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THE FUEL FLOW MODELLING IN THE FUEL PIPE IN MARINE ENGINE WITH CONSIDERING THE WAVE PHENOMENA

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Abstract

In the paper has been make an attempt to replace the conventional system of fuel dose control and injection passing angle with elecrtronic control system, which has been realized this manner, that selected hydraulic accumulator, injector C-R type and fuel dose controller has been attached the the marine engine.

It has been assumed, that by controlling the current impulse of controller it is possible to model whichever/any size of fuel dose, injected to the combustion chamber and to control the injection lasting time.

The wave phenomenon and the flow loss in the fuel pipe of high pressure have been presented.

Keywords: *common rail, fuel pipe, wave phenomena.*

1. Introduction

In the conventional and dividing injection pumps and in the fuel injection unit, the relation of pressing and fuel dosing process and the shaft or ring of bend rotation brings unfavorable change of the course of fuel injection parameter along with the change of the pumpshaft rotational speed.

Broadening the scope of optimal engine operation becomes possible, thanks to applying the electronic control system, which enables controlling the course of basic dosing and fuel injection parameters in the whole scope of engine operation, in the various surrounding conditions, considering also fuel properties.

The replacement of a conventional control system of fuel dose control and injection passing angle with the electronic control system in the test engine was realized this manner:

- in the place of location the conventional injector was fixed selected in advance C-R injector produced by the Bosch Company
- controlling the injection passing angle, size and multiplicity of the dose is realized thanks to the controller with the amplifier
- fuel at demanded pressure is delivered by the pump through the hydraulic accumulator (Fig. 1).

In the paper have been presented selected phenomena, which occur in the fuel pipe of high pressure at the moment of fuel injection.

2. Scheme of the CR feeding system in the laboratory/test engine JSB type.

The scheme of fuel system with attached common rail and fuel dose_controller Fig 2.1. Similar feeding system was applied in the Sulzer RT – flex60C engine. By controlling the current impulse of controller it is possible to obtain the whichever modelling of size and multiplicity of fuel dose, which flows to the combustion chamber in engine cylinder.

The scheme of feeding system Common Rail in the one-cylinder test engine (JSB), which will replace the conventional fuel system, is presented below:

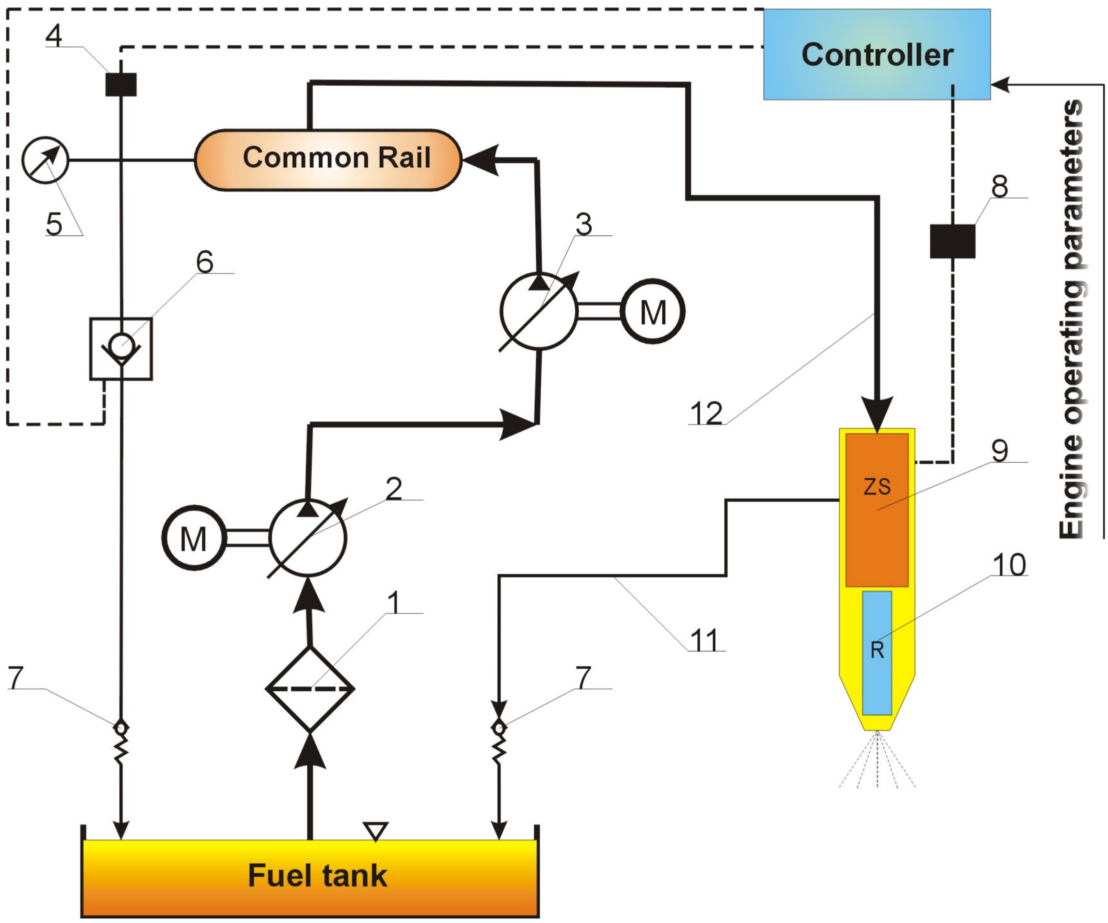

Fig. 2.1. Scheme of the injection system CR of JSB engine: 1 – filter, 2 – low pressure pump, 3 – high pressure pump, 4 – pressure sensor in the hydraulic accumulator, 5 – manometer, 6 – reversive valve with the opening control, 7 – overflow valve, 8 – signal amplifier, 9 – fuel dose controlling valve, 10 – pulverizer, 11 – low pressure fuel pipe (overflow), 12 – high pressure fuel pipe.

3. Impact waves dispersion in the fuel pipes

The wave flow in the centre, which fills the variable-section long pipe, is taken under consideration to describe the impact wave dispersion. The purpose is to explain the influence, which has the change of wave surface on the impact wave velocity.

It was assumed, that the surface A(x) of pipe section slowly changes along its length (axis x) – little at a length in order of the pipe dimension, it is called hydraulic. It offers a possibility of applying appoximation (called hydraulic), so it can be assumed that all values in the stream are constant along every cross-section pipe, and velocity is directed along its axis, in other words, the flow is treated as a quasi-one-dimension.

Such flow is defined by the equations:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}+\frac{1}{\rho}\frac{\partial p}{\partial x}=0 \qquad (3.1)$$

$$\frac{\partial p}{\partial t}+v\frac{\partial p}{\partial x}-c^2\left(\frac{\partial \rho}{\partial t}+v\frac{\partial \rho}{\partial x}\right)=0 \tag{3.2}$$

$$A\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho v A)=0 \tag{3.3}$$

The first of them is Euler equation, the second – adiabatic equation, and the third – continuity equation.

To explain this problem, it is enough to consider the pipe, where the change of surface A(x) is not only slow, but absolute value of the change is low at the whole pipe length as well.Then, the stream disorder, related to the variable section, would be also low and equations (3.1) – (3.3) could be linearized. At last, the initial conditions should be imposed to eliminate appearing any foreign disorder, which could affect on the impact wave motion; only disorders related to the change A(x) are taken under consideration. The purpose will be accomplished/achieved, if it would be assumed, that impact wave initially moves at constant velocity through constant-section pipe and section surface changes only on at/on the right from certain point (which is assumed as x = 0).

The linearized equations (3.1) – (3.3) have following form:

$$\frac{\partial \delta v}{\partial t}+v\frac{\partial \delta v}{\partial x}+\frac{1}{\rho}\frac{\partial \delta p}{\partial x}=0$$

$$\frac{\partial \delta p}{\partial t}+v\frac{\partial \delta p}{\partial x}-c^2\left(\frac{\partial \delta \rho}{\partial t}+v\frac{\partial \delta \rho}{\partial x}\right)=0$$

$$\frac{\partial \delta \rho}{\partial t}+v\frac{\partial \delta \rho}{\partial x}+\rho\frac{\partial \delta v}{\partial x}+\frac{\rho v}{A}\frac{\partial \delta A}{\partial x}=0$$

where symbols without indexes mean constant values in the homogenous stream in the homogenous part of the pipe, and symbol δ means a change of these values in the variable-section pipe. Multiplying the first and the third of these equations adequately by ρa and a^2 and summing up all three equations, can be written:

$$\left(\frac{\partial}{\partial t}+(v+a)\frac{\partial}{\partial x}\right)(\delta p+\rho a\,\delta v)=-\frac{\rho v a^2}{A}\frac{\partial \delta A}{\partial x} \tag{3.4}$$

The general result of this equation is a sum of the general result of homogenous equation and the result of specific equation, which has non-zero right side. The first result is F(x – vt – at), where F is any function; it describes the sound disorder, approaching from the left side of the point, a – speed of sound. However, there are no disorders in the homogenous area, for x < 0, that is why it should be assumed that F ≡ 0. So, the result amounts to the non-homogenous equation integral:

$$\delta p+\rho a\,\delta v=-\frac{\rho v a^2}{v+a}\frac{\partial A}{A} \tag{3.5}$$

The impact wave moves from a left to the right side at velocity $v_1 > a_1$ in the immobile centre with given values p_1, ρ_1. However, the motion of centre at the back of impact wave is defined by the result (3.5) in the whole pipe area at left side from the point, which discontinuity has reached at particular moment. After the wave crossing, all values in every of the pipe section remain constant in time, i.e. equal to the values, which they obtain at the moment of discontinuity crossing: pressure p_2, density ρ_2 and velocity $v_1 - v_2$ (acoording to the symbols accepted in this paper, v_2 means velocity of gas in relation to the moving impact wave; its velocity in relation to the walls of pipe is then equal to $v_1 - v_2$). In these symbols (after dispering various terms of these values) identity could be formulated as follows:

$$\frac{\partial A}{A} = -\frac{v_1 - v_2 + a_2}{\rho_2 (v_1 - v_2) a_2^2} \left(\delta p_2 + \rho_2 a_2 (\delta v_1 - \delta v_2) \right) \tag{3.6}$$

All values δv_1, δv_2, δp_2 could be defined by one of them, for instance δv_1. To this end dependence variations could be described as $\rho_1 v_1 = \rho_2 v_2$ and $p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2$ for the discontinuity (at given p_1 i ρ_1) in the form of:

$$\rho_1 \delta v_1 = v_2 \delta \rho_2 + \rho_2 \delta v_2, \quad 2j(\delta v_1 - \delta v_2) = \delta p_2 + v_2^2 \delta \rho_2$$

where $j = \rho_1 v_1 = \rho_2 v_2$ is an undisordered stream value. The following relation should be also included

$$\delta p_2 = \frac{dp_2}{d\rho_2} \delta \rho_2$$

where derivate is calculated along the Hugoniot adiabatic curve. The calculations lead to a relation, which combine the change of impact wave velocity δv_1 in regard to the immobile gas before this change with the change of pipe section area, which means:

$$-\frac{1}{A}\frac{\delta A}{\delta v_1} = \frac{v_1 - v_2 + a_2}{v_1 a_2} \left(\frac{1 + 2 v_2 a_2^{-1} - h}{1 + h} \right) \tag{3.7}$$

where the symbol is introduced again

$$h = -\frac{j^2}{\rho_2^2}\frac{d\rho_2}{dp_2} = j^2 \frac{dV_2}{dp_2} \tag{3.8}$$

The coefficient w, standing before the square bracket, is positive. Thus, the quotient symbol $\delta v_1/\delta A$ depends on the expression symbol in this brackets, for every stable impact wave is positive and when $\delta v_1/\delta A < 0$. However, if any of discontinuity conditions $j^2 \frac{dV_2}{dp_2} < -1$ and $j^2 \frac{dV_2}{dp_2} < 1 + 2\frac{v_2}{a_2}$, which are caused by corrugation, is fulfilled, the expression in brackets becomes negative and when $\delta v_1/\delta A > 0$.

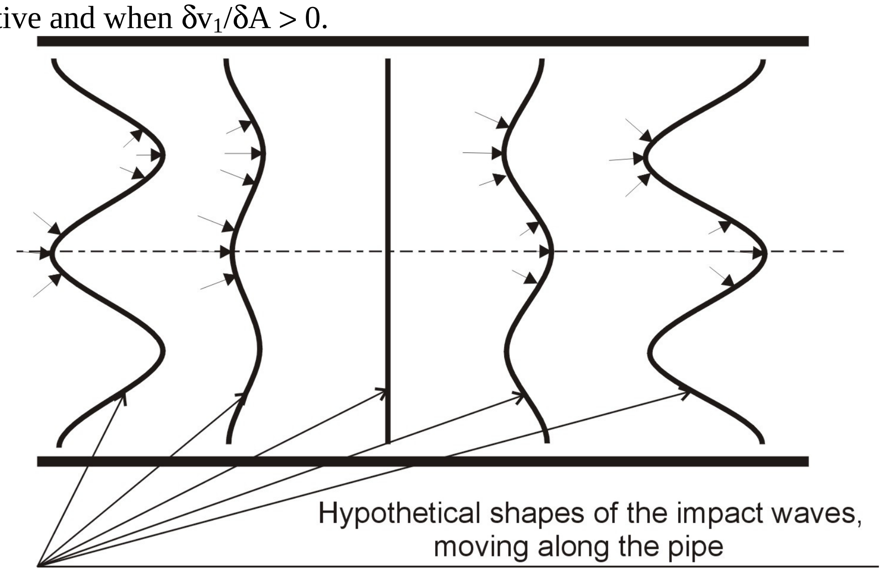

Fig. 3.1

The result offers possiblities of outlook explaining the origin of intability. Fig. 3.1 presents the "corrugated" surface of impact wave, moving to the right side; the directions of current lines are schematicly described by the pointers. During the impact wave crossing on the front protruding parts of the surface, the area δA increases and on the back parts of the surface it decreases. In case, if $\delta v_1/\delta A < 0$, it leads to the delay of the protruding parts and to the acceleration of the back parts and in relation to this the surface aims at smoothing.

On the contrary, in case if $\delta v_1/\delta A > 0$ the disorder of surface shape would demand: the protruding parts will be more protruding and the back parts will stay behind in higher extend.

4. Fuel flow in the elements with constant axis-symmetrical-section area

The d'Alembert solution, which was used by Allievi in the form of equations [5], was assumed to describe the unstable one-dimension fuel flow:

$$p(x,t) = P_0 + f_d\left(t - \frac{x}{a}\right) exp\left(-k_x \xi \frac{x}{a}\right) - f_u\left(t + \frac{x}{a}\right) exp\left(-k_x \xi \frac{x}{a}\right) \tag{4.1}$$

$$u(x,t) = u_0 + \frac{1}{a\rho} f_d\left(t - \frac{x}{a}\right) exp\left(-k_x \xi \frac{x}{a}\right) + \frac{1}{a\rho} f_u\left(t + \frac{x}{a}\right) exp\left(-k_x \xi \frac{x}{a}\right) \tag{4.2}$$

term, complemented byW. Bosch:

$$exp\left(-k_x \xi \frac{x}{a}\right) \tag{4.3}$$

taking under consideration the flow loss with the momentum at length x.

Symbols:

$$f_d\left(t - \frac{x}{a}\right) = P_d\left(t - \frac{x}{a}\right) = a\rho u_d\left(t - \frac{x}{a}\right) \tag{4.4}$$

- is an amplitude of pressure wave, which moves in the same direction as the flow at velocity **a** at length **x**;

$$-f_u\left(t + \frac{x}{a}\right) = P_u\left(t + \frac{x}{a}\right) = -a\rho u_u\left(t + \frac{x}{a}\right) \tag{4.5}$$

- is an amplitude of pressure wave, which moves in the other direction than the flow at velocity **a** at length **x**;

$$a = x/t \tag{4.6}$$

– speed of sound in the fuel;

$$k_x = \frac{4\pi}{A} \nu\rho \tag{4.7}$$

– is a flow loss coefficient, considering the fuel mass momentum according to W. Bosch.

$\mathbf{P_0}$ – constant pressure before the disorder [N/m^2];
$\mathbf{u_0}$ - initial fuel velocity [m/s];
ρ - fuel density [kg/m^3];
ν - kinematic viscosity of fuel [m^2/s];
A - flow section area[m^2];
ξ - fuel flow momentum coefficient (according to Burman and Deluca [1]).

By introducing the same symbols as in the scheme, it is obtained:
- in case of $l = x_m - x = 0$

$$P(x_m, t) = P_m(t) = P_0 + P_{dm}(t) + P_{um}(t) \tag{4.8}$$

$$u(x_m, t) = u_m(t) = u_0 + u_{dm}(t) + u_{um}(t) \tag{4.9}$$

- if l = x_n - x = 0

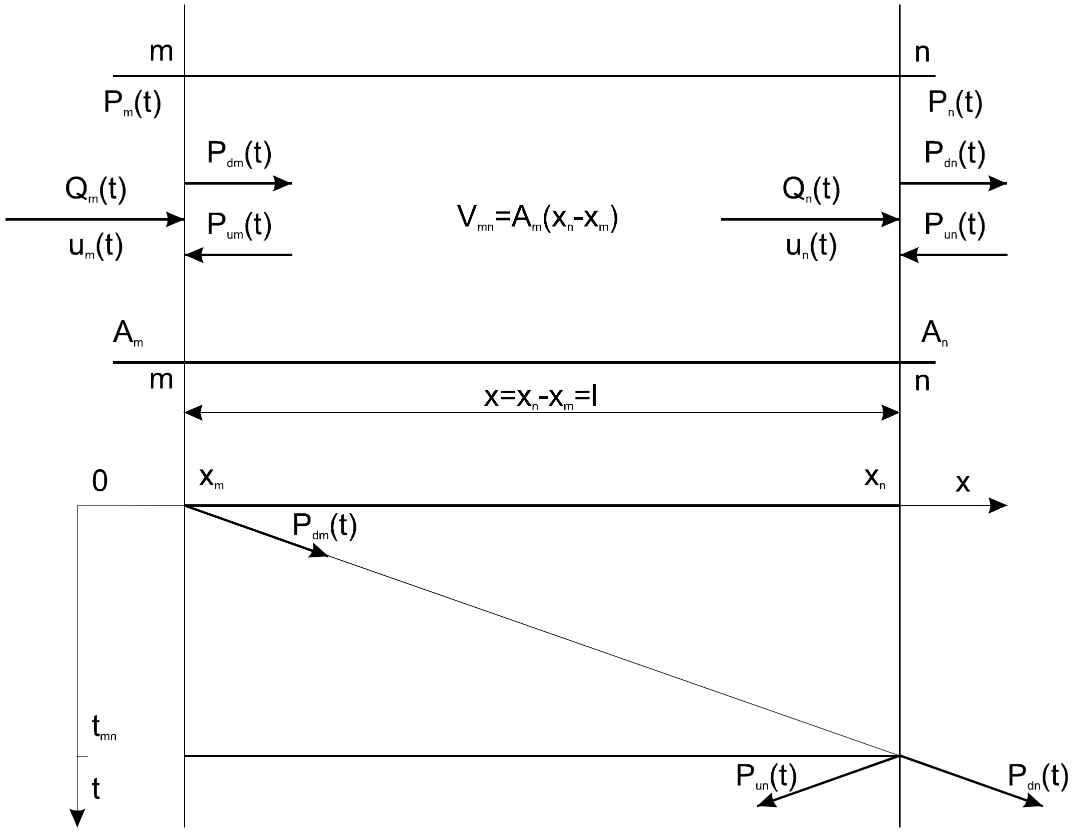

Fig. 4.1. Scheme of unstable fuel flow in the axis-symmetrical pipe.

$$P(x_n, t) = P_n(t) = P_0 + P_{dn}(t) + P_{un}(t) \tag{4.10}$$

$$u(x_n, t) = u_n(t) = u_0 + u_{dn}(t) + u_{un}(t) \tag{4.11}$$

- where l = x_m - x_n > 0,

$$P_n(t) = P_0 + exp\left(-k_{mn}\xi\frac{l}{a}\right)\cdot P_{dm}\left(t-\frac{l}{a}\right) + \\ + exp\left(-k_{mn}\xi\frac{l}{a}\right)\cdot P_{um}\left(t+\frac{l}{a}\right) \tag{4.12}$$

$$u_n(t) = u_0 + exp\left(-k_{mn}\xi\frac{l}{a}\right)\cdot\frac{1}{a\rho}P_{dm}\left(t-\frac{l}{a}\right) - exp\left(k_{mn}\xi\frac{l}{a}\right)\cdot\frac{1}{a\rho}P_{um}\left(t+\frac{l}{a}\right) \tag{4.13}$$

from the equations (8.60) and (8.62) follows relations:

$$P_{dn}(t) = exp\left(-k_{mn}\xi\frac{l}{a}\right)\cdot P_{dm}\left(t-\frac{l}{a}\right) \tag{4.14}$$

$$P_{un}(t) = exp\left(k_{mn}\xi\frac{l}{a}\right)\cdot P_{um}\left(t+\frac{l}{a}\right) \tag{4.15}$$

$$P_{un}(t) = exp\left(-k_{mn}\xi\frac{l}{a}\right)\cdot P_{um}\left(t-\frac{l}{a}\right) \tag{4.16}$$

Volumetric stream of fuel, flowing through the sections m-m and n-n is defined by relations:

$$Q_m(t) = \frac{A_m}{a\rho}\left[P_{dm}(t) - P_{um}(t)\right] \tag{4.17}$$

$$Q_n(t) = \frac{A_n}{a\rho}\left[P_{dn}(t) - P_{un}(t)\right] \tag{4.18}$$

$$Q_n(t) = Q_m(t - t_{mn}) - \frac{V_{mn}}{E}\frac{dP_n}{dt}(t) \tag{4.19}$$

$$Q_n(t) = \frac{A_m}{a\rho}\left[P_{dm}(t - t_{mn}) - P_{um}(t - t_{mn})\right] - \frac{V_{mn}}{E}\frac{dP_n}{dt}(t) \tag{4.20}$$

where E is a fuel compressibility module [N/m^2].

4.1. Fuel flow through the intermitten axis-symmertical-section of elements [2]

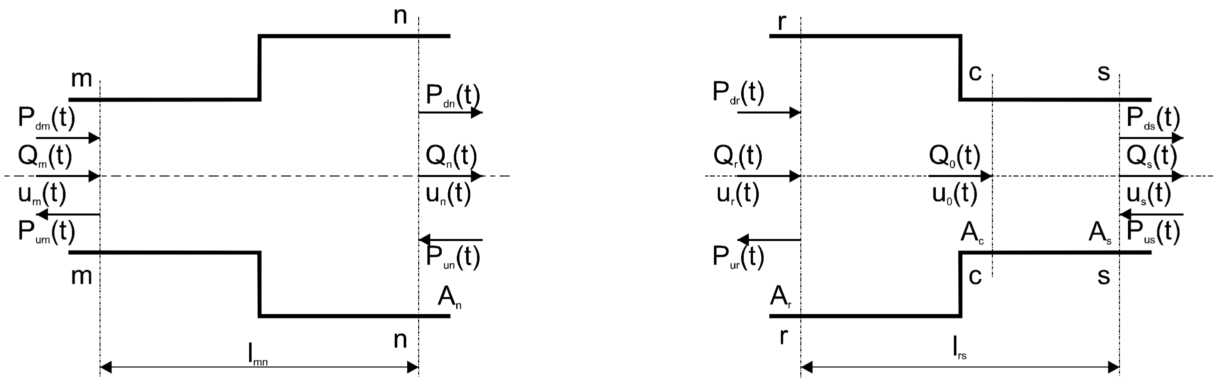

Fig. 4.2. Scheme of unstable fuel flow in the axis-symmetrical pipe.

The courses of pressure waves in the appropriate sections are equal to:

$$P_{um}(t) = P_{dm}(t) + C_m\left\{1 - D_m\left[P_{dm}(t) - P_{um}(t - t_{mn})\right]\right\}^{0.5} - C_m \tag{4.21}$$

$$P_{dn}(t) = P_{um}(t) - C_n\left\{1 - D_m\left[P_{dm}(t - t_{mn}) - P_{un}(t)\right]\right\}^{0.5} + C_n \tag{4.22}$$

$$P_{ur}(t) = P_{dr}(t) + C_r\left\{1 - D_r\left[P_{dr}(t) - P_{us}(t - t_{rs})\right]\right\}^{0.5} - C_r \tag{4.23}$$

$$P_{ds}(t) = P_{us}(t) - C_s\left\{1 - D_r\left[P_{dr}(t - t_{rs}) - P_{us}(t)\right]\right\}^{0.5} + C_s \tag{4.24}$$

Substitutions:

$$t_{mn} = \frac{l_{mn}}{a} \qquad t_{rs} = \frac{l_{rs}}{a} \tag{4.25}$$

$$C_m = 0.5\,a^2\rho\,k_m\frac{k_m + 1}{k_m - 1} \tag{4.26}$$

$$C_n = 0.5\,a^2\rho\frac{k_m + 1}{k_m - 1} \tag{4.27}$$

$$C_r = 2a^2\rho\frac{K + 1}{3K^2 - \left(K^2/k_r\right) - 2} \tag{4.28}$$

$$C_s = 2a^2\rho K\frac{K + 1}{3K^2 - \left(K^2/k_r\right) - 2} \tag{4.29}$$

$$D_m = \frac{8(k_m - 1)}{a^2 \rho (k_m + 1)^2} \tag{4.30}$$

$$D_r = 2\frac{3K^2 - \frac{K^2}{k_r} - 2}{a^2 \rho (K+1)^2} \tag{4.31}$$

$$k_m = \frac{A_n}{A_m} \quad k_r = \frac{A_r}{A_s} \quad K = \frac{u_s}{u_r} = \frac{A_0 u_0}{A_s u_r} \tag{4.32}$$

Symbols:

$\mathbf{A_0, A_m, A_n, A_r, A_s}$ – surface area of appropriate sections [m^2];

$\mathbf{u_0, u_r, u_s}$ – mean velocity of fuel flow[m/s].

Fig. 4.3. The volumetric stream of fuel, flowing through the variable sections, is defined by equations:

- throttles:

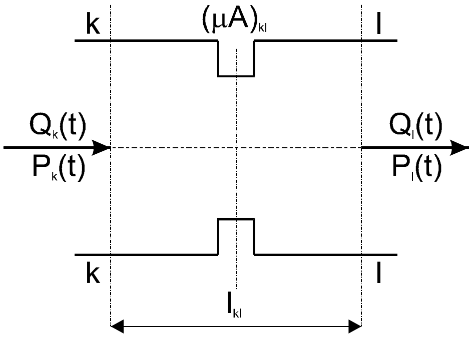

Fig. 4.3.

$$Q_l(t) = \left(\frac{2}{\rho}\right)^{0.5} (\mu A)_{kl}\, sgn\, kl \left[p_k(t) - p_l(t)\right]^{0.5} \tag{4.33}$$

where:

$$sgn\, kl \begin{cases} 1 \quad dla \quad p_k(t) > p_l(t) \\ 0 \quad dla \quad p_k(t) = p_l(t) \\ -1 \quad dla \quad p_k(t) < p_l(t) \end{cases} \tag{4.34}$$

($\mu A)_{kl}$ - is an equivalent flow section between the sections k-l [m^2];

Q_{kn}, Q_{In} – are volumetric streams of fuel, which follows from the leak [m^3/s].

4.2. Mild change of direction – bend

The Weisbach formula of loss coefficients for the circular-section bends is following:

$$\xi = \left[0{,}131 + \left(\frac{d}{\rho}\right)^{3{,}5}\right] \frac{\alpha^o}{90^o}$$

In the table are given loss coefficient values, which are calculated according to above given formula for various angles α and relation d/ρ.

The more detailed researches proves, that loss coefficient ξ depends not only on the relation d/ρ and the angle α, but also on the Reynolds number and the roughness of the bend.

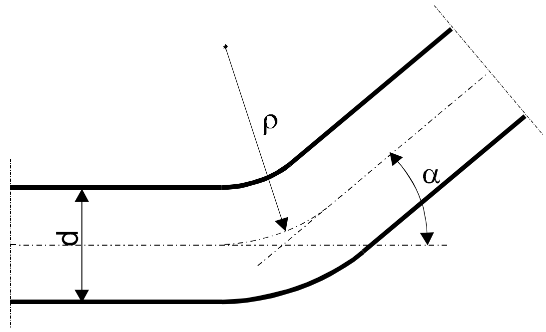

Fig. 4.4. Circular-section bend

5. Conclusions

Adapting the individual elements of electronic control system , which means an electronic control injector, a fuel dose controller with the amplifier and a common rail – for the conventional JSB engine there is a possibility of obtaining fully controlled process of electronic control.

By controlling the current impulse it is possible to control size of fuel dose and also to model the manifold injection, which is characteristic of the electronic control injection systems.

The simulation calculation were conducted basic of theoretical and empirical relations without verification and tests on actual model of valve and that is why they should be treated as a rated results.

To verify the accepted model it would be necessary to perform empirical studies on the actual valve and use obtained results to revise the approved calculation model.

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