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Optimizacija konstruktivnih parametrov sistema vbrizgavanja goriva**Optimization of Fuel Injection System Design Parameters**

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V prispevku je predstavljen nov način za določitev konstruktivnih in krmilnih parametrov konvencionalnega vbrizgalnega sistema (CFIE), z željo, da se izboljšajo sposobnosti vbrizgavanja in s tem tudi emisija ob ugodni specifični porabi goriva in sprejemljivem računskem času.

Sodobno oblikovanje konfiguracije vbrizgalnega sistema zahteva inverzno računsko pot zasnovano na želenih izhodnih karakteristikah procesa vbrizgavanja. Ta pot je v prispevku izpeljana z uporabo želene karakteristike vbrizgavanja na enem delovnem režimu in z vpeljavo postopka optimalnega projektiranja. Tako dobljeni konstruktivni in krmilni parametri CFIE zagotavljajo optimalno karakteristiko vbrizgavanja, ki se dokaj dobro ujema z želeno.

Problem optimalnega projektiranja je rešen z uporabo metode zaporednega kvadratičnega programiranja (RQP), ki je ena od metod matematičnega programiranja.

In this paper, a new approach to the determination of design and control parameters of a conventional fuel injection system (CFIE) is described. The aim is to improve the injection characteristics and to minimize the emission and specific fuel consumption with acceptable computational effort.

The future improvement of CFIE requires an inverse calculation route based on the projected output characteristics of the injection process. In this work this route is realized by using a projected injection rate history at a single operating condition and by employing the procedure of optimum design. So the obtained design and control parameters of CFIE realize an optimum injection rate history which meets the projected one with reasonable accuracy.

The problem of optimum design is solved by using the recursive quadratic programming (RQP) method, which is one of the methods of mathematical programming.

0. UVOD

Vedno strožji ekološki in ekonomski predpisi in vse večje zahteve glede zmogljivosti motorja usmerjajo razvoj dizelskih motorjev vozil, ki naj bi bili v bližnji prihodnosti bolj primerni za notranje kakor tudi zunanje elektronsko krmiljenje (PROMETHEUS). Velik del tega bremena pride na sisteme za vbrizgavanje goriva (FIE), med katerimi je še vedno najbolj razširjen konvencionalni sistem (CFIE).

CFIE (tlačilka – cev – vbrizgalna šoba) se je od svojega nastanka (Bosch, 1930) vse do danes ne-nenavrhno izboljševal, da bi uspešnejše preoblikoval kemično energijo goriva v koristno delo. V zadnjem času so poudarjene ekološke in ekonomske zahteve, kar terja boljše krmiljenje procesa v CFIE.

V ta namen mora biti CFIE konstruiran tako, da omogoča:

- hitro vbrizgavanje,
- dobro razpršitev goriva in
- fazno krmiljenje procesa,

zaradi čim manjše škodljive emisije in ugodne porabe goriva.

0. INTRODUCTION

Ever stronger regulation of ecological and economy aspects and increasing requirements for engine performance govern the development of vehicular diesel engines. This development should include future demands in relation to internal and external engine control (PROMETHEUS). A large part of the burden in meeting these requirements falls on the fuel injection equipment (FIE). Among all FIE developed for automotive diesel engines the conventional fuel injection equipment (CFIE) is by far the most used.

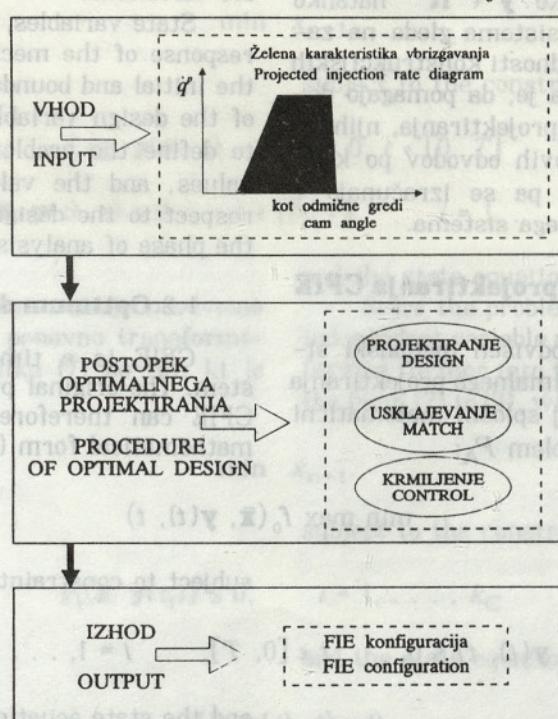
CFIE (pump – tube – injector) has been improved since its introduction (Bosch, 1930). The goal of this development has been to transform more effectively the chemical energy of fuel into useful work. In recent years, the most important requirements are those ecological and economic. This requires better control of CFIE processes.

To achieve this, the CFIE structure should be properly upgraded by:

- fast injection,
- good atomization of fuel and
- phase process control.

Izpolnjevanje teh zahtev je deloma protislovno. Znano je, da na primer hitrost vbrizgavanja in kot predvbrizga ne vplivata enako na specifično porabo goriva, emisija delcev, nezgorelih ogljikovodikov in NO_x . Z ukrepi, ki zmanjšujejo emisijo NO_x , se povečuje emisijo delcev, nezgorelih ogljikovodikov ter specifična poraba goriva in nasproto. Torej ni mogoče določiti CFIE, ki bi v celoti ustrezal vsem navedenim zahtevam, predvsem pa ne v celotnem režimu delovanja dizelskega motorja vozil. Določimo pa lahko CFIE, ki je le v izbranem pomenu optimalen. Pri tem je treba upoštevati, da je pri optimirjanju krmilnih in konstruktivnih parametrov CFIE treba izhajati iz želenih, vnaprej predpisanih izhodnih karakteristik procesa vbrizgavanja (sl. 1). Pri tem zahteva sistematični način za določitev optimalne konfiguracije CFIE vpeljavo postopkov optimalnega projektiranja z uporabo metod matematičnega programiranja, kar pomeni jedro te raziskave.

The fulfilment of these requirements is mostly contradictory, since it is known, for example, that injection duration and timing have different influences on specific fuel consumption and on particulate, unburned hydrocarbon and NO_x emissions. Factors, which reduce NO_x emission create an increase of both soot emission and fuel consumption. Consequently, it is not possible to determine a CFIE which could meet all of the above quoted requirements, especially not for the wide operating conditions that apply in the case of a truck engine. It is possible, however, to determine a CFIE which is optimised in a selected sense. In this case, the optimization of the CFIE configuration should be based on the desired or projected output characteristics of the injection process fig. 1. Here, a systematic approach for determining the optimum CFIE configuration requires the introduction of optimum design procedures by using the methods of mathematical programming. This is the subject of the present study.



Sl. 1. Inverzna računska pot
Fig. 1. Inverse calculation route

1. OPTIMALNO PROJEKTIRANJE CFIE

1.1 Osnove

Optimalno projektiranje pomeni sistematično določanje mehanskega sistema, ki mora biti v izbranem pomenu najboljši. Izraz »sistematično določanje« pomeni uporabo ustreznih matematičnih pripomočkov – metod matematičnega programiranja (metoda projekcije gradiента – GPM, metoda zaporednega kvadratičnega programiranja – RQP, aproksimacijske metode itn.).

1. OPTIMUM DESIGN OF CFIE

1.1 Generally

Optimum design presents a systematic determination of a mechanical system, which should be optimised with regard to the proposed goal. The expression »systematic determination« means that suitable mathematical technique – methods of mathematical programming (gradient projection method – GPM, recursive quadratic programming method – RQP, approximation methods, etc.) are employed.

Optimalno projektiranje temelji na iteracijskem načinu izboljšave mehanskega sistema, pri čemer je treba izbrati začetni sistem. Postopek optimalnega projektiranja je sestavljen iz naslednjih dveh ponavljajočih se faz:

a) *analiza modela mehanskega sistema*

— analiza odziva,

— občutljivostna analiza;

b) *izboljšava mehanskega sistema glede na izbrani kriterij.*

Optimalno projektiranje zahteva uvedbo dveh vrst spremenljivk, in sicer *konstrukcijske* in *sistemske* spremenljivke.

Konstrukcijske spremenljivke, $\bar{\mathbf{x}} \in \mathbf{R}^n$ so tisti parametri mehanskega sistema, katerih vrednosti določimo med procesom optimiranja. Njihove vrednosti sprememljamo, da bi izboljšali mehanski sistem, pri čemer so začetne izbrane vrednosti samo ena od mogočih različic sistema.

Sistemski spremenljivki $\mathbf{y} \in \mathbf{R}^m$ natanko opisujejo odziv mehanskega sistema glede na začetne in robne pogoje ter vrednosti konstrukcijskih spremenljivk. Njihova naloga je, da pomagajo definirati problem optimalnega projektiranja, njihove vrednosti in vrednosti njihovih odvodov po konstrukcijskih spremenljivkah pa se izračunajo v fazi analize modela mehanskega sistema.

1.2 Problem optimalnega projektiranja CFIE

CFIE pomeni časovno odvisen mehanski sistem. Originalni problem optimalnega projektiranja CFIE je zato zapisan v dokaj splošni matematični obliki (1) do (3) [4], kot problem P_A :

$$\min \max_t f_0(\bar{\mathbf{x}}, \mathbf{y}(t), t)$$

ob upoštevanju pogojev:

$$f_i(\bar{\mathbf{x}}, \mathbf{y}(t), t) \leq 0, \quad t \in [0, T], \quad i = 1, \dots, k_A \quad (2)$$

in enačbe stanja:

$$h(\bar{\mathbf{x}}, \mathbf{y}(t), t) = 0, \quad (3)$$

kjer pomenijo: f_0 — časovno odvisno namensko funkcijo, f_i — omejitveno funkcijo, k_A — število omejitvenih pogojev, $\bar{\mathbf{x}}$ — vektor konstrukcijskih spremenljivk ($\bar{\mathbf{x}} \in \mathbf{R}^n$), \mathbf{y} — vektor sistemskih spremenljivk ($\mathbf{y} \in \mathbf{R}^m$), t — čas, T — dolžina časovnega intervala.

Namenska funkcija $\max_t f_0$, skupaj z operatorem min, kaže želje konstrukterja. Omejitvene funkcije f_i oziroma ustrezni omejitveni pogoji, pa kažejo različne zahteve konstrukterja, od tehno-loških do mehanskih. Pri tem je treba poudariti,

The optimum design procedure is based on an iterative improvement of the design of the mechanical system, where the initial system has to be proposed. The procedure consists of two major steps repeated sequentially, as follows:

a) *analysis of the mechanical system*

— response analysis,

— sensitivity analysis

b) *improvement of the mechanical system.*

The optimum design procedure requires the introduction of two types of variables: design and state (process) variables.

Design variables, $\bar{\mathbf{x}} \in \mathbf{R}^n$ are understood to be those parameters of the mechanical system which should be defined quantitatively by the procedure of optimum design. Their values change during iterations in agreement with the goal of the improvement of the mechanical system and their proposed initial values present only one of the possible variations.

State variables, $\mathbf{y} \in \mathbf{R}^m$ exactly describe the response of the mechanical system dependent on the initial and boundary conditions and the values of the design variables. The state variables help to define the problem of optimum design. Their values, and the values of their gradients with respect to the design variables, are calculated in the phase of analysis of the mechanical system.

1.2 Optimum design problem of CFIE

CFIE is a time-dependent mechanical system. The original problem of optimum design of CFIE can therefore be defined in the general mathematical form (1) to (3) [4] as problem P_A :

$$\min \max_t f_0(\bar{\mathbf{x}}, \mathbf{y}(t), t) \quad (1),$$

subject to constraints:

$$f_i(\bar{\mathbf{x}}, \mathbf{y}(t), t) \leq 0, \quad t \in [0, T], \quad i = 1, \dots, k_A \quad (2)$$

and the state equation:

$$h(\bar{\mathbf{x}}, \mathbf{y}(t), t) = 0, \quad (3)$$

where: f_0 — a time dependent objective function, f_i — a constraint function, k_A — the number of constraints, $\bar{\mathbf{x}}$ — a vector of design variables ($\bar{\mathbf{x}} \in \mathbf{R}^n$), \mathbf{y} — a vector of system variables $\mathbf{y} \in \mathbf{R}^m$, t — time, T — the length of the time interval.

The objective function $\max_t f_0$ with the operator min reflects the requirements of the designer. The constraints f_i reflect different designer demands and limitations, from technological to mechanical. The state equation (3) represents the mathematical model for numerical simulation of

da enačba stanja (3) v problemu P_A podaja zvezo med konstrukcijskimi in sistemskimi spremenljivkami. To je enačba, ki predstavlja matematični model za numerično simuliranje procesov v CFIE [4], [5]. Enačba stanja je potrebna, ker ni mogoče izraziti omejitvenih pogojev in namenske funkcije eksplizitno v odvisnosti od samih konstrukcijskih spremenljivk.

V problemu P_A se pojavljata neodvisna spremenljivka t in operator max, ki maksimizira vrednost $f_0(\bar{\mathbf{x}}, \mathbf{y}(t), t)$ v izbranem časovnem intervalu $[0, T]$. Zaradi tega ni mogoča neposredna uporaba gradientnih metod matematičnega programiranja, ki so verjetno najuspešnejše metode za reševanje problemov optimiranja mehanskih sistemov.

Operator max se lahko odpravi z uvedbo dodatne konstrukcijske spremenljivke x_{n+1} [2] in s transformacijo problema P_A v ustreznega z obliko (4) do (6), ki je označen kot problem P_B :

ob upoštevanju pogojev:

$$\min x_{n+1} \quad (4),$$

x_{n+1}

subject to the constraints:

$$f_0(\bar{\mathbf{x}}, \mathbf{y}(t), t) - x_{n+1} \leq 0, \quad t \in [0, T] \quad (5),$$

$$f_i(\bar{\mathbf{x}}, \mathbf{y}(t), t) \leq 0, \quad t \in [0, T], \quad i = 1, \dots, k_A \quad (6)$$

in enačbe stanja (3).

Ker problem P_B še vedno vsebuje neodvisno spremenljivko t , ga je treba ponovno transformirati v ustreznega [3], z obliko (7) do (9), ki je označen kot problem P_C :

$$\min x_{n+1} \quad (7),$$

x_{n+1}

subject to the constraints:

$$i = 1, \dots, k_C \quad (8)$$

and the state equation (3):

$$h(\bar{\mathbf{x}}, \mathbf{y}(t), t) = 0 \quad (9)$$

kjer pomenijo: $\bar{\mathbf{x}}$ – vektor konstrukcijskih spremenljivk, ki vsebuje tudi dodatno konstrukcijsko spremenljivko ($\bar{\mathbf{x}} \in \mathbf{R}^{n+1}$), t_i – čas, v katerem dosegne funkcija g_i (pri izbranem $\bar{\mathbf{x}}$) lokalni maksimum, k_C – število omejitvenih pogojev v transformiranem problemu ($k_C \geq k_A + 1$).

Problem P_C je primeren za uporabo metod matematičnega programiranja, od katerih so se na področju optimiranja mehanskih sistemov najbolj uveljavile metoda RQP in aproksimacijske metode. Metoda RQP [1], [6] je edina, ki ima matematično dokazano globalno konvergenco, kar je bil tudi razlog za uporabo te metode v predstavljenem delu.

CFIE processes [4], [5]. This equation constitutes the relationship between the design and the state variables. The state equation is necessary since the constraints and objective function can not be expressed as explicit functions of the design variables only.

Problem P_A involves the independent variable t and the operator max, which maximizes the value of $f_0(\bar{\mathbf{x}}, \mathbf{y}(t), t)$ in the selected time interval $[0, T]$. The direct employment of gradient methods of mathematical programming, which represent probably the most efficient methods to solve an optimum design problem of a mechanical system, is therefore not possible.

Operator max should be eliminated with the introduction of an artificial design variable x_{n+1} [2] and with the transformation of the problem P_A into the equivalent problem of the form (4) to (6), which is denoted as problem P_B :

$$x_{n+1} \quad (4),$$

subject to the constraints:

$$f_0(\bar{\mathbf{x}}, \mathbf{y}(t), t) - x_{n+1} \leq 0, \quad t \in [0, T] \quad (5),$$

$$f_i(\bar{\mathbf{x}}, \mathbf{y}(t), t) \leq 0, \quad t \in [0, T], \quad i = 1, \dots, k_A \quad (6)$$

and the state equation (3).

Since the problem P_B still contains the time independent variable t , this problem has to be transformed further into the equivalent problem [3], of the form (7) to (9), which is denoted as problem P_C :

$$\min x_{n+1} \quad (7),$$

x_{n+1}

subject to the constraints:

$$i = 1, \dots, k_C \quad (8)$$

and the state equation (3):

$$h(\bar{\mathbf{x}}, \mathbf{y}(t), t) = 0 \quad (9)$$

where: $\bar{\mathbf{x}}$ – a vector of design variables, which also contains the artificial design variable ($\bar{\mathbf{x}} \in \mathbf{R}^{n+1}$), t_i – time, at which the function g_i (at fixed $\bar{\mathbf{x}}$) achieves a local maximum, k_C – the number of constraints in the transformed problem ($k_C \geq k_A + 1$).

The problem P_C has a form suitable to employ the standard methods of mathematical programming. Among all these methods in the field of optimization of mechanical systems, RQP and approximation methods are the most used. The RQP method [1], [6] is the only one which has a mathematically proved global convergence. This is why the RQP method is employed in this work.

2. PRIMER POSTAVITVE PROBLEMA OPTIMALNEGA PROJEKTIRANJA CFIE

Pri postavitevi problema optimalnega projektiranja CFIE je treba izbrati konstrukcijske spremenljivke, namensko funkcijo in omejitvene pogoje. Kot konstrukcijske spremenljivke smo izbrali naslednje parametre [4]:

- minimalni krivinski polmer na tangencialnem odmiku r_{cir} ,
- polmer osnovnega kroga T-odmikala r_0 ,
- polmer valjčka r_{rol} ,
- premer bata tlačilke d_k ,
- premer prelivnih odprtin d_p (predvih bata tlačilke h_p),
- dolžina visokotlačne (HP) cevi L ,
- premer izvrtin vbrizgalne šobe d_m .

2.1 Namenska funkcija

Proces vbrizgavanja zelo dobro ponazarja karakteristika vbrizgavanja, ki ima odločilen vpliv na proces zgorevanja. Zaradi tega je pomembno, da novi projektirani sistemi CFIE zagotovijo karakteristiko vbrizgavanja (IR), ki se čim manj razlikuje od želene (idealne) karakteristike. Na tej podlagi je narejena predstavljena optimizacija CFIE. Namenska funkcija je definirana kot največja razlika (v časovnem intervalu $[0, T]$) med želeno in dejansko karakteristiko vbrizgavanja. Rezultat minimizacije takšne namenske funkcije po konstrukcijskih spremenljivkah je sistem CFIE z optimalno karakteristiko vbrizgavanja, ki je najbliže želeni IR.

2.2 Omejitveni pogoji

Med postopkom minimiziranja namenske funkcije vrednosti konstrukcijskih parametrov \bar{x} seveda ni mogoče izbirati popolnoma poljubno. S tem bi bili namreč posredno ali neposredno zanemarjeni drugi parametri procesa vbrizgavanja ali omejitveni parametri (instalacijska razmerja, itn.) ki niso v neposredni zvezi s karakteristiko vbrizgavanja. Poleg tega je treba upoštevati še nekatere tehnološke omejitve, ki se največkrat nanašajo na postopek izdelave.

Zaradi vsega navedenega je v postopek optimiranja CFIE treba uvesti nekatere pogoje, ki se imenujejo omejitveni pogoji. V tem pogledu smo v primeru optimiranja sistema CFIE upoštevali omejitve, ki se nanašajo na:

- zaostali tlak p_0 (poznejši vbrizg goriva),
- teoretično hitrost curka w_r (razprševanje goriva),
- razmerje srednjega in največjega tlaka vbrizgavanja s_q (ekonomičnost sistema),
- omejitve konstrukcijskih spremenljivk (dejanska možnost izdelave in uporabnost).

2. A SAMPLE DEFINITION OF A CFIE OPTIMUM DESIGN PROBLEM

To define a CFIE optimum design problem, it is necessary to select the design variables, the objective function and the constraints. The following parameters have been selected as design variables [4]:

- minimum local radius of T-cam profile r_{cir} ,
- cam basic radius r_0 ,
- radius of the pump roller r_{rol} ,
- pump plunger diameter d_k ,
- intake and spill port diameter d_p (pump plunger prelift h_p),
- length of high pressure (HP) tube L ,
- nozzle hole diameter d_m .

2.1 Objective function

The injection process is very well illustrated by the injection rate, which has a decisive influence on the combustion process. It is therefore very important that the optimum CFIE systems realize an injection rate (IR) similar to the projected (idealized) IR. This idea forms the foundation for the presented optimization of CFIE. The objective function is defined as a maximum difference (on the time interval $[0, T]$) between the projected and the actual injection rate. The result of the minimization of this objective function, with respect to the design variables \bar{x} , is the CFIE system with the optimum injection rate, which is as close to the projected one as possible.

2.2 Constraints

Clearly, during minimization of the objective function, the values of the design parameters \bar{x} can not be varied total arbitrarily. This would mean that other parameters of the injection process or some constraining parameters (installation conditions, etc.), which are not directly connected with the injection rate, would be ignored. Furthermore, several technological constraints in relation to production must also be taken into account.

For this reason, some constraints have to be introduced into the procedure of CFIE optimization. In the following example, the introduced constraints refer to the:

- residual pressure p_0 (after-injection)
- rated loading figure w_r (fuel atomization)
- squareness s_q (system economy)
- lower and/or upper limits of the design variables (real possibility of production and applicability).

2.3 Optimizacijski model CFIE

Ko so določeni namenska funkcija in omejitveni pogoji ter izbrane konstrukcijske spremenljivke, lahko problem optimalnega projektiranja sistema CFIE zapišemo v matematični obliki. Za predstavljen osnovni izbor konstrukcijskih spremenljivk, omejitvenih pogojev in namenske funkcije veljajo izrazi (10) do (12), seveda pa lahko v primeru drugačnih zahtev konstrukterja nekatere pogoje odvzamemo, ali dodamo ali celo sprememimo namensko funkcijo:

$$\min \left(\max_t |\dot{q}^P - \dot{q}| \right) \quad (10),$$

ob upoštevanju pogojev:

$$\begin{array}{ll} r_{\text{cir}} \geq r_{\text{cir}, \min} & r_{\text{rol}} \leq r_{\text{rol}, \max} \\ r_0 \leq r_0, \max & d_k \leq d_k, \max \\ d_p \leq d_p, \max & L \geq L_{\min} \\ d_m \leq d_m, \max & p_0 \leq p_0, \max \\ s_q \geq s_q, \min & w_r \geq w_r, \min \end{array} \quad (11)$$

in enačbe stanja:

(model mehanskega sistema [4], [5]

kjer sta \dot{q} in \dot{q}^P dejanska in želena karakteristika vbrizgavanja, število omejitvenih pogojev je $k_A = 10$. Simboli na desni strani neenačb (11) pomenijo največje oziloma najmanjše predpisane vrednosti.

Problem (10) do (12) ima obliko P_A , zato ga je treba, v skladu z že opisanimi navodili, preoblikovati v obliko P_C :

ob upoštevanju pogojev (11) in

$$g_{k_A+j}(\mathbf{x}, \mathbf{y}(t_j), t_j) = |\dot{q}^P(t_j) - \dot{q}(t_j)| - x_{n+1} \leq 0, \quad j = 1, \dots, (k_C - k_A) \quad (14)$$

in enačbe stanja (12).

Zaradi lastnosti izračunane krivulje $|\dot{q}^P(t_j) - \dot{q}(t_j)|$, katere potek je zelo nazobčan, so se pojavili problemi v zvezi s številom in obnašanjem pogojev (14). Izkazalo se je namreč, da veliko število pogojev (14) precej ovira normalen postopek optimiranja. Ker takšen problem še ni bil obravnavan v literaturi, smo problem skušali rešiti s transformacijo pogojev (14) v obliko:

$$\int_{t_{j-1}}^{t_j} (|\dot{q}^P(t) - \dot{q}(t)|) dt - x_{n+1} \leq 0, \quad j = 1, \dots, k_D \quad (15)$$

dobljeno na podlagi integralnih vrednosti funkcije $|\dot{q}^P - \dot{q}|$ v izbranih časovnih intervalih $[t_{j-1}, t_j]$, kjer so $j = 1, \dots, k_D$, $t_0 = 0$, $t_{k_D} = T$ (k_D je število integracijskih intervalov). Mnogi numerični primeri so potrdili učinkovitost tega načina.

2.3 Optimization model of CFIE

After the objective function and constraints are defined and the design variables are selected, the problem of optimum design of CFIE can be expressed in a mathematical form. The terms (10) to (12) reflect the presented basic selection of design variables as well as the selected objective function and constraints. Clearly these expressions can vary in accordance with different designer requirements:

$$\min \left(\max_t |\dot{q}^P - \dot{q}| \right) \quad (10),$$

subject to the constraints:

$$\begin{array}{ll} r_{\text{cir}} \geq r_{\text{cir}, \min} & r_{\text{rol}} \leq r_{\text{rol}, \max} \\ r_0 \leq r_0, \max & d_k \leq d_k, \max \\ d_p \leq d_p, \max & L \geq L_{\min} \\ d_m \leq d_m, \max & p_0 \leq p_0, \max \\ s_q \geq s_q, \min & w_r \geq w_r, \min \end{array} \quad (11)$$

and the state equation:

(mathem. model of the mechanical system, [4], [5] where the symbols \dot{q} and \dot{q}^P denote the predicted and projected injection rate, respectively, the number of constraints is $k_A = 10$ and the symbols on the right side of inequalities (11) denote corresponding upper or lower prescribed values.

The problem (10) to (12) has the form P_A , so it must be transformed as already described into the form P_C :

$$\min x_{n+1} \quad (13),$$

subject to the constraints:

and the state equation (12).

Since the calculated shape of the curve $|\dot{q}^P(t_j) - \dot{q}(t_j)|$ is not smooth, specific problems appear in relation to the number and behaviour of constraints (14). It turns out that a large number of constraints (14) hinders the normal optimization procedure. Since such a problem has not been considered in the literature yet, we tried to solve it by transforming the constraints (14) into the following form:

$$\int_{t_{j-1}}^{t_j} (|\dot{q}^P(t) - \dot{q}(t)|) dt - x_{n+1} \leq 0, \quad j = 1, \dots, k_D \quad (15)$$

obtained on the basis of the integral values of the function $|\dot{q}^P - \dot{q}|$ in the selected time intervals $[t_{j-1}, t_j]$, where $j = 1, \dots, k_D$, $t_0 = 0$, $t_{k_D} = T$ (k_D is the number of intervals of integration). Many numerical examples confirmed the efficiency of this approach.

3. NUMERIČNI ZGLED

Za obravnavani primer so nekatere nespremenljive vrednosti konstrukcijskih parametrov CFIE podane v preglednici 1. Optimizacija CFIE je izvedena na režimu maksimalne moči.

Preglednica 1: Nespremenljivi parametri CFIE med procesom optimizacije
Table 1: Invariable CFIE parameters through the optimization procedure

Tlačilka Pump BOSCH PES6P120A	dvig bata plunger lift	11 mm
	razbremenilni volumen retraction volume	90 mm ³
	premer izvrtine dušilnega ventila snubber valve hole diameter	0,5 mm
HP cev HP tube	notranji premer inner diameter	2 mm
Vbrizgalna šoba Injector BOSCH KBAL65S/55-270	premer sedeža igle needle seat diameter	2,5 mm
	premer stebla igle needle guide diameter	5,0 mm
	dvig igle needle lift	0,35 mm

V tem primeru je želena IR izbrana glede na že omenjene zahteve po obliki karakteristike vbrizgavanja na režimu maksimalne moči [7] (Parkerjev ideal). Po »predpisanih« razmerjih in želenem času vbrizgavanja (čas vbrizgavanja 1,82 ms, izbran iz povprečnih vrednosti eksperimentalnih testiranj – RAPIER diagrami) je izračunana vbrizgana količina goriva $q = 168 \text{ mm}^3/\text{cikel}$ (želena q). Izračunana srednja hitrost vbrizgavanja (MIR) želenega CFIE tako znaša $92,3 \text{ mm}^3/\text{ms}$.

Omejitveni pogoji, ki se nanašajo na konstrukcijske spremenljivke in dodatne pogoje, so:

$$\begin{aligned} r_{clr} &\geq 1,9 \text{ mm} \\ r_{rol} &\leq 13 \text{ mm} \\ d_p &\leq 13 \text{ mm} \\ d_m &\leq 0,4 \text{ mm} \\ s_q &\geq 0,6 \end{aligned}$$

3.1 Rezultati

V prikazanih rezultatih tega primera so uporabljeni izrazi, ki označujejo najpomembnejša stanja pri postopku optimizacije:

– *želeno stanje* (definirano je z vnaprej predpisano želeno karakteristiko vbrizgavanja, ki mu ustreza želeni CFIE);

– *začetno stanje* (definirano je z začetnimi (izbranimi) vrednostmi konstrukcijskih spremenljivk, ki mu ustreza začetni CFIE);

3. A NUMERICAL EXAMPLE

Some values of CFIE invariable design parameters for the discussed example are shown in Table 1. The optimization of CFIE is performed under rated conditions.

In this example, the projected IR is selected in accordance with already mentioned requirements on the IR shape under rated conditions [7] (»Parker's dream«). On the basis of »prescribed« ratios and projected injection duration (time of injection 1.82 ms is selected on the base of average values of the experimental tests – RAPIER diagrams) the fuelling $q = 168 \text{ mm}^3/\text{stroke}$ (projected q) is calculated. The calculated mean injection rate (MIR) of the projected CFIE is $92.3 \text{ mm}^3/\text{ms}$.

The constraints relating to the design variables and to other CFIE parameters are as follows:

$$\begin{aligned} r_0 &\leq 17 \text{ mm} \\ d_k &\leq 4 \text{ mm} \\ L &\geq 0,3 \text{ m} \\ p_0 &\leq 3 \text{ MPa} \\ w_r &\geq 750 \text{ m/s} \end{aligned}$$

3.1 Results

In discussing the results, the following terms denoting the most important states in the optimization procedure are used:

– *projected state* (defined by the projected injection rate corresponding to the projected CFIE),

– *initial state* (defined by the initial (selected) values of the design variables corresponding to the initial CFIE),

— optimirano stanje (definirano je z optimiranimi vrednostmi konstrukcijskih spremenljivk, ki mu ustreza optimiran CFIE).

V preglednici 2 je podano priporočeno območje, v katerem naj bi bile vrednosti konstrukcijskih spremenljivk za dizelske motorje vozil. Prav tako so v tej preglednici podane začetne in optimirane vrednosti konstrukcijskih spremenljivk. Optimirane vrednosti so dobljene po 9 iteracijah.

— optimized state (defined by the optimized values of the design variables corresponding to the optimized CFIE).

Table 2 shows the recommended intervals of the design variable values for vehicular diesel engines as well as the initial and optimized values of the design variables. The optimized values of the design variables are obtained after 9 iterations.

Preglednica 2: Priporočeno območje, začetne in optimirane vrednosti konstrukcijskih spremenljivk
Table 2: Recommended Interval, Initial and optimized values of the design variables

	priporočeno območje recommended interval	začetno initial	optimirano optimized
d_k mm	10–13	12,00	11,45962
r_0 mm	15–17	16,00	15,93941
r_{rol} mm	11–13	12,00	11,83506
r_{clr} mm	1,8–2,5	2,00	1,90025
d_p mm	3,3–3,7	3,50	3,30000
L m	odvisno od lege tlačilke depending on the pump position	0,45	0,64658
d_m mm	omejitve glede tlaka in razpršitve curka limitation in relation to pressure and spray atomization	0,375	0,37036

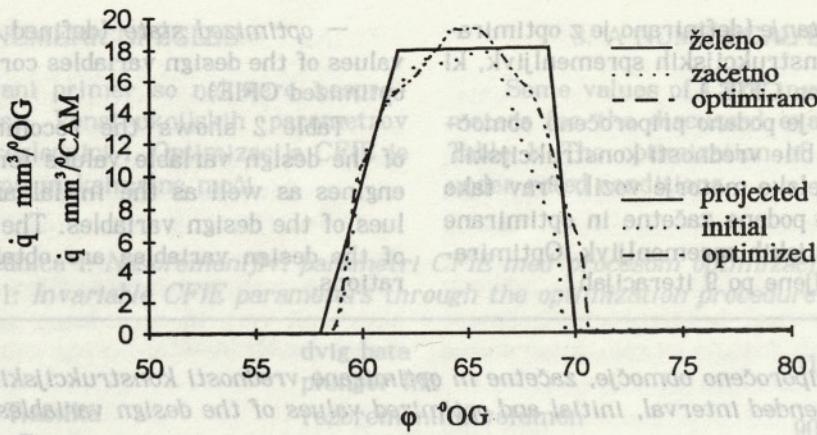
Z izbranimi začetnimi vrednostmi konstrukcijskih spremenljivk (preglednica 2) so izračunane zmogljivosti začetnega CFIE, podane v preglednici 3. Prav tako so v tej preglednici podane tudi zmogljivosti optimiranega CFIE, ki so izračunane z optimiranimi vrednostmi konstrukcijskih spremenljivk. Označbe v tej preglednici pomenijo: q – vbrizgano količino goriva v enem ciklu, t_{inj} – trajanje vbrizgavanja, MEIP – srednji dejanski tlak vbrizgavanja, $q_{0,5}$ – vbrizgano količino goriva v prvih 0,5 ms vbrizgavanja.

With the selected initial values of the design variables (table 2) the performance of the initial CFIE is calculated, which is given in table 3. In this table, the performance of the optimized CFIE, calculated with optimized values of the design variables, is also given. The following notation is used: q – fuelling, t_{inj} – injection duration, MEIP – mean effective injection pressure and $q_{0,5}$ – fuelling during first 0.5 ms.

Preglednica 3: Izračunane zmožnosti CFIE

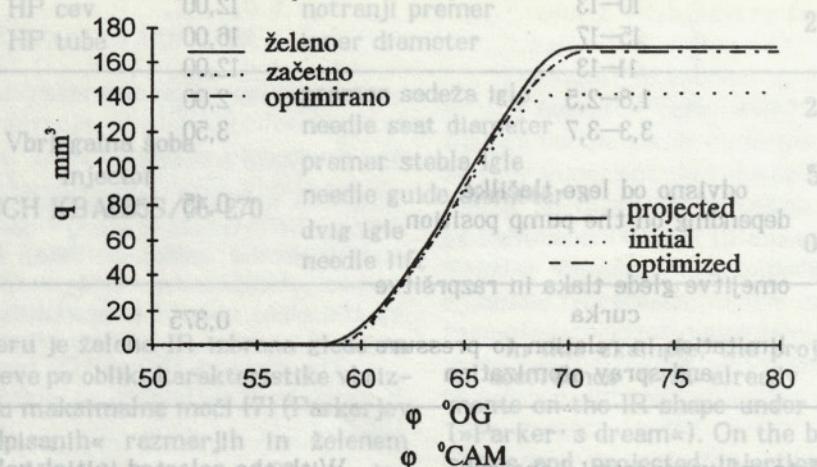
Table 3: CFIE performance data

CFIE	začetni initial	optimirani optimized	želeni projected
q mm^3/cikel	141,44	166,15	168,00
q $\text{mm}^3/\text{stroke}$			
MIR mm^3/ms	82,12	86,34	92,30
t_{inj} ms	1,72	1,92	1,82
MEIP MPa	41,86	47,47	
$q_{0,5}$ mm^3	25,87	24,65	



SI. 2. Primerjava karakteristik vbrizgavanja

Fig. 2. Comparison of injection rate histories



SI. 3. Primerjava integralnih karakteristik vbrizgavanja

Fig. 3. Cumulative injection rate diagrams

Slika 2 prikazuje rezultat optimizacije. Podana je karakteristika vbrizgavanja želenega, začetnega in optimiranega CFIE. Na sliki 3 je podana primerjava integralnih karakteristik vbrizgavanja.

Poleg izboljšanega poteka karakteristike vbrizgavanja je pri optimiranem CFIE izboljšana tudi razpršitev goriva. Teoretična hitrost iztekanja goriva iz vbrizgalne šobe znaša namreč $w_r = 750,03 \text{ m/s}$ (najmanjša predpisana vrednost je 750 m/s), medtem ko je pri začetnem CFIE hitrost iztekanja le 695 m/s . Razmerje srednjega nasproti največjemu tlaku vbrizgavanja znaša $s_q = 0,615$, kar je tudi nad najmanjšo »predpisano« vrednostjo. Prav tako je zaostali tlak optimiranega CFIE v »dovoljenem območju«. »Predpisano« in »dovoljeno območje« se nanašata na omejitvene pogoje.

Dobljeni rezultati kažejo, da se je mogoče do-kaj dobro približati želeni, še tako idealizirani karakteristiki vbrizgavanja. Dobljen je optimalen CFIE glede na želeno IR, pri čemer so vsi ome-jitveni pogoji izpolnjeni.

Fig. 2 illustrates the result of the optimization. It shows the injection rates of the projected, initial and optimized CFIE. Fig. 3 offers a similar comparison of cumulative injection rates.

In addition to the improved injection rate history, the fuel atomization of the optimized CFIE is also improved. Namely, the rated loading figure is $w_r = 750,03 \text{ m/s}$ (the minimum prescribed value is 750 m/s), while the rated loading figure of the initial CFIE is 695 m/s . The squareness $s_q = 0,615$ is also somewhat higher than the minimum »prescribed« value. In addition, the residual pressure of the optimized CFIE is in the »permissible interval«. The terms »prescribed« and »permissible interval« concern the constraints.

The results show that good agreement was achieved between the optimized and the projected (idealized) injection rate, as well as between all other CFIE performances. Additionally, it should be pointed out that all of the imposed constraints have been fulfilled.

4. SKLEP

Z vpeljavo optimalnega projektiranja na področje CFIE je torej mogoče sistematično določiti takšno konfiguracijo CFIE, ki je v izbranem pomenu optimalna. S tem načinom lahko določimo vrednosti konstrukcijskih parametrov CFIE v skladu s sodobnimi zahtevami motorja, prav tako pa lahko zmanjšamo obseg dragega eksperimentalnega dela. Opisani način je splošno uporaben, saj je izbira konstrukcijskih spremenljivk, namenske in omejitvenih funkcij odvisna od želja in zahtev konstrukterja.

Predlagani postopek nakazuje tudi nekatere smernice za nadaljnje delo:

- vpeljavo diskretnih konstrukcijskih spremenljivk za preprečitev nestandardnih dimenzij (premer bata, premer osnovnega kroga odmikača itn.);

- razširitev na ciklično optimizacijo z upoštevanjem različnih delovnih režimov (13 MODE).

4. CONCLUSIONS

By introducing optimal design in the field of CFIE development, it is possible to determine the optimum configuration of the CFIE in a systematic way in accordance with recent engine requirements. Expensive experimental work can be essentially reduced. The proposed approach is generally usable, since the selection of the design variables, the objective function and the constraints can reflect a wide palette of engineering requirements.

The proposed approach also suggests some directions for further work:

- the introduction of discrete design variables to prevent non-standard dimensions (plunger diameter, cam base diameter, etc.),
- extension to cyclic optimization by considering several engine conditions (13-MODE).

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