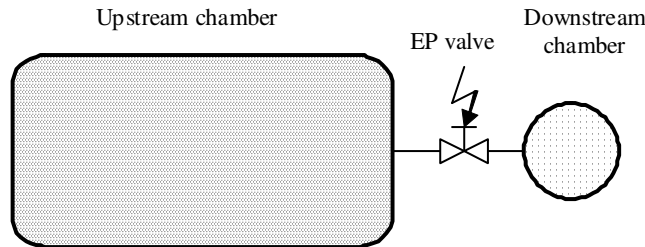


Fig. 2.: Theoretical layout of the from-chamber-to-chamber measurement method

Computational fluid dynamics (CFD) is often the only possibility to acquire information about the details of the flow. The current measurement tools and methods are unable to map the whole flow domain in several cases. It is possible, however, to measure the upstream and downstream pressure and temperature, and the flow rate can be measured as well, with which the results of the CFD simulations can be validated. The other advantage of the CFD analysis is that the geometric changes are much easier to incorporate than it is with measurements. Therefore I have prepared the CFD model of the investigated EP valve family using the Fluent finite volume CFD solver [25]. Using this CFD model I have prepared a number of simulation runs, and the results have been validated with measurements. A number of different numerical meshes have also been prepared in order to verify the grid dependency, and it has been found out that the different meshes have less than 1% effect on the mass flow. In view of the results it has been proven that the CFD model is capable of predict the flow characteristics of the EP valve with accuracy adequate from engineering point of view. **Fig. 3**. shows the results of the measurements using rotameter (Cq_{rot}), orifice meter (Cq_{mp}), the from-chamber-to-chamber method ($Cq_{k2k-0.1}$), and the characteristics calculated by CFD

simulation (C_{q_cfd}) and by the Perry-polynomial (C_{q_perry}). The most important statements of the CFD simulation results can be found in **Thesis 4**.

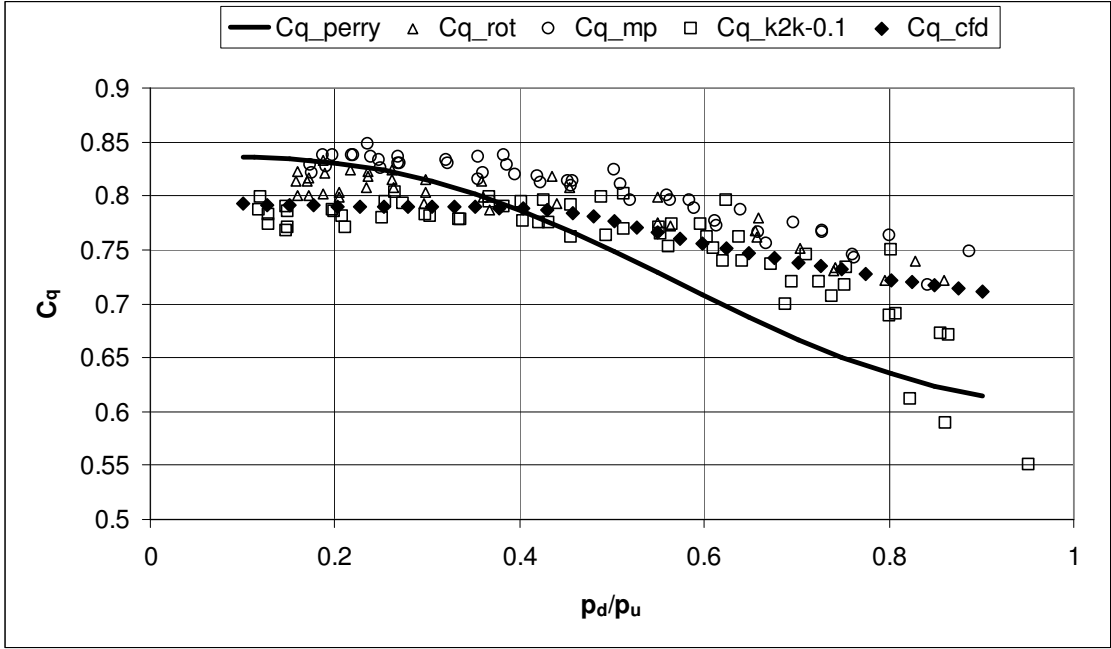


Fig. 3.: Comparison of measurement and simulation

One of the most important aspects of my investigation was to create a 1D model which can predict the flow characteristics of the investigated EP valve with adequate accuracy. The analytical model discussed above is unable to provide such results because of the assumptions and simplifications used. However, this analytical model is based on theoretical background, and as such, it can serve as a foundation for a semi-empirical model. The semi-empirical model thus relies upon theoretical expressions, and the result of these expressions can then be corrected to incorporate the effects of modifications in the geometry. As it is much easier to analyze the effects of these modifications in CFD simulations, and the measurement errors may make recognizing trends more complicated, I have investigated the effects of several parameters using CFD simulations. The most important statements of the semi-empirical model can be found in **Thesis 5**.

3. New scientific results, theses

Thesis 1.: The parameters influencing the stationary mass flow rate have been systematically determined in a wider range than it has been found in the literature for the investigated valve family. The methods published for this valve family have been expanded by using dimensional analysis; the help of which a wider range of dimensionless groups have been defined than it has been found in the literature for the investigated valve family. It has been determined that, besides the ones in the dimensional matrix, there are some additional parameters influencing the mass flow rate. So in addition to the parameters in the dimensional matrix, the effects of another one has been investigated, which has not been found in the literature (valve seat angle).

Thesis 2.: An analytical model has been elaborated which can provide the characteristics of the flow coefficient (C_q) against the pressure ratio (p_d/p_u) for stationary flow through a Borda-type orifice. This model, unlike the ones found in the literature, is able to provide these characteristics through the entire pressure ratio domain for this geometry. The trends shown by the empirical models found in the literature, i.e. the pressure ratio dependency through the sonic pressure ratio domain has been explained based on the characteristics of the analytical model and on the results of the CFD simulations. Although the critical values (pressure, temperature) appear in the vena contracta, the downstream pressure can still act around the jet in orifice meter-type and Borda-type geometries. That's why the empirical models investigating those geometries show that the flow coefficient is increasing with decreasing pressure ratio. It has been determined that in the investigated EP valve family, the downstream pressure affects the flow coefficient only partially, as after the separation zone at the inlet of the orifice, the flow reattaches to the orifice wall, thereby the downstream pressure is unable to reach the vena contracta. It has been shown that these effects and the results of the CFD simulations explain the constant trend of the flow coefficient in the sonic domain, and the decreasing trend in the subsonic domain for the investigated valve family.

Related publications: [P1],[P2]

Thesis 3.: A new measurement method has been developed which can provide pressure ratio-dependent stationary flow characteristics for EP valves through the entire pressure ratio domain. It has been proven that the mass flow rate measurement can be deduced by measuring the time-dependent pressure change in a chamber. This approximation can only provide acceptable results within a very short time frame at the beginning of the discharge process. This method can provide results which are acceptable from engineering point of view in the sonic pressure ratio domain only, while in the subsonic domain it can provide approximate results. This method is advantageous in EP systems used in commercial vehicles, as those systems already equipped with fast and accurate pressure transducers and external connections for data logging.

Related publications: [P3],[P4],[P5],[P6]

Thesis 4.: CFD simulations validated by measurements have been carried out during which the flow coefficient characteristics and the flow structures have been analyzed in a wider range than it has been found in the literature for the investigated EP valve family. It has been shown that the flow cross-section influenced by the separation zone forms a virtual Laval nozzle in the sonic pressure ratio domain, therefore supersonic flow develops inside of the EP valve. It has been pointed out that the flow structure bears a strong resemblance of the flow developing in a constant area duct connected after a converging cross-section operating in the supersonic domain. It has been shown that the structure of the shock waves developing at the inlet of the valve orifice, and the size of the separation zone exhibits only minor variations within the sonic pressure ratio range. In subsonic range however, the size of the separation zone increases along with the pressure ratio, thereby reducing the flow coefficient.

Related publications: [P1],[P2],[P3],[P6]

Thesis 5.: A semi-empirical model of the EP valve has been elaborated based on the new analytical model and the results of the validated CFD simulations. It has been shown that, within the investigated domain, all C_q characteristics can be derived from the new analytical model using simple transformation functions, and these characteristics are within a 3% maximum relative difference compared to the CFD data. It has been proven that different transformation functions are needed in the sonic and in the subsonic pressure ratio domain. It has been demonstrated that the dependence of the correction factor of the flow coefficient from the valve seat angle is (α) linear, while from the s/d ratio it is second order. It has been determined that the dependence of the correction factor of the flow coefficient from the s/d ratio is different above and below of 0.25, but both are second order. It has been established that the $s/d > 0.5$ range should not be used as the increase of the flow coefficient here is minimal. It has been demonstrated that the increase of the L/d ratio shows minimal influence on the flow coefficient, therefore the effects of the wall friction after the normal shock, or, in the subsonic range, after the reattachment, is minimal compared to the effects at the inlet of the orifice.

Related publications: [P1],[P2],[P6]

4. Publications related directly to theses

The following articles have been published which are directly related to one or more theses (the related theses can be found in brackets):

- [P1] 102 V. Szente, J. Vad: *A semi-empirical model for characterisation of flow coefficient for pneumatic solenoid valves*, Periodica Polytechnica Mechanical Engineering Series, Vol. 47, pp. 131-142, 2003. (Thesis 2., 4., 5.)
- [P2] 119 V. Szente, J. Vad: *Félempirikus modell kisméretű pneumatikus mágnesszelepekre*, Gép, Vol. 2, pp. 22-27, 2004. (Thesis 2., 4., 5.)
- [P3] 57 V. Szente, J. Vad: *Computational and experimental investigation on the flow characteristics of electropneumatic valves*, Gépészet '02, május 30-31, Budapest, 2002. (Thesis 3., 4.)
- [P4] 106 V. Szente, Z. Mózer, Á. Tajti: *Experimental investigation on pneumatic components*, Proc. Conference of Modelling Fluid Flow (CMFF '03), Budapest, 2003. (Thesis 3.)
- [P5] 107 V. Szente: *Comparison on different measurement methods on electro-pneumatic valves*, Proc. Gépészet '06, Budapest, 2006. (Thesis 3.)
- [P6] 120 V. Szente, J. Vad: *Computational and experimental investigation on the flow characteristics of small-scale pneumatic solenoid valves*, Proc. 2nd International Conference on Heat Transfer, Fluid Mechanics, and Thermodynamics, Victoria Falls, Zambia, 2003. (Thesis 3., 4., 5.)

5. Publications connected to the dissertation

- [K1]H. Németh, G. Kristóf, V. Szente, L. Palkovics: *Advanced CFD simulation of a compressed air injection module*, Proc. Conference of Modelling Fluid Flow (CMFF '06), Budapest, 2006.
- [K2]B. Istók, J. Vad, V. Szente: *Behavior of a pneumatic pressure regulator valve under leakage circumstances*, Proc. 2nd International Conference on Heat Transfer, Fluid Mechanics, and Thermodynamics, Victoria Falls, Zambia, 2003.
- [K3]V. Szente, J. Vad: *Noise and vibration studies on pneumatic circuit protection valves*, XXXVI. Combined Conference on Heavy Vehicles (BusTruck '05), Budapest, 2005.
- [K4]V. Szente, J. Vad, G. Lóránt, A. Fries: *Computational and Experimental Investigation on Dynamics of Electric Braking Systems*, Proc. 7th Scandinavian International Conference on Fluid Power, Vol. 1., pp. 263 – 275, Linköping, Sweden, 2001.
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- [K7]V. Szente, J. Vad: *Computational and Experimental Investigation on Solenoid Valve Dynamics*, 2001 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Como, Italy, 2001.

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