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Simplified numerical simulation as the base for throttle flow characteristics designation

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1. Introduction

In the classic piston internal combustion engine with spark ignition, the control of external indicators is being conducted through the regulation of combustible mixture mass flow approaching the cylinder. From one hand, this process is driven by fuelling system, on the other hand - intake system with throttle valve mounted inside it. The knowledge of flow characteristics of throttle valve lets finally estimate the capability of the intake system. There are several solutions, which in their operation omit throttles, i.e. Valvetronic by BMW and Valvematic by Toyota. All other engines are equipped with subjected component in their controlling system. It deserves the special attention in the filling control of hydrogen powered engines [1, 2].

The flow characteristics of the throttle valve is mainly used in the modeling course. By wanting to implement own components (subsystems), their characteristics are being researched, while adequacy of model description significantly influences the quality of simulation results [3, 4].

Experimental designation of the throttle conductance (μA) as a whole, without separating to the flow coefficient μ and instantaneous area of flow A is dictated by the fact, that in the available literature, the analytical designation of instantaneous area of flow is problematic. The opening is divided to ranges, depending on the throttle opening angle [4, 5]. It requires the correctional coefficient, which could also find the reflection in the flow coefficient μ.

There are different functional dependencies available, which describe the flow capabilities of the throttle valve. In the elaboration [6] the most popular were subjected to verification. In the comparison the function showed in [7] was omitted due to some imperfections in projection of the full range related with significant disconnections in the range of maximum opening, as well as the function presented in [8], due to significant complexity of dependencies. Usage of the research results of three different in construction throttle valves it was showed that commonly used functions [9] and [10] does not fully satisfy the flow characteristics of any of them, especially in the range of wide open throttle. The greater alignment of the model with the experiments was achieved by using function [5], where the average error is smaller by ca. 30% than in the previous two. The Bell's function introduces itself quantitatively similarly to [5], with similar complexity of the figure. It was stated that the Gauss functions, taken from statistics, imitate throttle flow characteristics to the highest degree.

The simulation research of the air flow through the throttle valve is intended to elaborated the flow character. In [11] the simulation research results were presented, while the research itself was run in SolidWorks Flow Simulation for various throttle valves. The comparison of numerical research in the Fire software with the experiment was showed in [12], giving the great alignment for the simplified constructional variant. The simulation software lets preliminarily assess the performance of new throttle solutions, e.g. VGTV (Variable Geometry Throttle Valve) [13].

Therefore it was attempted to elaborate the numerical research methodology in the SolidWorks Flow Simulation software for prototypical solutions research needs. The results were subjected to experimental verification.

2. Subject of the research

The objects of the investigation were throttle bodies different in terms of the design. The technical specification of throttle bodies has been presented in Table 1.

Table 1
Makes and models of throttle used in the research

Code	Diameter, mm	Axis, mm	Max flow field, mm^2	Examples of application
Car engines - sheet				
I-1	46	9.5	1248.0	FSO 1500
I-2	35+44	8+8	1855.0	VW K-Jetronic
I-3	57	10	1984.7	VW VR6
Motorcycle engines – slider				
II-1	24	0	452.4	M 72
II-2	25	0	490.9	eMZETZ 250
II-3	27	0	572.5	Panonia

3. Research methodology

3.1. Simulation tests

The basic equations used for the mathematical description of the flow phenomena related to possibly most general model of fluid (for 3D space) and based on three main principles of mechanics are as follows:
– for the principle of mass conservation (the continuity equation):

$$\frac{\partial \rho}{\partial t} + div(\rho u) = 0; \qquad (1)$$

– for the principle of momentum and angular momentum conservation:

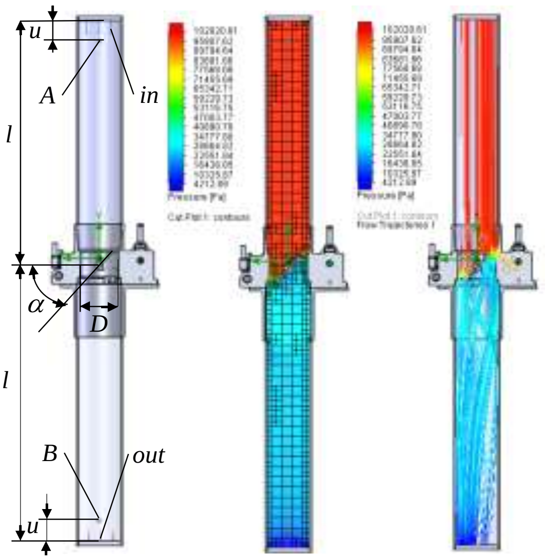
$$\rho \frac{\partial u}{\partial t} = \rho F + divS \; ; \qquad (2)$$

– for the principle of energy conservation:

$$\rho \frac{d}{dt}\left(TC_v + \frac{u^2}{2} \right) = \rho Fu + \rho q + div\left(\Gamma \, gradT \right) + div\left(Su \right), \qquad (3)$$

where t is time, u is fluid velocity, ρ is fluid density, F is mass specific force, S is stress tensor, C_v is specific heat capacity with fixed volume, T is temperature, q is unit output of internal source of heat, Γ is thermal conductivity.

The calculations were carried out in the SolidWorks Flow Simulation environment, with the computational algorithm based on Navier-Stokes equations. The equations were supplemented by equation of state of the fluid describing its nature and by the empirical dependencies of fluid viscosity and thermal conductivity on temperature. The topic is ultimately precisely made by introduction of geometry, boundary conditions and initial conditions for the investigated case.



a b c

Fig. 1 Necessary guidelines needed for simulation initiation

To initiate the simulation research some guidelines were settled. The lengths of connecting lines before and after the throttle should provide the stability of the flow (Fig. 1, c). The measurement of the pressures is realized in A and B points (Fig. 1, a). Minimum of the length *l* was set as 5*D*, where *D* is the inner throttle diameter. The *u* length is (0.5…1) *D*. The boundary conditions were set as *in* and *out*. From the inlet side (*in*) the ambient parameters should be applied, whereas from the other side (*out*) - the mass flow causing air suction through the throttle. Preliminary trials showed that the mass flow should be within (100…350) g/s depending on the inner throttle diameter. It is necessary to dense the mesh in the most sensitive spots, to (1…2.5) mm (Fig. 1, b). The geometry of the objects was implemented basing on the solid objects of the SolidWorks.

During run calculations, in the communicator window the succeeding iterations can be observed (Fig. 2) displayed as the pressure values in points *A* and *B* - *1*, and as isobars *2*.

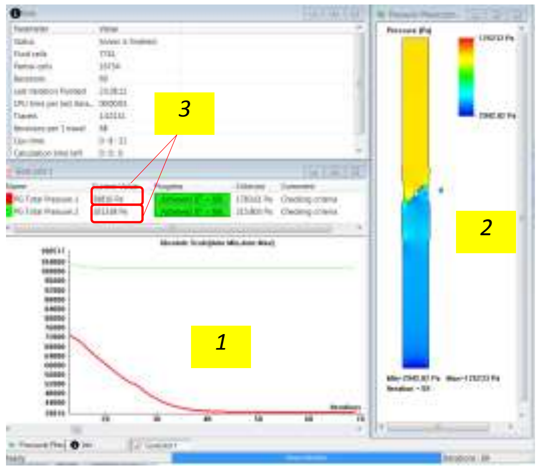


Fig. 2 Communicator window during simulation research (SolidWorks Flow Simulation)

The differences in pressure are given after simulation end (*3* in Fig. 2), set in the function of throttle opening designate the flow characteristics in the appearance of coefficients ranging from 0 to 1.

3.2. Experimental tests

In order to determine the flow capacity of the investigated throttle bodies a dynamic method was used consisting in determining of the courses of the pressure changes in time in the measurement chamber (a mass flow meter), where in the flow trajectory, triggered by the difference in pressures (chamber vs. ambient pressure), an obstacle in the form of an adjustable throttle body is provided. The methodology is similar to that described in [14, 15]. In the case of the investigation of pneumatic systems a method of determining of flow losses [16] is also used or the method using the mass flow meters ISO 6358 [17], but it is applied only in pipelines and brake systems.

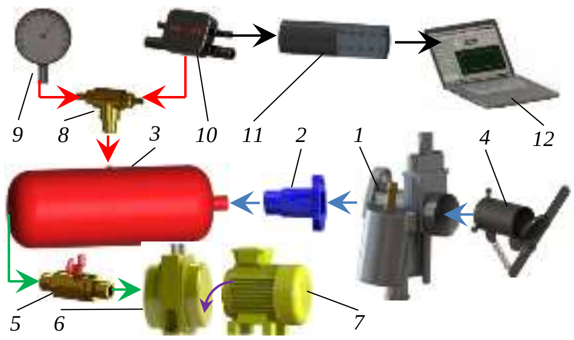


Fig. 3 Structural schematics of the test stand (description in text)

Vacuum pump (*1* in Fig. 3) is driven by electric engine *7* induces a vacuum in measurement tank *3*, the flap closed diffuser *4*. The researched object - throttle *1* is mounted to the measurement tank adapter *2*. After obtaining a vacuum 0.5 bar, vacuum pump is stopped and ball valve *5* is closed. In the case of sudden intake diffuser flap *4* opening, the pressure in the measurement tank *3* will grow, what will be observable on the manometer *9* and PS-

02 AC LLC pressure sensor *10* connected with the joint *8* to the measurement tank. The pressure profile measurement card *11* by National Instruments NI-USB 6215 was connected to the laptop *12* with LabVIEW 8.5 Developer Suite software installed.

Courses were identified based on a mathematical model presented below.
by a high complexity of the occurring phenomena, simplifications have been introduced as follows:

– the air is treated as an ideal gas of a constant specific heat;
– the flow takes place without internal friction and heat exchange with the surroundings;
– the state of the air is constant in a given diameter and depends on time;
– the tested portion is treated as a pipe of a constant diameter;
– the temperature of the flowing medium is constant [18];
– the joints of the individual elements of the tested object are perfectly airtight.

Having considered the above assumptions, the stream of air flowing through the local drag can be expressed:

$$\frac{dm}{dt} = \frac{V}{\kappa RT}\frac{dp}{dt}. \tag{4}$$

Air mass flow going through local resistance:

$$\dot{m} = (\mu A)\frac{p_a}{\sqrt{RT}}\varphi_{max}(\sigma) f(\sigma), \tag{5}$$

where p is pressure in measurement tank, Pa; p_a is atmospheric pressure, Pa; V is volume, m^3; μA is conductance, m^2; T is temperature, K; R is gas constant $R = 287.9$ J/(kg K); κ is adiabatic exponent $\kappa = 1.405$; $\varphi_{max}(\sigma)$ is maximum value of St`Venant and Wantzel function, $\varphi_{max}(\sigma) = 0.578$; $f(\sigma)$ is dimensionless function of flow, the form according to Miatluk–Avtuszko [19], $f(\sigma) = 1.13\,(1-\sigma / (1.13-\sigma))$, $\sigma = p_{in} / p_{out}$.

The final model of the adiabatic process of the filling of the measurement tank we can express in the form of a differential equation:

$$\frac{dp}{dt} = \frac{\kappa RT}{V}(\mu A)\frac{p_a}{\sqrt{RT}}\varphi_{max}(\sigma) f(\sigma). \tag{6}$$

Determining the throughput from the course of the dynamic characteristics allows an evaluation in the entire tested range determined by the pressure difference at the start of the measurement, which is vital because this difference during operation varies widely.

The differential equation (3) was solved numerically with the implicit trapezoidal method combined with reverse differentiation, using Matlab.

The throughputs determined in the course of the identification, based on the recorded and calculated courses of pressures. To this end, a non-linear regression was used, minimizing the FPE_1 estimator through the Nelder-Mead simplex, until the required calculation accuracy was obtained (10^{-6}).The minimization was performed with the use of Matlab–Simulink-Guide, *fminsearch* procedure [20].

$$FPE_1 = \frac{m+l}{m(m-1)}\sum_{i=l}^{m}\left(p_{exp} - p_{mod}\right)^2, \tag{7}$$

where m is number of points of the identified curve; l is number of significant points in the model; p_{exp} is experimental pressure, Pa; and p_{mod} is modeling pressure, Pa.

The coefficient of determination adjusted to the degrees of freedom:

$$R^2 = 1 - \frac{m-l}{m-1}\frac{\sum_{i=1}^{m}\left(p_{exp} - p_{mod}\right)^2}{\sum_{i=1}^{m}\left(p_{exp} - \overline{p_{mod}}\right)^2}. \tag{8}$$

The average error:

$$FPE_2 = \frac{1}{m}\sum_{i=1}^{m}\left|p_{exp} - p_{mod}\right|. \tag{9}$$

The maximum error value:

$$FPE_3 = \mathrm{MAX}\left|p_{exp} - p_{mod}\right|. \tag{10}$$

The calculation procedures have been written in the Matlab code [21], the Guide add-on according to the calculation schematics has been shown in Fig. 4.

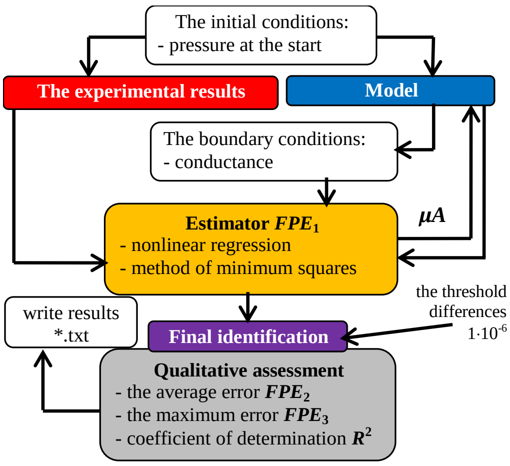


Fig. 4 Block diagram of the identification program

Fig. 5 presents a communication panel of the identification software (Matlab-Simulink-Guide).

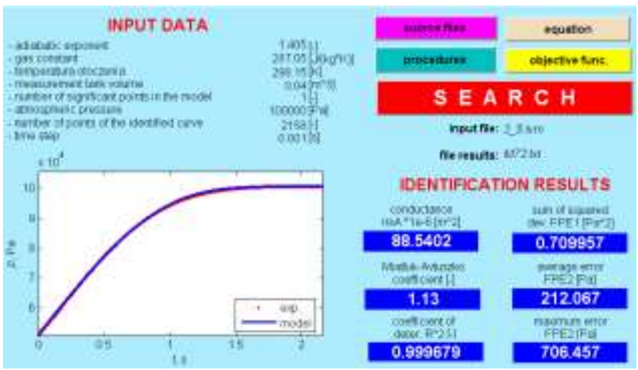


Fig. 5 Communication panel of the identification software

5. Results analysis

The experimental research, which verified the numerical research, showed the applicability of the method for the throttles simplified in construction. Designated characteristics (Fig. 6) were set in the way, that from one side, on the left axis the maximum flow area was the maximum, from the other side, on the right axis the pressure ratio in the measurement points reached maximum value of 1.

It is apparent, that the designated characteristics of motorcycle sliding throttles (Fig. 6, c-e) are closed to the linear, independently on the sort of slider - flat (Fig. 6, c) or cylindrical (Fig. 6, c and e). Characteristics of flap throttles used in car engines (Fig. 6, a-c) are closed to the Gaussian distribution, the closest is the classic variant (Fig. 6, b) and with some disconnections - two channel ones (Fig. 6, b) and with profiled air intake (Fig. 6, c).

The smallest average error was noted in the case of motorcycle throttle with flat slider II-1 (10%) and classic car throttle I-1 (15%). All other motorcycle throttles with cylindrical slider with cut edge, were average different consequently of II-2 – 36% and II-3 – 25%. The worst situation is in the cases of car throttles I-2 and I-3. In the first case, due to 2 passages, the swirl was noted resulting in the variety of pressure by the measuring point *B* (Fig. 1, a), what significantly influences on the p_B / p_A value. In the second case, the profiled inlet is shaping the flow characteristics in the huge experiment-model disconnection from 40 degrees of opening. Therefore the proposed method finds the limited use for the design solutions of that type.

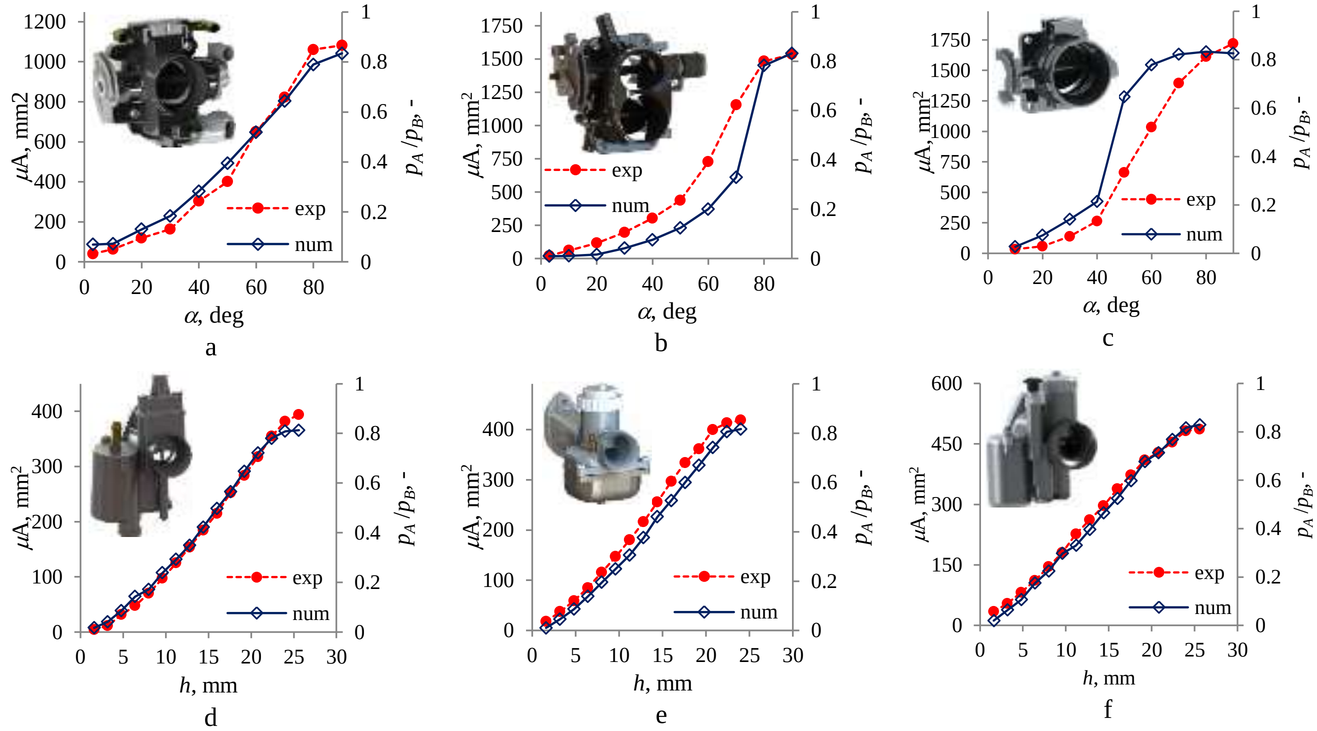


Fig. 6 Flow characteristics of the tested throttle bodies: I-1 (a), I-2 (b), I-3 (c), II-1 (d), II-2 (e), II-2 (f)

6. Conclusions

1. The simplified methodology of throttle flow characteristics was proposed, basing on the numeric simulation in SolidWorks Flow Simulation.

2. The experimental data verified the proposed methodology and pointed the applicability for simplified design variants.

3. The flow characteristics of slider throttles used in motorcycles are closed to the linear, what also showed the experimental research.

4. The flap throttles, due to the characteristics closed to the Gaussian distribution, did not confirm the applicability of proposed numerical method in every case. More complex design solutions (two channel, profiled inlet) cause the differences between numerical and experimental data.

5. Further research was planned to focus on the spherical throttles, to research the applicability of this method in this case.

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SIMPLIFIED NUMERICAL SIMULATION AS THE BASE FOR THROTTLE FLOW CHARACTERISTICS DESIGNATION

S u m m a r y

In the article the simplified numerical research methodology was presented, to designate the throttle valve flow characteristics. It was agreed that it is the alternative for long and expensive experimental research, especially referring to the prototypes. The 6 subsystems in two groups were subjected to the analysis. In the first one, the flap throttles used in car engines were grouped, in the second one - motorcycle slider throttles. The experimental verification showed the alignment of the numerical concluding with the experimental one in some cases.

Keywords: internal combustion engine, throttle valve, numerical research, experimental research.

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