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MODELING THE THROTTLE AIRFLOW IN RELATION TO THE LOAD REGULATION IN INTERNAL COMBUSTION ENGINES

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Abstract: *Vehicles operate in a variety of regimes, including steady-speed operating modes and transient operating modes. The operation of the internal combustion engine at various regimes involves a change in load. The throttle regulates the mass of air entering the engine by closing the intake manifold. In relation to the fact that the vast majority of operating modes are transient, the paper develops the modeling and simulations of the throttle system.*
Keywords: *butterfly throttle, air flow, isentropic*

1. INTRODUCTION

The energy performance and pollutant emissions of the internal combustion engine are massively influenced by the gas exchange processes that take place during the engine cycle. The power developed by the engine is proportional to the air mass available in the cylinder. At the same time, the air-fuel ratio must be kept as close as possible to the stoichiometric value in order to obtain low emissions and fuel economy.

The operation of the internal combustion engine at various regimes involves load changes. At constant engine speed, this can be achieved by adjusting the fuel dose. Depending on the place of formation of the fuel mixture, the adjustment method can be qualitative (with in-cylinder formation specific to compression ignition and spark ignition direct injection engines) or quantitative (with formation outside the cylinder characteristic of most spark ignition engines, with indirect injection). In the case of quantitative adjustment, both air and fuel enter the cylinder simultaneously [1].

The role of the throttle is to control the air flow that enters the intake system and then the cylinders. The amount of fuel injected is calculated to obtain the desired air-fuel ratio. The throttle facilitates the entry of air into the intake manifold and the cylinder draws air or fuel mixture at the other end of the intake [2,3,4].

Conventionally, in cars, the so-called "butterfly" throttles are used. The accelerator pedal is equipped with a position sensor that sends information to the injection computer. Depending on the position of the accelerator pedal, the injection computer controls the electric motor to adjust the position of the throttle. On older, mechanically operated throttles, the throttle adjustment is done by using a mechanical cable.

2. MATHEMATICAL MODELING OF AIR FLOW

The modeling of the throttle is based on the theory of compressible, isentropic, quasi-static, one-dimensional flow of an ideal gas through an orifice [5,6,7].

The air flow through the throttle is dependent on the throttle opening angle, the ambient pressure and the inlet pressure, being calculated with the relation [8]:

$$\dot{m}_t = \frac{P_0}{\sqrt{R_a T_0}} \times C_d \times A(\theta) \times f(p_r) \quad (1)$$

m_t – air flow mass through throttle (kg/s)
P_o – ambiental pressure (Pa)
T_0 – ambiental temperature (°K)
R_a – air specific constant (J/(kgK))
C_d – discharge coefficient
$A(\Theta)$ – throttle open area (m^2)
$f(p_r)$ – function that takes into account the possible sonic choking of the air flow

The throttle open area $A(\Theta)$ depends on the throttle opening angle and is determined by [6]:

$$A(\theta) = \frac{\pi D^2}{4} \times \left(1 - \frac{\cos(\theta+\theta_i+\theta_0)}{\cos(\theta_0)}\right) \quad (2)$$

Θ - throttle opening angle (rad)
Θ_i – idle throttle angle (rad)
Θ_0 – closed throttle angle (rad)
D – throttle plate diameter (m)

The function $f(p_r)$ is a function that takes into account the possible sonic choking of the air flow through the throttle:

$$p_r = \frac{P_m}{P_0} \quad (3)$$

p_r – pressure ratio
P_m – intake pressure (Pa)

At constant ambiental temperature and pressure, the maximum air flow is obtained at the pressure ratio:

$$p_r = p_{r,crit} = \left(\frac{2}{k+1}\right)^{\frac{k}{k+1}} \quad (4)$$

$p_{r,crit}$ – critical pressure ratio
k – isentropic coefficent (for air, $k \approx 1{,}4$)

Therefore, the value of the function f (p_r) is given by [8]:

$$f(p_r) = \begin{cases} \sqrt{\frac{2k}{k-1}\left(p_r^{\frac{2}{k}} - p_r^{\frac{k+1}{k}}\right)}, \ p_r > p_{r,crit} \\ \sqrt{k}\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}}, \ p_r \le p_{r,crit} \end{cases} \quad (5)$$

The discharge coefficient C_d takes into account the losses due to the friction of the air through the throttle and is determined empirically. It can be defined as the ratio between the ideal theoretical mass and the actual air flow [3,5]:

$$C_d = \frac{\dot{m}_{real}}{\dot{m}_{ideal}} \quad (6)$$

Research has shown that C_d varies with changing the angle of the throttle but many models in the literature have used a fixed value [9]. If in [10], the author advanced the idea of determining the discharge coefficient as a function of two terms (throttle angle and pressure ratio), in [11], it is divided into two other different functions, each referring to one of the terms already stated:

$$C_d = C_d(A(\theta), p_r) = C_d(\theta) \times C_d(p_r) \quad (7)$$

In a naturally aspirated internal combustion engine, the discharge coefficient can be treated as a function of Θ angle only. Experimentally, it has been shown that C_d varies from 0,7 to 1 [12].

To facilitate the computational process, the discharge coefficient and the throttle open area $A(\Theta)$ can be combined in one term, the effective area A_e [2]:

$$A_e = C_d \times A(\theta) \quad (8)$$

In real driving conditions, vehicle circulation is performed in variable regimes with multiple load changes. Its adjustment is made, in most cases by operating the accelerator pedal, which has a direct effect on the position of the throttle. Therefore, expressing the evolution of the mass flow of air entering the engine as a function of the throttle angle provides a simpler picture of the whole process.

Environmental conditions were considered to be P_0=1 bar and T_0=293°K (20°C) and the initial pressure in the intake manifold P_m=0,7 bar. Intake air is treated as an ideal gas and heat transfer between the air and the intake walls is considered insignificant. Thus, the temperature is assumed to be constant at the value of the ambient temperature. The ratio p_r at which the airflow reaches the critical limit has been calculated as $p_{r,crit} \approx 0.53$. A throttle with a diameter D = 50 mm was considered for the study, and its discharge coefficient was adopted to be C_d=0,8.

The following table shows the air flow values as a function of the throttle angle.

Table 1

Air flow values as function of throttle angle

Θ(°)	10	30	50	60	70	80
m_t(kg/s)	0.006	0.05	0.135	0.19	0.25	0.313

The dependence of the air flow on the position of the throttle is shown in the Figure 2.

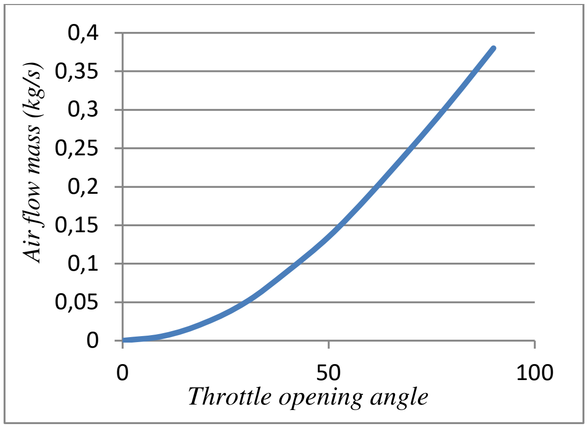

Fig. 2. Air flow mass dependence on throttle opening angle

It should be noted that all calculations were made without taking into account the influence of the throttle shaft. At angles greater than 70-75 degrees, depending on its thickness, it has a restrictive effect on air flow. In [6], the throttle open area is computed using the next expression which considers the throttle shaft diameter d:

$$A(\theta)=\frac{\pi D^2}{4}\left\{\left(1-\frac{cos\theta}{cos\theta_0}\right)+\frac{2}{\pi}\left[\frac{d}{cos\theta}\left(cos^2\theta-d^2cos^2\theta_0\right)^{\frac{1}{2}}+\frac{cos\theta}{cos\theta_0}sin^{-1}\left(\frac{dcos\theta_0}{cos\theta}\right)-d\left(1-d^2\right)^{\frac{1}{2}}-sin^{-1}d\right]\right\} \quad (9)$$

Figure 3 illustrates the difference between the 2 models and the limitation of intake area due to the throttle shaft (with a diameter of 8 mm for the studied throttle). It can be easily concluded that this limitation leads to the restriction of air flow.

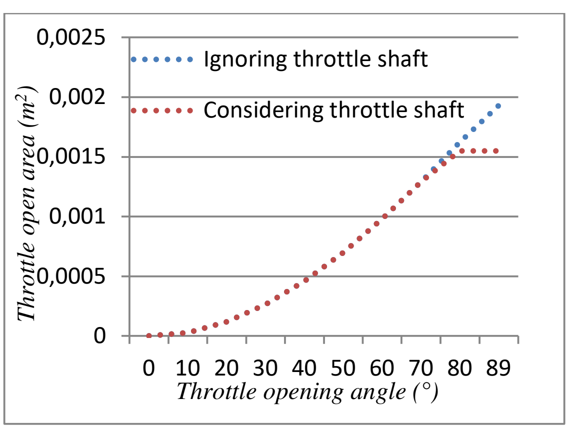

Fig 3. Throttle area estimation with/without considering the influence of throttle shaft

The greater the thickness of the throttle shaft, the lower this restriction angle. Less air reaching the cylinders means a limitation of the power developed by the engine. Therefore, when designing the throttle, one can also take into account this aspect (within the necessary dimensional landmarks) that influences the engine performance (generally at high engine speeds).

In an urban travel cycle, though, full-throttle or close to full-throttle driving is almost impossible to achieve due to traffic characteristics and speed limitations. Considering that the engine runs most of the time at partial load speeds and that this operating range is of the greatest interest for field studies, then the adoption of simplified mathematical modeling that does not take into account the thickness of the throttle shaft does not influence negatively the subsequent results.

The leak throttle area is a parameter determined for each throttle body that gains importance at very small throttle angle ($\Theta<5°$).

However, the error caused by neglecting it is insignificant at most usual throttle opening angles.

3. SIMULINK MODEL

The numerical modeling proposed by the authors was made through the Matlab / Simulink modeling / simulation platform with the help of the available control blocks.

In order to be able to capture the possible air flow choking at large depressions in the throttle, $f(p_r)$ was approached as a separate subsystem, using the *Switch* function to assess a possible exceeding of the critical threshold (Figure 4). It is calculated according to the coefficient k ($k\approx1,4$ for air), its value being $p_{r,crit}\approx 0,53$.

Another individually treated subsystem is represented by the throttle opening factor, which depends directly on the variation of the angle Θ. For a clearer understanding of the results, the value of the angle Θ was converted from radians to degrees.

The variation of air mass flow with throttle opening angle was plotted in Matlab by using *To Workspace* function (Figure 5).

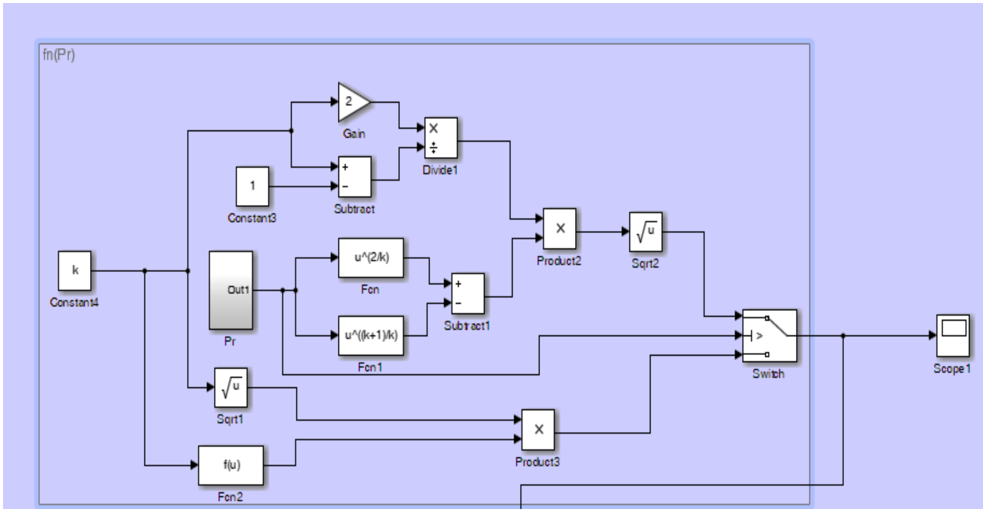

Fig 4. Function f(p_r) computation

4. 2D FLOW SIMULATION

A model of the throttle used was built in SolidWorks. Based on this, through FlowSimulation, the evolution of the air flow was simulated. The graphic and numerical results obtained give us a representative image of the studied process. Also, properties such as pressure, density or airflow speed become easy to visualize and analyze.

The computational domain consists of the valve body positioned between two pipes of 200 mm lenght and 50 mm diameter. The aspirated fluid is considered to be an ideal gas at ambient pressure and temperature of 1 bar and 293.2 K respectively.

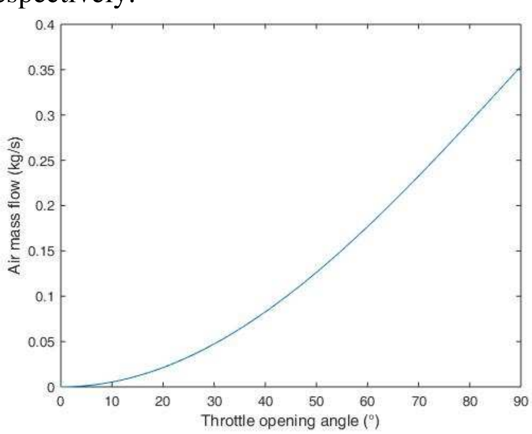

Fig. 5. The variation of air mass flow with throttle opening angle

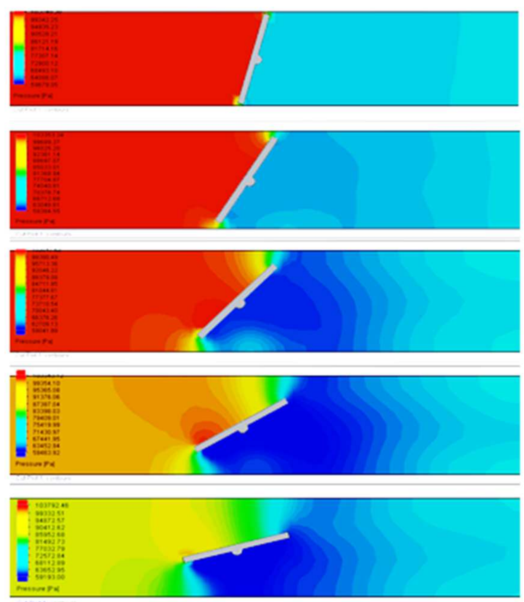

Fig. 6 Pressure contours for Θ (15°, 30°, 45°, 60°, 75°)

The ambiental pressure represents the inlet boundary while the outlet boundary is the manifold pressure with an initial value of Pm= 0,7 bar. The depression created is necessary for the air to be drawn towards the engine.

The process is adiabatic (no heat exchange with the walls), isentropic and the fluid obeys the ideal gas law (PV=νRT).

As the opening angle increases, more and more air enters the cylinders, which leads to a decrease in upstream pressure. In the vicinity of the throttle body, a depression area can be observed, especially at larger angles. This area is oriented according to the position of the throttle (Figure 6).

According to Bernoulli's law, due to pressure differences at identical temperatures, the speed of air flow is higher downstream than upstream of the throttle plate (Figure 7).

At small angles, the highest air flow velocity is reached near the intake walls as a result of the decrease in the fluid passage area (Venturi's principle).

At higher angles, this zone of maximum speed extends and migrates towards the throttle body.

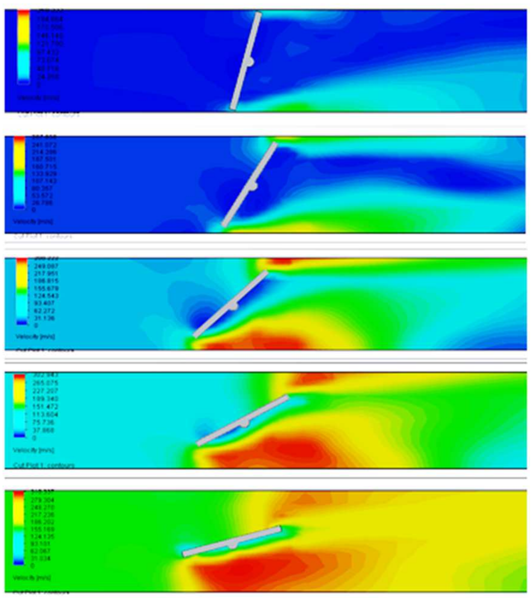

Fig. 7 Velocity contours for Θ (15°, 30°, 45°, 60°, 75°)

5. CONCLUSIONS

The vehicle movement in traffic involves a lot of load changes via the throttle. The throttle role is to regulate the amount of air that enters the intake system and then the cylinders. This paper presents a simplified modeling of the mass air flow variation with the throttle angle in Simulink. Comparing the variation curves (fig. 8), the results of the model created in Simulink are very close to those of the mathematical calculation model. Thus, it can be said that the built model offers a good enough accuracy to represent a starting point for further research.

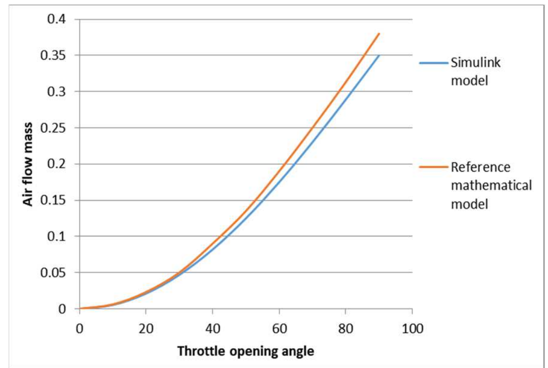

Fig. 8. Comparison: Simulink model vs reference model

Further, a fluid simulation was realised in SolidWorks in order to capture the features of air flow through the throttle and to study parameters such as pressure or speed.

Observations were made regarding the evolution of the air flow and its behavior at different throttle opening angles.

6. REFERENCES

[1] Roșca A.S., Dumitru I., *Aplicații de proiectare în ingineria automobilelor*. Mecanismul motor, Craiova, 2016;

[2] Bordjane Mustapha, Chalet David. *Numerical Investigation Of Throttle Valve Flow Characteristics For Internal Combustion Engines*, JMEST, 2015;

[3] Carlsson Per. *Flow Through a Throttle Body, A Comparative Study of Heat Transfer, Wall Surface Roughness and Discharge Coefficient*, February 23, 2007;

[4] Tutunea D., Dumitru I., Racila L., Otat O., Geonea I., Matei L., Rotea C., *Experimental Stand to Evaluate Engine MAF Sensor*, International Congress Of Automotive And Transport Engineering;

[5] Cristea Dumitru. *Căi de optimizare a motoarelor cu ardere internă*, Pitești, 2009

[6] Heywood, J.B. *Internal combustion engine fundamentals*. McGraw-Hill, 1988;

[7] Moskwa, J.J. *Automotive engine modeling for real time control*, 1998;

[8] Saerens B., Vandersteen J., Persoons T., Swevers J., Diehl M., Van den Bulck E.. *Minimization of the fuel consumption of a gasoline engine using dynamic optimization*, Applied Energy 86 (2009);

[9] Hendricks Ebert, Luther Jim Benjamin. *Model and Observer Based Control of Internal Combustion Engines*, Proc. MECA, Salerno, Italy, 2001;

[10] Blair P. Gordon. *Design and simulation of four-stroke engines.* Warrendale, PA: Society of Automotive Engineers, 1999;

[11] Andersson Per., *Air Charge Estimation in Turbocharged Spark Ignition Engines* 2005

[12] Pursifull Ross, Kotwiscki J. Alain, and Hong Sulgi. *Throttle flow characterization*. SAE Technical Paper No. 2000-01-0571.

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MODELAREA FLUXULUI DE AER PRIN CLAPETA DE ACCELERAȚIE ÎN FUNCȚIE DE REGLAREA SARCINII LA MOTOARELE CU ARDERE INTERNĂ

Funcționarea vehiculelor la diferite regimuri (cvasistatice și tranzitorii) implică modificări ale sarcinii. Rolul clapetei de accelerație este de a regla masa de aer care pătrunde în cilindri. În raport cu faptul că marea majoritate a modurilor de operare sunt tranzitorii, lucrarea dezvoltă modelarea și simularea clapetei de accelerație.

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