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Napovedni brezdimenzionalni enoconski modeli za simuliranje zgorevanja v dieselskem motorju

Predictive Zero-Dimensional Single-Zone Diesel-Combustion Simulation Models

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Članek obravnava napovedne, brezdimenzijske, enoconske termodinamične modele, ki opisujejo potek zgorevanja z dokaj preprostimi matematičnimi izrazi. Najprej podajamo pregled skupine modelov karakteristik sproščanja toplote, ki temeljijo na Vibejevi funkciji, in to po zaporedju, kakor so se se pojavljali v literaturi.

Sledi kratek pregled druge skupine modelov, ki sicer temeljijo na Vibejevem načinu, vendar vključujejo učinek karakteristike vbrizgavanja na sproščanje toplote.

Modeli tretje skupine so obravnavani bolj podrobno. Upoštevajoč Janikijev prijem so izvedeni trije izvirni modeli, ki vključujejo učinek spremembe trenutne vrednosti količine in hitrosti vbrizgavanja goriva ter razmernika zrak/gorivo med vbrizgavanjem, vendar je ohranjena njihova matematična preprostost.

Podan je opis modelov in primerjava računskih in eksperimentalnih rezultatov ter sklepi o primernosti uporabe takšnih simulirnih modelov pri reševanju pogostih problemov v tehnični praksi.

Predictive, zero-dimensional, single-zone thermodynamic combustion models based on simple mathematical descriptions are presented. The category of semi-empirical expressions based on Viebe function is reviewed first, following the chronological sequence in which the expressions appeared in literature.

The second category of modelling expressions concerning essentially Viebe's approach and incorporating the effect of fuel injection on heat release is then surveyed briefly as well.

Under the third category the models based on Janikiev's approach are presented in more detail. Three original models have been generated incorporating in the expressions the effect of change of fuelling, injection rate and air equivalence ratio at any instant during the injection and combustion process, but still preserving their mathematical simplicity.

The models are described and discussed and the comparison of computed and experimental results is given. The conclusions concerning the suitability of presented models for routine simulation exercises are given.

0. UVOD

Pri razvoju termodinamičnih modelov motorjev z notranjim zgorevanjem je poglavitni problem, kako kolikostno pravilno in dovolj natančno opisati proces zgorevanja. Razsežnost in zapletenost matematičnega opisa fizikalnih dogodkov dejanskega poteka in kinetike kemičnih reakcij med zgorevanjem sta načeloma odvisna od namena in uporabe računalniškega programa pri reševanju sprotnih problemov razvoja in raziskav ali od potreb za izvajanje rutinskih simulirnih nalog, ko inženir — konstrukter potrebuje takšne matematične modele, ki zagotavljajo hitro rešitev.

V tem prispevku bomo obravnavali napovedne (predicirne), brezdimenzijske, enoconske, termodinamične modele (PTM), pri katerih temelji podprogram za opis zgorevanja na dokaj preprostem matematičnem opisu karakteristike sproščanja toplote. Ta je vodilni člen v osnovni energijski enačbi fizikalno-matematičnega modela $T = F(\Theta)$ in $p = f(\Theta)$, (0.1) [1] za napoved trenutnega termodinamičnega stanja delovne snovi v valju motorja ter notranjih in dejanskih parametrov, ki določajo karakteristike motorja.

Načeloma omogoča ta model samo zelo omejen vpogled v podrobnosti procesa zgorevanja in ga uporabljamo v primerih, ko nas te pri simuliranju procesov ne zanimajo. V te namene se je kot izredno primerna pokazala Vibejeva funkcija [3],[4] in jo pogosto uporabljamo. Daje dovolj informacij, da lahko napovemo vrsto potrebnih značilnosti motorja.

Brezdimenzionalni nenapovedni (NPTM) modeli so bili podrobno opisani v več objavah, na primer [1], [2]. V vseh modelih temelji izvajanje osnovnih enačb na ohranitvi snovi, gibalne količine in energije ter vsebuje vrsto predpostavk, ki enačbe matematično poenostavljajo. Tako ima npr. energijska enačba naslednjo obliko:

0. INTRODUCTION

The main problem in developing a predictive type of thermodynamic model for I.C. engines is quantitatively to describe combustion phenomena properly and accurately. The extent and the complexity of the mathematical description of physical processes, the true mechanism and kinetics of chemical reactions during combustion depend generally on the purposes of use of a simulation computer program to solve current engineering problems in development and research. Moreover, a design engineer often requires mathematical models which produce quick solutions, in order to accomplish suitable routine simulation exercises for overall engine performance analyses.

In predictive, zero-dimensional, single-zone, thermodynamic models (PTM), the combustion submodel should generate a fairly simple mathematical description for the rate of heat release, incorporated in the main equation $T = F(\Theta)$ or $p = f(\Theta)$, expression (0.1) [1] in order to predict: the instantaneous theromodynamic state of the working fluid within the cylinder, indicated and effective engine data, determining engine output performance.

Basically, this model offers limited or hardly any insight into combustion events and it is used in cases when they are not of interest in engine process simulation. The Viebe function [3], [4], has been considered very suitable for simulating the fuel burning rate and it has achieved a broad application, because it provides enough data for appropriate engine data prediction.

The nonpredictive models (NPTM) have so far been described in detail in a number of sources (for example [1], [2]) and the derivation of basic equations in all models is founded on equations of change with several simplifications and assumptions. The final energy equation can be presented in the following form:

$$\frac{dp}{d\Theta} = \frac{\dfrac{dQ_s}{d\Theta} - \dfrac{dQ_c}{d\Theta} - p\dfrac{dV}{d\Theta} + (h_F - u)\dfrac{dm}{d\Theta} - \dfrac{\partial u}{\partial T}\dfrac{p\dfrac{dV}{d\Theta} - TR\dfrac{dm}{d\Theta} - mT\dfrac{\partial R}{\partial \alpha}\dfrac{d\alpha}{d\Theta}}{R + \dfrac{\partial R}{\partial T}T} - m\dfrac{\partial u}{\partial \alpha}\dfrac{d\alpha}{d\Theta}}{\dfrac{\partial u}{\partial T}\dfrac{V - mT\dfrac{\partial R}{\partial p}}{R + \dfrac{\partial R}{\partial T}\cdot T} + \dfrac{\partial u}{\partial p}m} \qquad (0.1).$$

V članku je naša pozornost namenjena opisu člena, ki določa sproščanje toplote med zgorevanjem. V modelu PT skušamo ta člen izraziti s primerno matematično funkcijo ali korelacijo, ki samo globalno simulira proces zgorevanja. Do sedaj so mnogi avtorji predlagali vrsto izrazov za značilnico sproščanja toplote, izhajajoč iz zasnove koncepta zgorevanja z namenom vgraditi v model posebnosti procesa zgorevanja v dieselskem motorju v čim preprostejši obliki.

In this paper, attention is focused on the combustion term — Fuel Burning Rate or Rate of Heat Release (ROHR). In a predictive model, this term is expressed with some mathematical function or correlation simulating combustion phenomena in a global form. Several macro-concepts, generating numerous relationships, have been proposed for ROHR by many authors with the aim of expressing the specific features of diesel combustion in a mathematically simple form.

Namen članka je predstaviti modele za sproščanje toplote, ki se dandanes uporabljajo, ter predloge avtorjev za izboljšave. Še posebej pa je naša pozornost posvečena modelom, ki v svojo kompozicijo vključujejo vpliv karakteristike vbrizgavanja goriva [5], [6], [7] na sproščanje toplote. Pri razlagi bomo upoštevali kronologijo objav modelov.

The main objective of this paper is to present an overview of ROHR models used and to introduce the authors' proposals for model improvement. Moreover, our attention will also be focused on models including the effect of injection rate IR [5], [6], [7] on ROHR. The presentation will follow the chronological sequence in which the models have appeared in the literature.

1. MODELI SPROŠČANJA TOPLOTE (pregled)

1. FBR-MODELS (overview)

1.1 Vibejeva funkcija

Vibejevo karakteristiko sproščanja toplote bomo samo povzeli, saj je bilo njeno izvajanje podano že v mnogih objavah. V nadaljevanju pa bomo predstavili predloge novih modelov.

Vibejeva karakteristika sproščanja toplote [3] temelji na teoriji verjetnosti poteka kemičnih reakcij in nastajanja aktivnih centrov (radikalov), ki spodbujajo prehod molekul goriva v produkte zgorevanja:

1.1 Viebe function

The models based on the Viebe function are briefly summarized only, because their derivations have been presented elsewhere.

Viebe's burning law [3] is based on the theory of probability, related to the development of chemical reactions and the formation of active centers (radicals), initiating the transition of fuel molecules to combustion products:

$$x = 1 - \exp\left(-\int_0^t n\rho\,dt\right) \qquad (1.1)$$

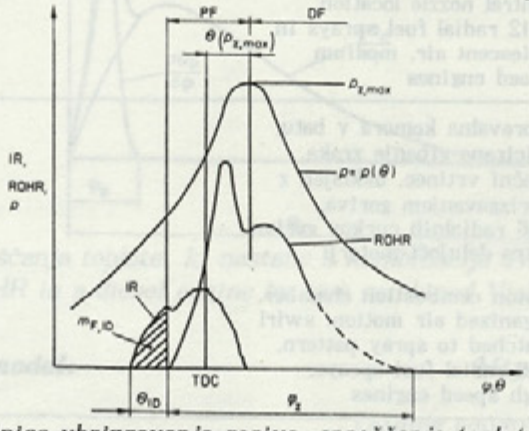
Člen $\rho\,dt$ pomeni povprečno verjetnost, da bo molekula v časovnem intervalu dt reagirala. Za to predpostavko je Vibe izpeljal izhodiščno funkcijo:

The term $\rho\,dt$ represents a »mean probability«, with which the fuel molecule will react during the time interval dt. At this point, Viebe had to find the governing function:

$$f(t) = \int_0^t n\rho(t)\,dt \qquad (1.2)$$

kjer je $\rho(t) = k\,t^m$ (potenčna funkcija) in je k koeficient sorazmernosti.

where $\rho(t) = k\,t^m$ (potential function) and k is the coefficient of proportionality.



Sl. 1. *Povezanost značilnice vbrizgavanja goriva, sproščanja toplote in tlaka v valju motorja.*
PF – plamen poprej pomešanih reaktantov; DF – difuzijski plamen

Fig. 1. *Relationship between IR, ROHR and in-cylinder pressure history.*
PF – premixed flame; DF – diffusion flame.

S posplošitvijo pojavov, ki potekajo v zgorevalnem prostoru, je Vibe izpeljal izraz za sproščanje toplote v brezdimenzijski obliki, znan kot Vibejeva funkcija:

Generalizing the combustion phenomena occurring in the engine cylinder, Viebe proposed an expression for ROHR in the following nondimensional form, known as the Viebe function.

$$\frac{dx}{dy} = a\,(m+1)\,y^{m}\exp(-ay)^{m+1} \qquad (1.3),$$

kjer so:

a — konstanta, odvisna od deleža goriva, ki zgori med zgorevanjem, t.j. v časovnem intervalu t_z oziroma v kotnem intervalu φ_z (če predpostavimo, da zgori 99,9 odstotkov goriva, ima konstanta a vrednost 6,908);

m — faktor oblike karakteristike zgorevanja v motorju, ki oblikuje potek sproščanja toplote in je odvisen od vrste dejavnikov, od katerih je odvisno nastajanje zmesi in potek zgorevanja;

$y = t/t_z$ oziroma $y = \varphi/\varphi_z$ — relativni čas zgorevanja.

V preglednici 1 so podane nekatere približne vrednosti parametrov m in φ_z, ki so jih predlagali in eksperimentalno potrdili različni avtorji. Zaradi zapletenosti zgorevanja in raznolikosti načinov priprave zmesi so vrednosti, ki jih navajamo v preglednici 1, v veliki meri rezultat izkušenj. Mnogi avtorji [8], [9], [10] so poskušali Vibejeva pararametra m in φ_z izraziti v obliki korelacijskih odvisnosti (od vrtilne hitrosti, tlaka polnjenja, obremenitve itn.).

where:

a — the degree of fuel burnt during combustion, i.e. in time interval t_z or angle interval φ_z (if it is estimated that 99.9% of fuel is burnt, the constant becomes $a = 6.908$);

m — the ROHR shape factor and is a qualitative kinetic characteristic of engine combustion, depending on several factors influencing mixture formation and development of combustion processes.

$y = t/t_z$ or $y = \varphi/\varphi_z$ — dimensionless burning time.

A great deal of m in φ_z data generated and proposed by many authors, has been gathered during the past, weighed and experimentally validated. Because of the complex nature of the combustion process, and a great variety of mixture formation models, data presented in Table 1 are inevitably based on past engineering experience. Several authors [8], [9], [10] have tried to correlate Viebe parameters m in φ_z to satisfy a wide range of engine operating conditions (speed, load, boots pressure etc.).

Preglednica 1: *Vrednosti m in φ_z glede na postopek priprave zmesi v dieselskih motorjih [3], [11], [14].*
Table 1: *m and φ_z values in relation to mixture formation mode in diesel engines [3], [11], [14].*

Vrsta motorja Type of engine	postopek priprave zmesi mode of mixture formation	m	φ_z [°] [1]
Neposredni vbrizg goriva	enotni zgorevalni prostor, osrednja lega vbrizg. šobe, 8–12 radialnih curkov goriva v mirni zrak, srednje hitro delujoči motorji		
Direct fuel injection	single combustion space, central nozzle location, 8–12 radial fuel sprays in quiescent air, medium speed engines	0.05–0.015	100–150
	zgorevalna komora v batu, inicirano gibanje zraka, zračni vrtinec, usklajen z vbrizgavanjem goriva, 3–6 radialnih curkov goriva, hitro delujoči motorji		
	piston combustion chamber, organized air motion, swirl matched to spray pattern, 3–6 radial fuel sprays, high speed engines	0.35–0.5	60–90
	M - proces M - process	0.8–1.2	60–75
Posredni vbrizg goriva	vrtinčna komora swirl combustion chamber	0.4–1.0	60–100
Indirect fuel injection	predkomora prechamber	0.3–0.9	60–100

[1] Vse stopinje v besedilu so °RG (ročične gredi).

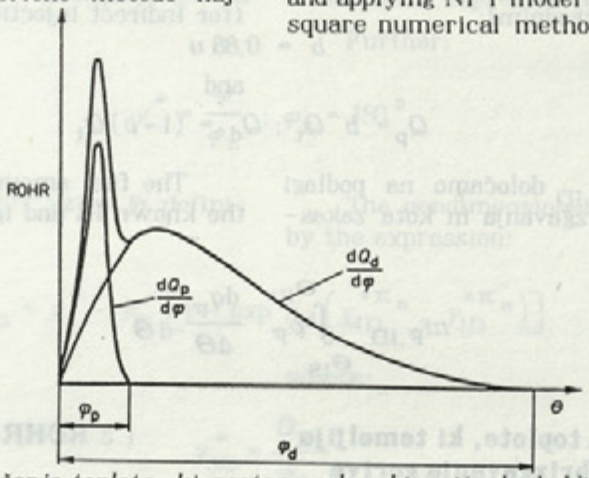
[1] Degrees indicated throughout the text are in °CA (crank angle).

1.2 Kombinacija dveh Vibejevih funkcij

Osnovna Vibejeva funkcija (1.3) ima samo en vrh. Tipična krivulja sproščanja toplote enoconskega modela zgorevanja pa ima s predpostavko, da poteka zgorevanje v dveh fazah, načeloma dva vrhova. Dve fazi zgorevanja razlagamo kot zgorevanje kinetskega in difuzijskega plamena. Da bi obliko korelacijske krivulje sproščanja toplote prilagodili dejanski, so nekateri avtorji, npr. Watson [12], Oberg [13], Ghojel [15], Miyamoto [16] in Craddok [17], sproščanje toplote z dvema vrhovoma skušali doseči s seštevanjem dveh Vibejevih funkcij. Kot značilen primer bomo kratko prikazali model Miyamota in soavtorjev [16], ki je podan z izrazi (1.5) do (1.14). Indeks p se nanaša na zgorevanje poprej pomešanih reaktantov, indeks d pa na difuzijsko zgorevanje. Tako sta φ_p in φ_d intervala sproščanja toplote, m_p in m_d pa faktorja oblike sproščanja toplote v omenjenih fazah zgorevanja. Tako oblikovana dvojna Vibejeva funkcija NTP je definirana s šestimi parametri, s katerimi jo lahko ustrezno oblikujemo. Vrednosti teh parametrov oz. korelacijske enačbe zanje so določili tako, da so računsko prilagajali dvojne Vibejeve funkcije za sproščanje toplote, izračunane na temelju eksperimentalno določenih vrednosti tlaka v valju z uporabo modela NPT in numerične metode najmanjših kvadratov.

1.2 Combination of two Viebe functions

The original Viebe function (1.3) has only a single maximum peak. However, a typical heat release rate curve from a single zone model generally shows two characteristic peaks, and it is assumed that diesel combustion exhibits a two-stage behavior, commonly identified as premixed and diffusion burning, regardless of operating conditions. In order to adopt the shape of the ROHR correlation curve to the shape of the curve of a real diesel engine, curves with two maximum peaks have been obtained by combination of two Viebe functions. This approach has been used by many authors, such as Watson [12], Oberg [13], Ghojel [15], Miyamoto [16] Craddock [17]. A graphic presentation of such a model function is shown in Fig. 2. As an example of derivation of an adequate expression of this type, Miyamoto's model is summarized and presented with expressions (2.5) through (2.14). The subscripts p and d refer to the premixed and diffusion phases of burning, respectively φ_p, φ_d are durations of energy release and m_p and m_d are shape factors. Thus this double Viebe function (VF) contains six adjustable parameters. The values and dependence correlations of these parameters have been obtained by adjusting the double VF to the ROHR computed by using experimentally determined in-cylinder pressure data and applying NPT model and the conventional least square numerical method.



Sl. 2. *Primer sproščanja toplote, ki nastane s kombinacijo dveh Vibejevih funkcij.*
Fig. 2. *Description of ROHR in a diesel engine by two combined Viebe combustion functions.*

Miyamotov model:

Izhodiščna enačba je:

Miyamoto's model:

Leading equation is:

$$\frac{dQs}{d\varphi} = 6{,}9\,\frac{Q_p}{\varphi_p}\,(m_p+1)\left(\frac{\varphi}{\varphi_p}\right)^{m_p}\exp\left[-6{,}9\left(\frac{\varphi}{\varphi_p}\right)^{m_p+1}\right] + 6{,}9\,\frac{Q_d}{\varphi_d}\,(m_d+1)\left(\frac{\varphi}{\varphi_d}\right)^{m_d}\exp\left[-6{,}9\left(\frac{\varphi}{\varphi_d}\right)^{m_d+1}\right] \quad (1.4)$$

Predpostavke:
Motorji z neposrednim vbrizgom:

Approximations:
Direct injection engines:

$$m_p = 3,\ m_d = 0{,}5,\ \varphi_p = 7^0$$

$$\varphi_d = 0{,}93\ Q_d + 24{,}5\ [^0] \tag{1.5}$$

$$Q_p = 0{,}5\ Q_i \tag{1.6}$$

kjer so:
Q_i — toplota, ki se sprosti z zgorevanjem goriva vbrizganega v času zakasnitve vžiga $Q_i = m_{F,ID}\ H_f$.

where:
Q_i — heat released from the fuel injected during ignition delay, $Q_i = m_{F,ID}\ H_f$.

Motorji s posrednim vbrizgom:

Indirect injection engines:

$$m_p = 3,\ m_d = 0{,}9,\ \varphi_p = 7^0$$

$$\varphi_d = 0{,}93\ Q_d + 19{,}0\ [^0] \tag{1.7}$$

$$Q_p = 0{,}88\ Q_i \tag{1.8}$$

Celotna, z gorivom dovedena energija:

The energy of the total injected fuel is:

$$Q_t = m_{FC} H_f \tag{1.9}$$

$$Q_d = Q_t - Q_p \tag{1.10}$$

Če označimo:

If we designate:

$$u = \frac{m_{F,ID}}{m_{FC}} \tag{1.11}$$

je (za motorje z neposrednim):

then (for direct injection):

$$b = 0{,}5\ u$$

oziroma (za motorje s posrednim):

(for indirect injection):

$$b = 0{,}88\ u \tag{1.12}$$

in

and

$$Q_p = b\ Q_t\ ;\ Q_d = (1-b)\,Q_t \tag{1.13}$$

Količino goriva $m_{F,ID}$ določamo na podlagi znane karakteristike vbrizgavanja in kota zakasnitve vžiga Θ_{ID}:

The fuel amount $m_{F,ID}$ is determined from the known IR and ignition delay angle:

$$m_{F,ID} = \int_{\Theta_{IS}}^{\Theta_{ID}} \rho_F \frac{dq_F}{d\Theta}\, d\Theta \tag{1.4}$$

1.3 Modeli sproščanja toplote, ki temeljijo na karakteristiki vbrizgavanja goriva

Prvi je opisal model sproščanja toplote na tak način Shipinski s soavtorji [8]. Model so izrazili z Vibejevo funkcijo, korelacijske izraze parametrov pa izpeljali na podlagi eksperimentalno določene karakteristike vbrizgavanja. Avtorji Šokotov [18], Seleznjov [19] in Somov [20] so predlagali podoben način. Z vključevanjem značilnice vbrizganja goriva so skušali natančneje opisati hitrost zgorevanja, z uporabo različnih empiričnih in polempiričnih korelacij pa upoštevati vpliv glavnih konstrukcijskih (zgorevalni prostor) in obratovalnih dejavnikov na nastajanje zmesi in zgorevanje. Prikazali bomo samo model

1.3 ROHR models based on IR

An investigation of this kind was first conducted by Shipinski et al [8]. They described the ROHR with Viebe function and correlated the parameters with experimentally determined IR. The authors Shokotov [18], Sleznjov [19] and Somov [20] proposed almost the same approach. Moreover, they have sought a more precise physical description of the combustion rate. They have therefore included in the IR function, empirical and semi-empirical correlations aproximating the influence of main design and operating factors on diesel mixture formation and combustion. Only Shokotov's ROHR model will be briefly discussed here [18]. His leading equation of ROHR in nondimensional form is

sproščanja toplote po Šokotovu [18]. Osnovna izhodiščna enačba je podana v brezdimenzijski obliki z izrazom (1.15). Šokotov je predpostavil, da je potek sproščanja toplote proporcionalen vbrizgavanju goriva z zakasnitvijo enako zakasnitvi vžiga. Izpeljave izrazov (1.16) do (1.18) so podane v [18], zato smo jih izpustili. Model Šokotova temelji na dveh kritičnih pripombah k delu Vibeja:

— Vibejev parameter oblike sproščanja toplote, tj. parameter m, ne more biti konstanten med celotnim procesom zgorevanja, saj je močno odvisen od vrste dejavnikov, ki krmilijo potek kemičnih reakcij.

— Dolžina trajanja zgorevanja ($66 \leq \varphi_z \leq 150^0$) ne zadošča zahtevi, naj v tem času zgori 99,9 % goriva, saj se, kakor ugotavlja Šokotov, zadnja faza zgorevanja oziroma konec sproščanja toplote razteza globoko v takt ekspanzije. Zato je po Šokotovu $\varphi_z = 180^0$.

Model Šokotova

Relativna količina zgorelega goriva:

given with the relationship (1.15). Shokotov assumed that ROHR is proportional to IR and retarded for ignition delay. Further, only a few basic equations (1.16) through (1.18), representing the sense of this approach are given. The entire procedure of derivation is explained in the literature [18]. The set of correlations to evaluate the parameters in equation (1.16) is omitted. Shokotov's model is founded on his basic critical remarks in relation to Viebe's original approach:

— Viebe's ROHR shape parameter m cannot be kept constant throughout the burning process. It is a strong function of several factors controlling the history of chemical reactions.

— The combustion duration ($66 \leq \varphi_z \leq 150^0$) can hardly be estimated, bearing in mind that during this time of combustion duration 99.9 % of fuel is burnt. Shokotov has pointed out that this condition could never be met, because of the long period of late burning, stretching far into the expansion stroke. Thus, Shokotov proposed $\varphi_z = 180^0$.

Shokotov's model:

The relative amount of fuel burnt:

$$x = \sigma\left(y^* - y^*_{ID}\right) \tag{1.15}$$

$\sigma(y^*)$ je matematična korelacija kumulativne (integralne) krivulje značilnice vbrizganja goriva v brezdimenzijski obliki.

Nadalje sta:

$\sigma(y^*)$ is a mathematical correlation of cumulative IR expressed in nondimensional form:

Further:

$$y^* = \frac{\varphi}{\varphi_z}\ ;\ \varphi_z = 180^0$$

Brezdimenzijska zakasnitev vžiga je definirana z izrazom:

The nondimensional ignition delay is defined by the expression:

$$y_{ID} = y^* - \pi_c\left[1 - \exp \pi_d\left(y^{*\pi_n}_{ID} - y^{*\pi_n}_{ID}\right)\right] \tag{1.16}$$

kjer je:

where:

$$y^*_{ID} = \frac{\Theta_{ID}}{\varphi_z}$$

in so π_c, π_d, π_n parametri, zapisani s kompleksnimi korelacijskimi funkcijami.

Končna enačba integralnega sproščanja toplote je:

and π_c, π_d, π_n - are complex functions, correlating several design and operating parameters.

The final equation of cumulative burning characteristics:

$$x = C\left\{1 - \exp\left[a\left(y^{*m+1}_{ID} - y^{*m+1}\right)\right]\right\} \tag{1.17}$$

diferencialno enačbo pa dobimo z odvajanjem izraza (1.17) po času (ali kotu):

and the ROHR is obtained by differentiating the expression (1.17) by time (or angle):

$$\frac{dx}{dy^*} = a\,C\,(m+1)\,y^{*m} \exp\left[a\left(y^{*m+1}_{ID} - y^{*m+1}\right)\right] \tag{1.18}$$

Podobnost izraza (1.18) z Vibejevo funkcijo (1.3) je očitna, saj preide izraz (1.18) z vpeljavo $C = 1$ in $y_{ID}^* = 0$ v izraz (1.3). Po mnenju Šokotova je Vibejeva funkcija samo poseben primer njegove bolj posplošene formulacije sproščanja toplote. Uporaba Šokotovega modela zahteva celo vrsto konstant v korelacijskih enačbah, ki jih moramo predpostaviti ali pa določiti s preizkusi na reprezentativnem (vzorčnem motorju).

V *Janikijev model* sproščanja toplote je vbrizganje goriva vključeno neposredno. Janikijev model je še vedno enoconski model, ki pa je v fizikalnem pogledu doslednejši in v enačbe vključuje manj empirike, razen v primeru, ko zaradi nepoznavanja podrobnosti zgorevanja v dieselskem motorju uporabi Vibejevo potenčno funkcijo (1.2). Model je še vedno ostal matematično preprost in povsem očitno je, da ne more popolnoma nadomestiti nadrobnega opisa procesov dieselskega zgorevanja, ampak ponazarja le splošne vplive značilnice vbrizganja goriva na proces zgorevanja. V nadaljevanju v skrajšani obliki povzemamo Janikijev model po [5] in [21]. Proces zgorevanja je poenostavljeno obravnavan kot bimolekularna reakcija, katere kinetiko predstavlja izraz (1.19). Brezdimenzijska hitrost kemične reakcije je izražena z relativno količino zgorelega goriva (1.20), trenutni koncentraciji O_2 in goriva pa sta določeni z enačbama (1.23).

Here, the similarity between the expression (1.18) and Viebe's function (1.3) is obvious. By $C = 1$ and $y_{ID}^* = 0$ the equation (1.18) obtains the form of equation (1.3). According to Shokotov, Viebe function is only a special case of his more general formulation and a more detailed description of ROHR. The application of Shokotov's predictive model requires either the estimation of a number of constants in his correlations or these data must be obtained by previous experimental research, applied to a representative test engine.

In Janikiev's model the dominant influence of IR is directly included. His approach of modelling the combustion phenomena is still based on a singe -zone model, but it is more consequent in a physical sense. In order to overcome the lack of understanding of the diesel combustion mechanism, Viebe potential function (1.2) is used again. The mathematical simplicity of the model is still preserved. Obviously Janikiev's model can still not describe details of diesel combustion, but it does reproduce better the overall effects of combustion enabling predictions of engine performance required by a design engineer. A summarized version of JM is given here, but more can be found in the literature [5], [21]. The combustion process is simplified with a bimolecular reaction and equation (1.19) The nondimensional rate of chemical reaction expressed with the relative amount of fuel burnt, is given by equation (1.20). The current concentrations of O_2 and fuel are given by equation (1.23), respectively.

Izvirni Janikijev model

$$\frac{dC_F}{dt} = -k_f\, C_F\, C_{O_2} \qquad (1.19),$$

kjer je k_f — konstanta kemične reakcije:

$$\frac{dx}{dt} = -k_1\, \rho(\bar{t})\, C_{O_2}\, C_F = f_o(t) \qquad (1.20),$$

kjer je: $\rho(t)$ — Vibejeva potenčna funkcija in $k_1 = k_f\, k$.

Če definiramo:

$$\bar{t} = \frac{t - t_{cs}}{t_z}\ ;\quad t_z = t_{ce} - t_{cs} \quad \text{in} \quad \bar{\varphi} = \frac{\Theta - \Theta_{cs}}{\varphi_z} = \frac{\varphi}{\varphi_z}\ ;\quad \bar{t} = \frac{\bar{\varphi}}{360\, n} \qquad (1.21)$$

in

$$\alpha_0 = \frac{m_a\, l_0}{m_{FC}}\ ;\quad m_{F1} = \frac{\Delta_F\, m}{m_{FC}}\ ;\quad \Delta m_F = \int_{\Theta_{IS}}^{\Theta} \frac{dm_F}{d\Theta}\, d\Theta \qquad (1.22),$$

potem je:

$$C_{O_2} = k_{O_2}\,(\alpha_0 - x)\ ;\quad C_F = k_F\,(m_{F1} - x) \qquad (1.23).$$

Uvrstimo (1.23) v (1.19), dobimo:

$$\frac{dx}{dt} = -k_t\, \bar{t}^{\,m}\, (m_{F1} - x)(\alpha_0 - x) \qquad (1.24),$$

$$k_t = k_{O_2}\ k_F\ k_1$$

Original Janikiev's model

k_f — reaction rate constant

where $\rho(t)$ is Viebe potential function and $k_1 = k_f\, k$.

If we define:

and

then:

Introducing (1.23) into (1.19) we obtain:

$$dx = -k_\varphi \bar{\varphi}^m (m_{Fl} - x)(\alpha_0 - x) d\varphi = f_1(x) f_2(x) d\varphi \quad (1.25),$$

kjer je:

where:

$$\int f_1(x) = \int \frac{dx}{(m_{Fl} - x)(\alpha_0 - x)} = \frac{1}{\alpha_0 - m_{Fl}} \ln \frac{\alpha_0 - x}{m_{Fl} - x} \quad (1.26),$$

$$k_\varphi = \frac{k_t}{(360\, n)^m\, 6\, n}$$

in

and

$$\int f_2(x) = -k_\varphi \int \bar{\varphi}^m \, d\varphi = -k\, \bar{\varphi}^{m+1} + C \quad (1.27)$$

ter velja:

while:

$$k = \frac{k_\varphi\, \varphi_z}{(m+1)}$$

Izraza (1.26) in (1.27) uvrstimo v (1.25), integracijski konstanti pa določimo z uporabo robnih pogojev:

After inserting the equations (1.26) and (1.27) into (1.25) and calculating the integration constants applying boundary conditions:

$$\begin{aligned} \varphi &= 0 \;;\; \bar{\varphi} = 0 \;;\; x = 0 \\ \varphi &= \varphi_z \;;\; \bar{\varphi} = 1 \;;\; x = x_z \end{aligned} \quad (1.28)$$

ter tako dobimo Janikijevo enačbo za sproščanje toplote v končni obliki:

we obtain the final expression of Janikiev's ROHR:

$$\frac{dx}{d\varphi} = \frac{(m+1)\, L\, Q_\alpha \alpha_0 \dfrac{\alpha_0 - m_{Fl}}{m_{Fl}\, \varphi_z} \bar{\varphi}^m \exp\left(L\, Q_\alpha\, \bar{\varphi}^{m+1}\right)}{\left[\dfrac{\alpha_0}{m_{Fl}} \exp\left(L\, Q_\alpha\, \bar{\varphi}^{m+1}\right) - 1\right]^2} \quad (1.29),$$

pri čemer je:

where:

$$L = \ln \frac{\alpha_0 - x_z}{\alpha_0 (1 - x_z)} \;;\quad Q_\alpha = \frac{\alpha_0 - m_{Fl}}{\alpha_0 - 1} \quad (1.30).$$

Integralna oblika Janikijeve enačbe je:

The integral form of Janikiev's equation is:

$$x = \frac{\alpha_0 \exp\left(L\, Q_\alpha\, \bar{\varphi}^{m+1}\right) - \alpha_0}{\dfrac{\alpha_0}{m_{Fl}} \exp\left(L\, Q_\alpha\, \bar{\varphi}^{m+1}\right) - 1} \quad (1.31).$$

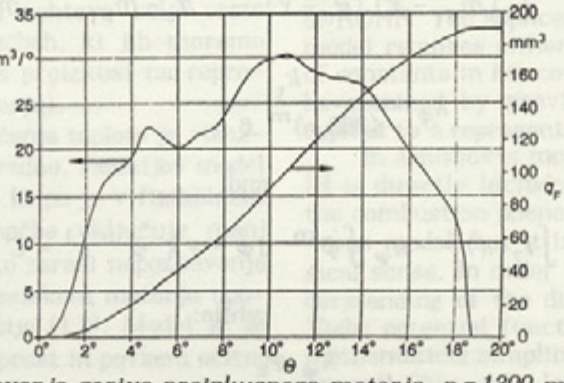
Nadaljnja izpeljava izrazov je neposredno podana. Obe funkciji $f_1(x)$ in $f_2(x)$ integriramo ločeno, integracijski konstanti pa določimo z uporabo robnih pogojev (1.28). Izraz (1.29) podaja hitrost sproščanja toplote, enačba (1.31) pa relativno količino zgorelega goriva (komulativno obliko značilnice sproščanja toplote). Hitrost sproščanja toplote v valju motorja nato določamo z izrazom:

The further derivation is quite straightforward. Both functions in equation (1.26) and (1.27) are separately integrated and constants C and k are obtained applying boundary conditions (1.28). The relative ammount of fuel burnt is given by the expression (1.31) and the fuel burning rate by equation (1.29). The rate of heat release is computed by:

$$\frac{dQ_s}{d\Theta} = m_{FC}\, H_f \frac{dx}{d\varphi} \quad (1.32).$$

V izraza (1.29) in (1.31) vključuje izvirni Janikijev model v potek sproščanja toplote tudi vpliv vbrizgane količine goriva m_F. Zato moramo vbrizganje goriva poznati ali v obliki krivulje (sl. 3), v diskretni obliki ali pa v obliki približne funkcije.

As can be seen from expression (1.29) the original Janikiev's ROHR model includes also the effect of fuelling. The cumulative (integral) characteristics of IR must therefore be given as input, either as a curve (Fig. 3), in a discretized form, or as a mathematical correlation.



Sl. 3. *Značilnica vbrizgavanja goriva preizkusnega motorja, n = 1300 min, q_{FC} = 190 mm³/cikel, trajanje vbrizga = 18,6°.*

(Velja za vse računske primere v nadaljevanju besedila)

Fig. 3. *IR of test engine: under near max. torque conditions, 1300 RPM, q_{FC} = 190 mm³/cycle, injection duration = 18.6° in all examples presented).*

(Used in all examples presented)

1.4 Izboljšava Janikijevega modela
Prvi predlog (J-1)

Pri notranji pripravi heterogene zmesi, katere tipični predstavnik je dieselski motor z direktnim vbrizgavanjem goriva, je sproščanje toplote rezultat procesov, ki jih krmili mešanje zraka in goriva. Največje število primerov modelov zgorevanja vsebuje izračun procesa oblikovanja mešanice gorivo — zrak, od koder dobijo sproščanje toplote in druge parametre dieselskega motorja. Kakovost zmesi pa je odvisna od razpoložljive količine zraka in goriva, razporeditve in razpršitve curka, prodorne cone zraka in njegove intenzivnosti gibanja. Proces razpršitve goriva je odvisen od strukture curka (dolžina prodiranja — domet, premer kapljic, kot pri vrhu curka idr.), na katero vpliva trenutna hitrost curka, ki je odvisna od poteka vbrizgavanja in od splošnega stanja v valju motorja. Prodiranje zraka v curek goriva in proces mešanja sta posledica velike gibalne količine curka in gibanja zraka v valju motorja, še posebej kadar je načrtovano uvedeno (zračni vrtinček, prečno gibanje zraka). Na podlagi povedanega lahko predpostavimo, da sledi fazi zgorevanja poprej pomešanih reaktantov naslednja faza zgorevanja, ki jo krmili hitrost mešanja goriva in zraka, pri čemer ima vodilno vlogo hitrost vbrizgavanja goriva. Zato smo pri dopolnitvi Janikijevega modela izraz za sproščanje toplote (1.29) razširili z vključitvijo hitrosti vbrizgavanja v vsakem intervalu $\Delta\varphi$ $(dm_{F1}/d\varphi)_{\Delta\varphi}$ = $\dot{m}_{F1}$ kot novo spremenljivko [6]. Vrednost gradienta $\dot{m}_{F1}$ izračunamo ali razberemo iz znane značilnice vbrizgavanja goriva. Pri odvajanju (1.31) po kotu φ dobimo nov izraz za sproščanje toplote:

1.4 Further development of Janikiev's model
Proposal No. 1 (J-1)

In heterogeneous charge engines, of which the direct-injection diesel engine is a prime example, ROHR is a fuel-air mixing controlled process. Most aproaches are based on a mixture formation model, enabling the computation of ROHR and other engine parameters. The quality of the mixture preparation can be limited either by the availability of fuel or air, location and atomization of spray, air entraiment zone and its motion intensity. The fuel disintegration proces depends on the spray structure (penetration length, droplet diameter, zone angle) affected also by instant fuel-jet velocity, depending on both injection time history and the overall state of ambient gas.

Furthermore, the air entraiment and fuel-air mixing process can be predominantly controlled by either high momentum of fuel jets or some form of deliberately induced air motion (swirl and squish). Following this path of thought, we have assumed that after the premixed burning period, diesel combustion during the next phase is essentially a fuel-air mixing-controlled process, with a predominant role of IR history. The proposal for further improvement of the Janikiev's model, therefore includes the injection rate during each interval $\Delta\varphi$, i.e. $(dm_{F1}/d\varphi)$ = $\dot{m}_{F1}$ as a new variable affecting the ROHR in the ROHR expression (1.29) [6]. The gradient $\dot{m}_{F1}$ has been computed or obtained from known IR characteristic. After differentiating (1.31), a new expression for ROHR has been obtained:

Izboljšava modela J-1

$$\frac{dx}{d\varphi}(\varphi, m_{F1}) = \left(L\,\alpha_0\,\bar{\varphi}^{\,m}\exp\left(L\,Q_\alpha\,\bar{\varphi}^{\,m+1}\right)\right)\left\{\left(\frac{(m+1)\,Q_\alpha}{\varphi_z} - \frac{\bar{\varphi}\;\dot{m}_{F1}}{\alpha_0 - 1}\right)\times\right.$$

$$\times\left[\frac{\alpha_0}{m_{F1}}\exp\left(L\,Q_\alpha\,\bar{\varphi}^{\,m+1}\right) - 1\right] - \frac{\alpha_0}{m_{F1}}\left[\exp\left(L\,Q_\alpha\,\bar{\varphi}^{\,m+1}\right) - 1\right]\times$$

$$\left.\times\left[\frac{(m+1)\,Q_\alpha}{\varphi_z} - \frac{\bar{\varphi}\;\dot{m}_{F1}}{\alpha_0 - 1} - \frac{\dot{m}_{F1}}{\bar{\varphi}^{\,m}\,m_{F1}\,L}\right]\right\}\left[\frac{\alpha_0}{m_{F1}}\exp\left(L\;Q_\alpha\;\bar{\varphi}^{\,m+1}\right) - 1\right]^{-2} \quad (1.33).$$

V izvirnem Janikijevem modelu je bil relativni razmernik zraka α_0 izračunan po znani definiciji:

$$\alpha_0 = \frac{m_a}{m_{FC}\;l_0} = \text{const} \quad (1.34)$$

in je bil med izračunom sproščanja toplote konstanten.

Drugi predlog (J-2)

Naslednja dopolnitev Jankijevega modela upošteva dejstvo, da se razmernik zraka med vbrizgavanjem zaradi spremembe m_{F1} od 0 do 1, spreminja od neskončno do α_0:

$$\alpha_0 = \alpha_0(\varphi) = \frac{m_a}{m_{FC}\,m_{F1}(\varphi)\,l_0} \quad (1.35).$$

Končni izraz sproščanja toplote (1.36) ponovno dobimo z odvajanjem enačbe (1.31) po kotu. Vrednost $\alpha_0(\varphi)$ v kotnem intervalu $\Delta\varphi$ določimo po enačbi (1.35), spremembo razmernika zraka in goriva $\dot{\alpha}_0$ pa po izrazu (1.41).

Izboljšava modela J-2

$$\frac{dx}{d\varphi} = \left(\dot{\alpha}_0(1 - E) + \alpha_0\,\dot{E}\,\frac{\alpha_0 - m_{F1}}{m_{F1}} + \frac{\alpha_0^2\,\dot{m}_{F1}\,E}{m_{F1}^2}(E - 1)\right)\left[\frac{\alpha_0}{m_{F1}}\,E - 1\right]^{-2} \quad (1.36),$$

kjer je:

$$E = \exp\left(L\,Q_\alpha\;\bar{\varphi}^{\,m+1}\right) \quad (1.37),$$

$$\dot{E} = E\left(L\,Q_\alpha\,(m+1)\frac{\bar{\varphi}^{\,m}}{\varphi_z} + \dot{L}\;Q_\alpha\;\bar{\varphi}^{\,m+1} + L\;\dot{Q}_\alpha\;\bar{\varphi}^{\,m+1}\right) \quad (1.38),$$

$$L = \ln\frac{\alpha_0 - x_z}{\alpha_0(1 - x_z)}\;; \qquad \dot{L} = \frac{\dot{\alpha}_0\;x_z}{\alpha_0(\alpha_0 - x_z)}\;; \quad (1.39),$$

JM Improvement J-1

In the original Janikiev's model the air equivalence ratio (α_0) is computed from the definition:

and is kept constant throughout the ROHR computation.

Proposal No. 2 (J-2)

The further development of the Janikiev's model has respected the fact that the equivalence air ratio is changing during fuel injection from infinity to α_0, when according to the m_{F1} definition in (1.22), m_{F1} increases from 0 to 1:

The final expression for ROHR (1.36) is summarized below and it begins with a differentiation of the expression (1.31). The value of $\alpha_0(\varphi)$ at each interval $\Delta\varphi$ is determined by equation (1.35) and the rate of change of the equivalence air/fuel ratio $\dot{\alpha}_0$ is obtained from equation (1.41).

JM Improvement J-3

where:

$$Q_\alpha = \frac{\alpha_0 - m_{Fl}}{\alpha_0 - 1}\ ; \quad \dot{Q}_\alpha = \frac{\dot{\alpha}_0\,(m_{Fl} - 1) + \dot{m}_{Fl}\,(1 - \alpha_0)}{(\alpha_0 - 1)^2} \tag{1.40}$$

$$\frac{d\alpha_0}{d\varphi} = -\frac{m_a\ \dot{m}_{Fl}}{m_{Fl}\ l_0\ m_{Fl}^2} = \dot{\alpha}_0 \tag{1.41}$$

Tretji predlog (J-3)

V zadnji dopolnitvi smo med difuzijskim zgorevanjem poskusili s preprostim matematičnim razmerjem opisati hitrost združevanja kisika iz zraka in goriva v ustreznem razmerju. Zato smo kot parameter izbrali hitrost spremembe razmernika zraka med zgorevanjem, tj. hitrost porabe kisika in goriva, da bi z njim simulirali verjetno hitrost difuzije obeh reaktantov v cono plamena in tako oblikovali zadnji, difuzijski del krivulje sproščanja toplote.

Proposal No. 3 (J-3):

We have attempted to describe with a simple mathematical expression, the rate at which oxygen from the surrounding air and fuel are brought together in a proper proportion during diffusion burning. The rate of change of the air equivalence ratio during the combustion process, i.e. the rate of consumption of fuel and oxygen, was chosen to simulate the probability of diffusion of both reactants in the flame zone and to control the shape of the last part of the ROHR curve.

Izboljšava modela J-3

JM Improvement J-3

$$M_a + M_r + \left[x(\varphi)\,\Delta M_s\right] = K_1 M_{P,s} + K_1\left[\alpha(\varphi) - 1\right]\cdot L_0 \tag{1.42}$$

kjer pomenita: M_a – količino sveže polnitve, M_r – količino zaostalih plinov (prejšnjega ciklusa):

where M_a – amount of fresh charge, M_r – amount of residual gases:

$$K_1 = \frac{x(\varphi)(L_0 + \Delta M_s) + M_{r,s}}{M_{P,s}} \tag{1.43}$$

in so:

ΔM_s – razlika med stehiometrijskima količinama produktov in reaktantov:

while:

ΔM_s – is the difference between stoichiometric mole quantities of products and reactants:

$$\Delta M_s = M_{P,s} - L_0 = L_0(\mu_0 - 1) \tag{1.44}$$

$M_{P,s}$ – stehiometrijska količina produktov zgorevanja

$M_{r,s}$ – stehiometrijska količina zaostalih produktov zgorevanja:

$M_{P,s}$ – stoichiometric mole quantity of products

$M_{r,s}$ – stoichiometric mole quantity of residual products

$$M_{P,s} = \mu_0\ L_0$$

$$M_{r,s} = \gamma\ \mu_0\ L_0 \tag{1.44 a}$$

$$K_1 = \frac{x(\varphi)\left[\alpha_0(\varphi) + \mu_0 + 1\right] + \gamma\,\alpha_0(\varphi)}{x(\varphi)\left[\alpha_0(\varphi) + \mu_0 - 1\right] + \alpha_0(\varphi)\,\gamma} \tag{1.45}$$

$$\alpha(\varphi) = \frac{\left[\alpha_0(\varphi)\right]^2(1 + \gamma) + \alpha_0(\varphi)(\mu_0 - 1)}{\alpha_0(\varphi)\,\gamma + x(\varphi)\left[\alpha_0(\varphi) + \mu_0 - 1\right]} \tag{1.46}$$

Desna stran enačbe (1.42) podaja hitrost, s katero se spreminja sestava produktov zgorevanja. Prvi člen je molski delež stehiometrijskih produktov zgorevanja, drugi člen pa je molski delež presežka zraka. Koeficient K_1 je določen z izrazom (1.43).

Z uvrstitvijo izrazov (1.44) in (1.44a) v (1.43) po preureditvi in okrajšavi dobimo izraz (1.45), v katerega uvrščamo $\alpha_0 = \alpha_0(\varphi)$, izračunan po enačbi (1.35).

Ko uvrstimo enačbo (1.45) v (1.42), izpeljemo okrajšave ter iz nje določimo $\alpha = \alpha(\varphi)$, dobimo enačbo (1.46) za spremembo relativnega razmernika zraka med zgorevanjem, ki jo uporabljamo v enačbah (1.36) do (1.41).

Da bi ovrednotili predstavljene spremembe sproščanja toplote Janikijevega modela, smo za naš testni motor zanje določili optimalne vrednosti faktorja oblike m in trajanja zgorevanja φ_z. V ta namen smo uporabili faktorski načrt 3^2 variacije neodvisnih spremenljivk m in φ_z in z računalniškim programom za model PT določili odzive, v našem primeru stopnjo ujemanja izmerjenega in izračunanega indikatorskega diagrama. Umeritev parametrov m in φ_z smo nato izvedli po metodi Webra in Bormana, opisani so v [22].

2. OCENA MODELOV

Opisane modele značilnice sproščanja toplote in model PT smo ocenili na podlagi primerjave izračunanih in izmerjenih tlakov v valju motorja. Posnete indikatorske diagrame smo uporabili tudi za izračun dejanske značilnice sproščanja toplote. V ta namen smo indikatorske diagrame poprej zgladili po metodi kubičnih zlepkov. Delež toplote ($dQ_c/d\Theta$), ki prehaja na stene valja, smo določili z Woschnijevim korelacijskim izrazom [23]. Korak numerične integracije po metodi Runge-Kutta 4 je bil 1^0.

Testni motor je bil 4-taktni, tlačno polnjeni (s hladilnikom polnilnega zraka), zračno hlajeni dieselski motor vozila (D = 125 mm, s = 145 mm, vrtinčno število 1,9, globoka zgorevalna komora v batu, vbrizgalna šoba s štirimi izvrtinami $4 \times \phi 0{,}375$ mm, tlačilka BOSCH S3000, ϕ 12 × 11 mm). Relativni razmernik zraka so določali z merjenjem pretoka goriva in zraka. Indikatorske diagrame so posneli z digitalnim osciloskopom in jih nato z vmesnikom prenašali na osebni računalnik. Kot zakasnitve vžiga so določali na podlagi posnetega indikatorskega diagrama [35]. Potek vbrizgavanja goriva smo izračunali s preprostim računalniškim programom na podlagi izmerjenih vrednosti tlaka pred vbrizgalno šobo in dviga igle vbrizgalne šobe [24], [25], prav tako pa smo z Boschevim indikatorjem lastne izdelave vbrizgavanja goriva tudi neposredno posneli značilnice vbrizganega goriva.

The right side of the equation (1.42) gives the rate of change of combustion product composition. The first term is related to a stoichiometric mole fraction, and the second one to the available air fraction. The coefficient K_1 is defined by equation (1.43).

After substitution of expressions of individual terms (1.44) and (1.44a) into equation (1.43) and after some algebraic operations, one gets the expression for the coefficient K_1 where $\alpha_0 = \alpha_0(\varphi)$ is calculated using equation (1.35).

Substituting (1.45) into (1.42), the expression (1.46) for the rate of change of the equivalence ratio at any instant throughout the combustion is obtained, and it is used now with equations (1.36) through (1.41).

Having established the three proposals for improvement of the initial Janikiev's rate of heat release model, it was necessary to determine the optimum values of shape parameter m and apparent combustion duration φ_z for our experimental engine. A 3^2 factorial plan has been used for a combination of setting variable and our PTM has been required to perform the parameter calibration to obtain the best match of predicted cylinder pressure diagrams with those obtained from measurements. The method of parameter calibration was similar to that used by Weber and Borman [22].

2. VALIDATION OF MODELS

The validation of presented ROHR and PT models was actually carried out by comparison of computed cylinder pressures with those obtained from experiments. Experimental cylinder pressure-time histories have been used to compute the ROHR as well. The pressure curves were previously smoothed by applying the cubic-spline analytical technique. The heat transfer term in equation (1.1.) was computed by using the Woschni's [23] correlation. Angle increment was 1^0 using the Runge-Kutta 4 numerical method.

The test engine was a four stroke DI-TC, air cooled vehicular diesel (D = 125 mm, s = 145 mm, SR = 1.9, with deep piston bowl and a nozzle with four holes $4 \times \phi 0.375$ mm, injection pump BOSCH S300, ϕ 12 × 11 mm, IR in Fig. 3). The air and fuel mass flow were measured and equivalence air ratio was calculated. A digital oscilloscope was used to capture cylinder pressure diagrams and the crank angle marker. The pressure v.s crank angle diagram could then be transferred to a professional microcomputer through an interface. The ID-angle was also obtained from experimental cylinder pressure — CA curves, applying the well known conventional technique [35]. The IR curve was computed using our computer program, needle lift traces and fuel pressure diagrams [24], [25]. Additionally, the IR diagram was also directly obtained by a home made Bosch tube in test bench experiments.

Eksperimentalne podatke in diagrame so izmerili pri različnih režimih delovanja motorja v področju polnih in delnih obremenitev in jih pozneje računalniško obdelali in analizirali. Za obravnavo smo izbrali samo nekaj značilnih primerov. Lastni računalniški program PTM (sl. 9) smo najprej uporabili za izračun značilnice sproščanja toplote na podlagi posnetega indikatorskega diagrama, nato pa smo s programom PTM z uporabo izbranega modela značilnice sproščanja toplote določili še računski indikatorski diagram. Slika 3 prikazuje potek diferencialne in integralne značilnice vbrizgavanja, ki sta bila izmerjena pri 1300 min^{-1} in polni obremenitvi. V nadaljevanju bomo obširneje prikazali rezultate samo pri tem režimu, medtem ko se ocena modelov, obravnava in sklepi nanašajo na več izmerjenih obratovalnih režimov.

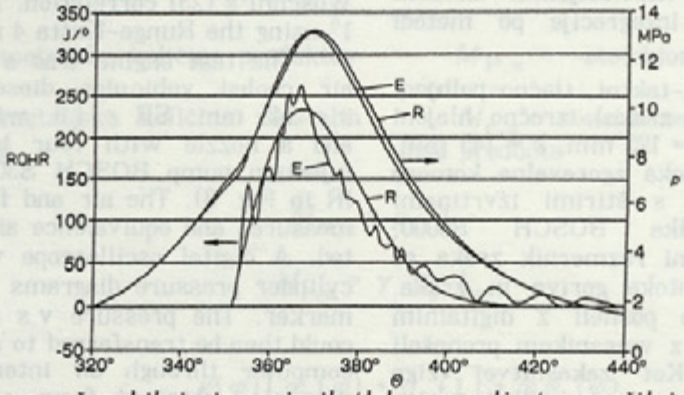
Preračun visokotlačnega dela indikatorskega diagrama smo začeli v trenutku zapiranja polnilnega ventila. Začetno stanje v valju smo predpisali z izmerjenim tlakom v trenutku zapiranja ventila in z maso sveže polnitve, povečano za maso zaostalih izpušnih plinov. Maso in značilnico vbrizgavanja goriva, kot zakasnitve vžiga in potrebne parametre uporabljenega modela značilnice sproščanja toplote pa smo predpisali kot robne pogoje. V trenutku odpiranja izpušnega ventila smo preračun ustavili. Program PTM je napovedal stanje v valju motorja (tlak, temperaturo in maso delovne snovi) in parametre, ki smo jih uporabili za ovrednotenje modela značilnice sproščanja toplote. Napovedani diagram tlaka smo primerjali z izmerjenimi vrednostmi in izračunali vsoto kvadratov relativnih razlik. To smo nato uporabili kot enega od kvantitativnih računskih pokazateljev ujemanja napovedanih in izmerjenih vrednosti, (ob njej pa navajamo še druge parametre primerjave).

Slika 4 prikazuje rezultate uporabe navadne Vibejeve funkcije. Zelo dobro ujemanje računskih in eksperimentalnih rezultatov smo dosegli z optimiranjem vrednosti obeh parametrov m in φ_z, ki definirata obliko sproščanja toplote.

Experimental data were collected for several full and partial load regimes, and a large number of pressure traces and effective engine data were generated and subsequently analyzed. Only a small selection of typical diagrams, important for the following discussion and conclusion is presented here. Our own PTM computer program (Fig. 9) was used, either to predict ROHR if cylinder pressure time history was given, or to predict pressure curves, when ROHR was given. Fig. 3 shows the experimental differential and cumulative IR curve, at full load and 1300 r.p.m. This operating regime has been chosen for comparison of experimental and computed data here, although the ROHR model validation, discussion and conclusion are drawn on the full results data base.

Computation of selected parts of the engine thermodynamic cycle was always started at the same crank angle (I.V.C.) based on a set of measured input data (pressure, mass of fresh charge, mass of fuel injected, IR, ID-angle, etc.) including the analytical ROHR expression related to the model under consideration, and it ended at E.V.O. The PTM predicted in-cylinder pressure, temperature and other data used in model validation. The predicted pressure diagram was compared with the measured data within the angle interval I.V.C. – E.V.O. and standard deviation was used as a quantitative criterion of agreement between measured and predicted values. A few other quantities defining the shape of pressure curve are also presented.

The ROHR curve generated by the original Viebe function and predicted and measured pressure diagrams are shown on Fig. 4. It must be pointed out that a good match was achieved by optimizing both parameters determining the ROHR shape.

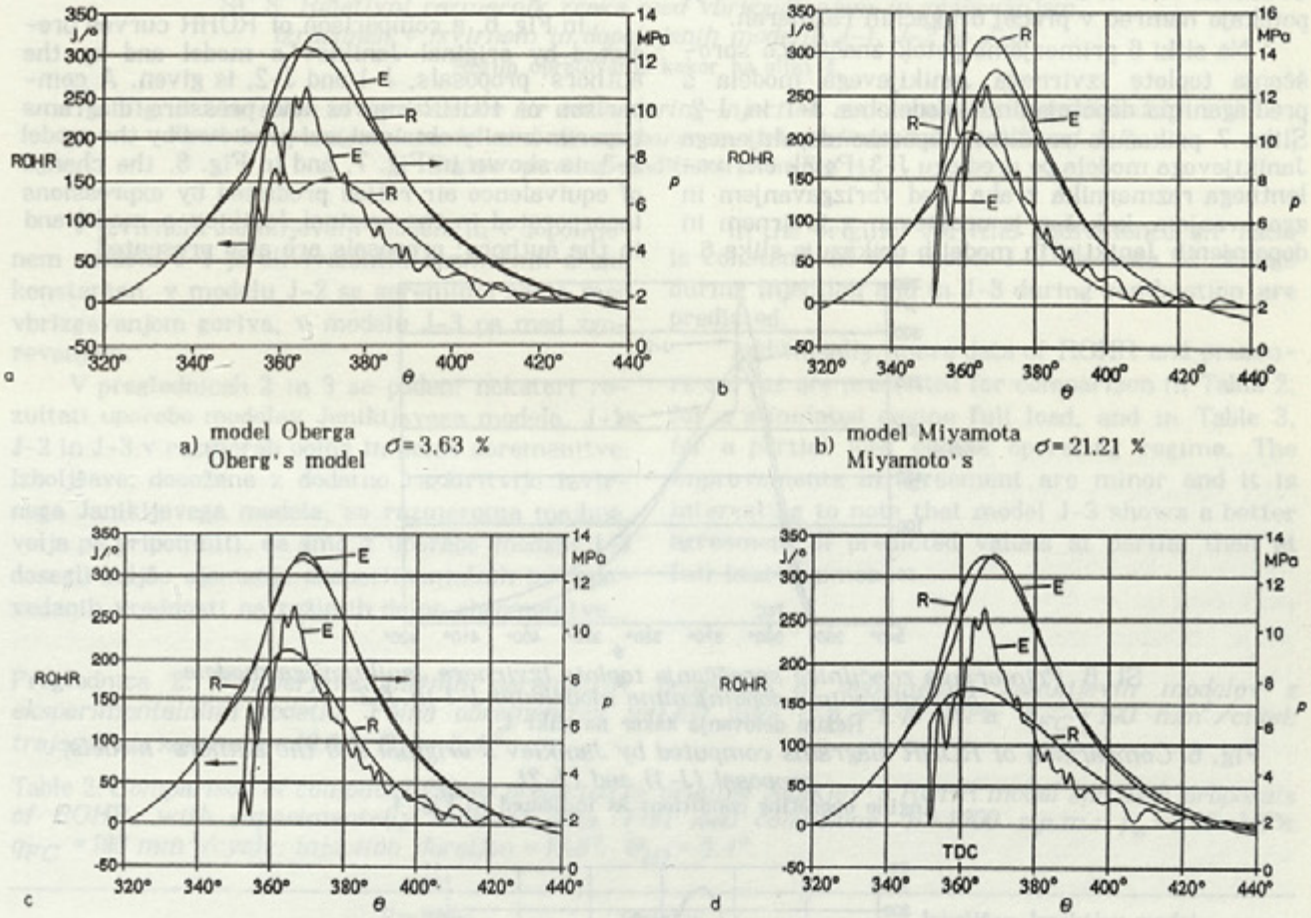


Sl. 4. *Primerjava računskih in izmerjenih tlakov v valju ter značilnica sproščanja toplote.*
VF: $m = 0.91$; $\varphi_z = 62.6$; $\sigma = 2.836$ %. Režim obratovanja $n = 1300$ min^{-1}; $p_e = 1.46$ MPa; $\Theta_{ID} = 5.4°$; $q_{FC} = 190$ mm^3/cikel; trajanje vbrizgavanja = 18.6°; $g_e = 197$ g/kWh
E – izmerjene vrednosti; R – izračunane vrednosti

Fig. 4. *Comparison of computed and measured cylinder pressure and heat release diagrams.*
VF $m = 0.91$; $\varphi_z = 62.6$; $\sigma = 2.836$ %. Operating regime: $n = 1300$ r.p.m.; $p_e = 1.46$ MPa; $\Theta_{ID} = 5.4°$; $q_{FC} = 190$ mm^3/cycle; injection duration = 18.6°; $g_e = 197$ g/kWh
E – experimental values; R – calculated values

Na sliki 5 so prikazani rezultati izračuna značilnice sproščanja toplote z nekaterimi drugimi modeli. Prvi trije so različne kombinacije dveh Vibejevih funkcij. Med seboj se razlikujejo le po načinih določanja vrednosti parametrov značilnice sproščanja toplote. Najboljše rezultate smo dosegli z uporabo Ghojelovega modela, ki podobno kakor Miyamoto predpostavlja, da traja faza zgorevanja poprej pomešanih reaktantov 7^0. Ob parametrih značilnice sproščanja toplote je za dobro ujemanje pomembna tudi natančna ocena kota zakasnitve vžiga.

In Fig. 5, the results of computation and comparison with measured data for four different ROHR models are shown. Three models are based on a combination of two Viebe functions. The best agreement of predicted and measured data was achieved with Ghojel's model. Both Ghojel and Miyamoto have estimated a premixed burning duration of $\Theta_p = 7^0$. The computation or estimation of an accurate value of ignition delay angle also plays a very important role in the prediction of the ROHR and pressure diagram.



a) model Oberga / Oberg's model $\sigma = 3.63$ %

b) model Miyamota / Miyamoto's $\sigma = 21.21$ %

c) model Ghojela / Ghojel's model $\sigma = 2.07$ %

d) model Škotova / Shokotov's model $\sigma = 6.37$ %

Sl. 5. *Primerjava računskih in eksperimentalnih diagramov.*
Režim obratovanja kakor na sliki 4.
E – izmerjene vrednosti; R – izračunane vrednosti

Fig. 5. *Comparison of computed and experimental diagrams.*
Engine operating regime, as given in Fig. 4.
E – experimental values; R – calculated values

V modelu Šokotova je treba predpostaviti ali eksperimentalno določiti podatke o strukturi curka in iniciranem zračnem vrtinčku v valju motorja. Pomanjkljivo definiranje teh detajlov je po vsej verjetnosti povzročilo slabše ujemanje rezultatov.

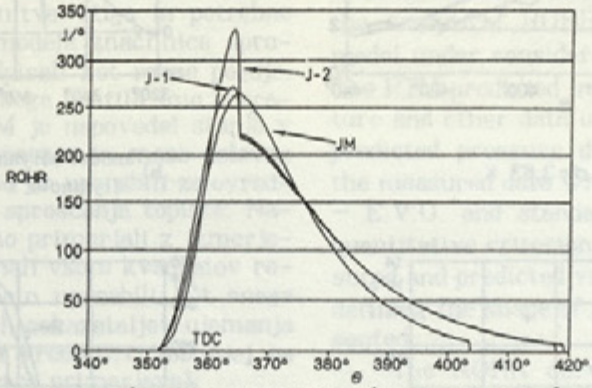
Shokotov's model requires the assumption or experimental determination of a set of data related to the spray structure and air swirl of the investigated engine. The lack of these details was probably the cause of rather poor agreement.

Izkazalo se je, da je za tlačno polnjene motorje Miyamotova ocena količine toplote (Q_p = 0,5 Q_1 za motorje z neposrednim vbrizgavanjem), ki se sprosti med zgorevanjem poprej pomešanega zraka in goriva vbrizganega med zakasnitvijo vžiga, prevelika in povzroči previsok vrh značilnice sproščanja toplote, s tem pa zelo velik gradient naraščanja tlaka v tej fazi zgorevanja. Miyamoto je namreč svoje raziskave omejil le na sesalne motorje, modeli značilnice sproščanja toplote motorjev, projektiranih za velike obremenitve (npr. s tlačnim polnjenjem) pa se lahko pomembno razlikujejo, kakor sta to v svojih raziskavah pokazala Craddock [17] in Costien [26]. Procesi zgorevanja potekajo namreč v precej drugačnih razmerah.

Na sliki 6 primerjamo potek značilnice sproščanja toplote izvirnega Janikijevega modela s predlaganima dopolnjenima modeloma J-1 in J-2. Slika 7 prikazuje rezultate uporabe dopolnjenega Janikijevega modela po predlogu J-3. Potek ekvivalentnega razmernika zraka med vbrizgavanjem in zgorevanjem, kakršen je upoštevan v izvirnem in dopolnjenih Janikijevih modelih prikazuje slika 8.

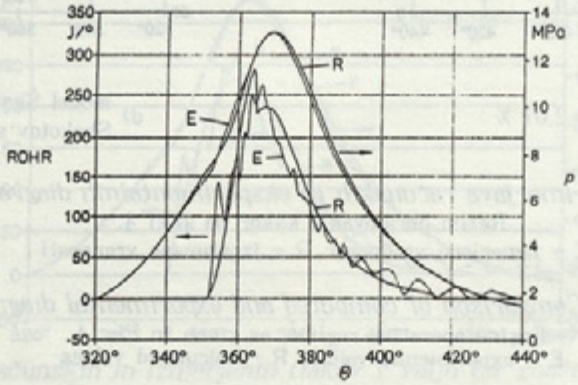
A short test has shown that the amount of heat released during premixed burning estimated by Miyamoto (Q_p = = 0.5 Q_1 for DI engines) is probably too high for this TC-engine, causing a very high peak in the ROHR curve and high pressure gradient of this stage of combustion. The correlations deduced by Miyamoto for premixed and diffusion curves of ROHR were obtained by performing tests with a natural aspirated (NA) diesel engine. However the heat release model of high power output (TC) diesel engines differ substantially, as has been pointed out by Craddock [17] and Costien [26], because the combustion processes take place under fairly different conditions.

In Fig. 6, a comparison of ROHR curves predicted by original Janikiev's model and by the authors' proposals, J-1 and J-2, is given. A comparison of ROHR curves and pressure diagrams experimentally obtained and predicted by the model J-3, is shown in Fig. 7, and in Fig. 8, the change of equivalence air ratios predicted by expressions incorporated in the original Janikiev's model and in the authors' proposals are also presented.



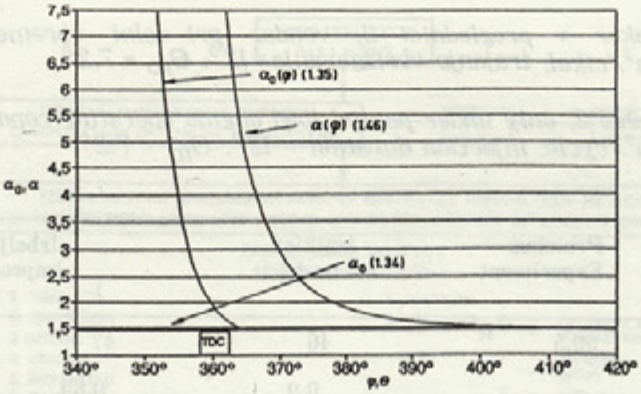
Sl. 6. *Primerjava značilnice sproščanja toplote izvirnega Janikijevega modela s predlaganima dopolnjenima modeloma J-1 in J-2.*
Režim delovanja kakor na sliki 4.

Fig. 6. *Comparison of ROHR diagrams computed by Janikiev's original and the authors' models, proposal (J-1) and (J-2).*
Engine operating conditions as indicated in Fig. 4.



Sl. 7. *Primerjava izračunanih in izmerjenih sproščanj toplote ter diagramov tlaka; model J-3 m = 0,75; φ_z = 63,4° σ = 2,353 %.*
Režim delovanja kakor na sliki 4.

Fig. 7. *Comparison of computed and measured ROHR curves and cylinder pressure diagrams, model (J-3) m = 0.75; φ_z = 63.4° σ = 2.353 %.*
Engine operating conditions as in Fig. 4.



Sl. 8. *Relativni razmernik zraka med vbrizgavanjem in zgorevanjem, izračunan v izvirnem in dopolnjenih modelih J-1, J-2 in J-3.*
Režim obratovanja kakor na sliki 4.

Fig. 8. *Variation of equivalence air ratio during injection and combustion predicted by Janikiev's original model and the authors' models indicated J-1, J-2 and J-3.*
Engine operating conditions as in Fig. 4.

V izvirnem Janikijevem modelu in v dopolnjenem modelu J-1 je ekvivalentni razmernik zraka konstanten, v modelu J-2 se spreminja samo med vbrizgavanjem goriva, v modelu J-3 pa med zgorevanjem.

V preglednicah 2 in 3 so podani nekateri rezultati uporabe modelov Janikijevega modela, J-1, J-2 in J-3 v razmerah polne in delne obremenitve. Izboljšave, dosežene z dodatno razširitvijo izvirnega Janikijevega modela, so razmeroma majhne, velja pa pripomniti, da smo z uporabo modela J-3 dosegli boljše ujemanje eksperimentalnih in napovedanih vrednosti na režimih delne obremenitve.

In the original JM, the equivalence air ratio is constant, in the model J-2 its rate of change during injection and in J-3 during combustion are predicted.

Additionally, more data of ROHR and pressure curves are presented for comparison in Table 2, for a simulated engine full load, and in Table 3, for a partial load engine operating regime. The improvements in agreement are minor and it is interesting to note that model J-3 shows a better agreement of predicted values at partial than at full load regimes.

Preglednica 2: *Primerjava glavnih parametrov izvirnega in dopolnjenih Janikijevih modelov z eksperimentalnimi podatki. Polna obremenitev $n=1300\ min^{-1}$: $p_o=1.46$ MPa: $q_{FC}=190\ mm^3$/cikel: trajanje vbrizgavanja = 18,6 ^{0}: $\Theta_{ID}=5.4\ ^0$.*

Table 2: *Comparison of computed values predicted by original Janikiev's ROHR model and new proposals of ROHR, with experimentally obtained data. Full load conditions, $n=1300$ r.p.m.: $p_o=1.46$ MPa: $q_{FC}=190\ mm^3$/cycle: injection duration = 18.6^0: $\Theta_{ID}=5.4^0$.*

		Preizkus Experiment		Janikiev model	Izboljšan Janikijev model Improved Janikiev's model J-1	J-2	J-3
φ_z	[°]	68.4	R	52.0	67.5	66.0	63.4
m	[-]	–		1.2	1.0	1.04	0.75
$p_{z,max}$	[MPa]	13.157	E	13.138	13.169	13.149	13.151
$\Theta(p_{z,max})$	[°]	9.0	E	9.4	8.4	8.6	8.6
$\left[\frac{dp}{d\Theta}\right]_{max}$	$\left[\frac{MPa}{°}\right]$	0.5527	R	0.5109	0.5737	0.6464	0.5653
W	[J]	2793.5	R	2671.9	2788.8	2796.0	2631.1
σ	[%]	–		3.69	1.77	2.28	2.35

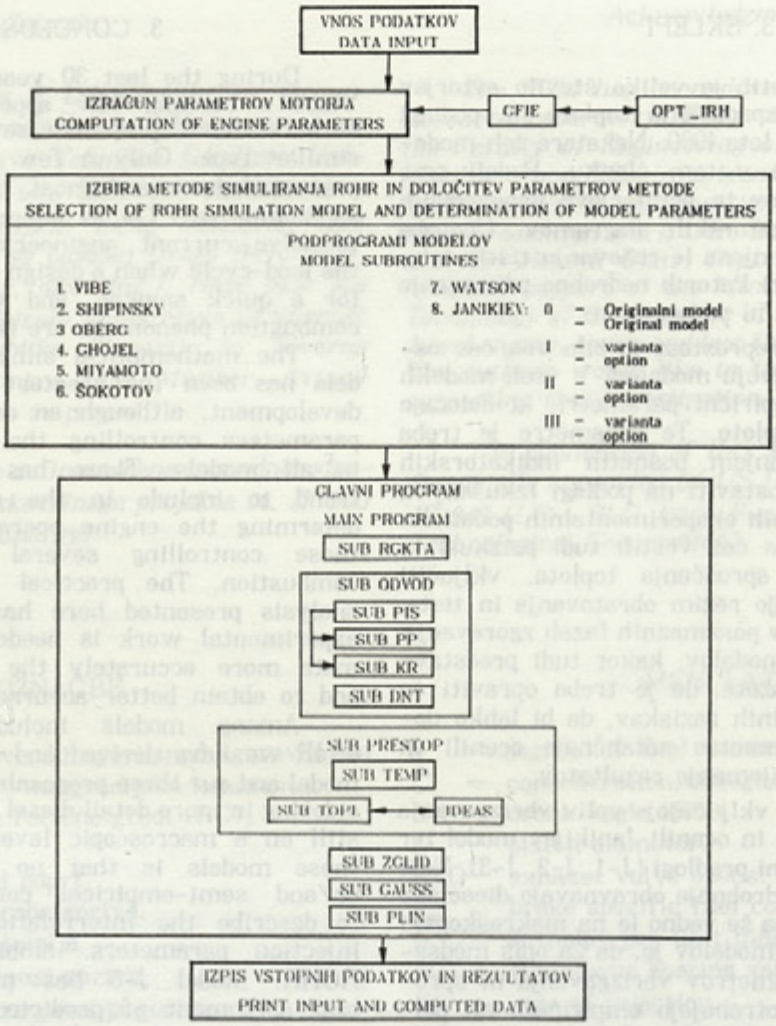
Preglednica 3: *Enako kakor v preglednici 2, vendar pri delni obremenitvi: $n = 1300\ min^{-1}$: $p_e = 0.72$ MPa: $q_{FC} = 96\ mm^3$/cikel: trajanje vbrizgavanja = 12^0: $\Theta_{ID} = 7.2^0$.*

Table 3: *The same as in Table 2, only under partial load engine operating conditions: $n = 1300$ r.p.m.: $p_e = 0.72$ MPa: $q_{FC} = 96\ mm^3$/cycle: injection duration = 12^0: $\Theta_{ID} = 7.2^0$.*

		Preizkus Experiment		Janikiev model	Izboljšan Janikijev model Improved Janikiev's model J-1	J-2	J-3
φ_z	[°]	50.5	R	46	47	48	43.4
m	[-]	-		0.9	0.89	0.88	0.77
$p_{z,max}$	[MPa]	8.3872	E	8.3815	8.3936	8.3271	8.3925
$\Theta(p_{z,max})$	[°]	8.7	E	8.8	8.8	8.8	9.0
$\left[\frac{dp}{d\Theta}\right]_{max}$	$\left[\frac{MPa}{°}\right]$	0.8238	R	0.3299	0.3537	0.3694	0.3474
W	[J]	1533.4	R	1598.8	1607.7	1605.0	1523.5
σ	[%]	-		3.878	4.068	4.137	2.959

Na sliki 9 je shematsko podana kompozicija našega računalniškega programa modelov PT in NPT. Procesi v valju so modelirani analogno, kakor je opisano v [1]. Metoda polnjenje — praznjenje je uporabljena za simuliranje procesov v polnilnem in izpušnem sistemu. Program omogoča dvoje: izračun značilnice sproščanja toplote na podlagi visokotlačnega indikatorskega diagrama ali izračun indikatorskega diagrama (nizko- in visokotlačnega) za izbrani model značilnice sproščanja toplote. Modele značilnice sproščanja toplote, vključene v program, smo v članku predstavili in ovrednotili. Za primere dimenzioniranja polnilnih in izpušnih sistemov ter za testiranje povezave motorja s turbokompresorjem smo razvili poseben podprogram, ki temelji na enodimenzionalnem, nestacionarnem, neizentropnem toku stisljivega fluida v razvejanih cevnih sistemih [27] s pripadajočimi robnimi pogoji, med katerimi moramo še posebej omeniti lasten analitični model dvonatočne turbine [28]. Za izračun vstopnih vrednosti vbrizgavanja goriva za dani sistem je na voljo podprogram CFIE (po modelu [25]) in podprogram OPT_IRH za optimiranje vbrizgavanja goriva [31]. Za določanje toplotne obremenitve, tj. razporeditev izoterm v puši valja (3D) in batu (2D) so razviti posebni podprogrami [32] do [34], indeks emisije NO_x (SUB EINO) pa računamo s preprostim korelacijskim izrazom.

In Fig. 9, a sketch of the general composition of the computer program of our PT and NPT models is shown. In-cylinder processes are modeled similarly as described in the literature [1]. The »filling-emptying« method is used to treat the process in the intake and exhaust manifold. The ROHR may be either calculated or predicted, depending on whether diagnostic or predictive engine cycle simulation is required. The ROHR models incorporated in the computer program have already been discussed. However, if an engineer needs more detailed data to design an intake and exhaust manifold or to match a turbo-charger to the engine, a separate submodel for prediction of an one-dimensional, non-steady, non-homentropic flow of compressible gas flow parameters (using either the method of characteristics or the finite-difference method) has been developed [27]. An additional submodel to solve analytically the complex boundary conditions at the entrance of a twin-turbine and to simulate the operation of TC under these conditions has also been developed [28]. To compute the IR history for a given configuration, SUB CFIE is used, based on the original model described in the literature [25], SUB OPT_IRH [31] may be included for IR optimization. For thermal load computation, i.e. isotherm distribution within the cylinder liner (3D) and piston (2D) the SUB Thermal Load combined with IDEAS package (models presented in the literature [32] through [34]) may be applied. The NO_x emission index is computed employing a simple empirical correlation — SUB EINO.



Sl. 9. *Načelna zasnova našega računalniškega programa za analizo motorskih pokazateljev [7], [27]–[34].*

CFIE – program numeričnih simuliranj za izračun osnovnih parametrov vbrizgavanja goriva; OPT_IRH – značilnica sproščanja toplote; SUB RGKTA– reševanje sistema diferencialnih enačb; SUB ODVOD – izračun gradienta iskanih spremenljivk; SUB PIS – izračun spremenljivk v polnilno izpušnem sistemu (izvedba sesalna ali s tlačnim polnjenjem); SUB PP – brezdimenzionalna metoda polnjenje – praznjenje; SUB KR – reševanje enačb (1D) nestacionarnega, nehomentropskega toka z dvokoračno diferenčno metodo LAX-Wenchoff; SUB DNT – izračun pretočnih števil in izkoristka dvonatočne turbine v pogojih delnega natoka; SUB EINO – izračun emisije NO_x; SUB PRESTOP – izračun prestopa toplote $dQ_c/d\Theta$; SUB TEMP – izračun temperature površin zgorevalnega prostora (glava, puša valja, bat, ventili); SUB TOPL – iskanje izoterm v valjevi puši (3D) in batu (2D); SUB ZGLID – zglajevanje indikatorskih diagramov; SUB GAUSS – izračun korenov sistema linearnih algeberskih enačb; SUB PLIN – izračun termodinamičnih veličin.

Fig. 9. *General presentation of our computer program for engine data analysis based on PT model [7], [27]–[34].*

CFIE – numerical simulation program to compute main parameters of fuel injection; OPT_IRH: injection rate optimization program; SUB RGKTA – to solve system of differential equations; SUB ODVOD – to determine gradients of computing variables; SUB PIS – computation of variables of intake and exhaust system (NA and TC engines); SUB PP – Nondimensional »Filling - Emptying« method; SUB KR – Solving the system of equations describing (1D) nonsteady nonhomentropic flow with two-step Lax–Wenchoff method; SUB DNT – Computation of discharge coefficients and efficiency of TC twin turbine under partial flow conditions; SUB EINO – Computation of NO_x emission index; SUB PRESTOP – Computation of heat transfer term $dQ_c/d\Theta$; SUB TEMP – computation of average surface temperatures of combustion space (head, cylinder liner, piston, valves); SUB TOPL – spatial temperature distribution (isotherms) cylinder liner (3D) and piston (2D); SUB ZGLID – Smoothing of cylinder pressure acquisition data; SUB GAUSS – Calculation of roots of the system of linear algebraic equations; SUB PLIN – to compute thermodynamic state variables.

3. SKLEPI

V zadnjih 30 letih je veliko število avtorjev predlagalo modele sproščanja toplote na podlagi Vibejeve funkcije iz leta 1960. Nekatere teh modelov smo predstavili v tem članku. Podali smo kratko oceno modelov in primerjavo napovedanih in izmerjenih indikatorskih diagramov. Uporaba teh modelov je namenjena le reševanju tistih tehničnih problemov, pri katerih nadrobno poznavanje procesov zgorevanja ni pomembno.

Matematična preprostost je bila ves čas osnovno vodilo pri razvoju modelov. V vseh modelih so zato vpeljani empirični parametri, ki določajo potek sproščanja toplote. Te parametre je treba določiti s preučevanjem posnetih indikatorskih diagramov ali predpostaviti na podlagi izkušenj in obsežne banke zbranih eksperimentalnih podatkov. Prav tako so se ves čas vrstili tudi poizkusi, v modele značilnice sproščanja toplote, vključiti dejavnike, ki določajo režim obratovanja in tiste, ki krmilijo procese v posameznih fazah zgorevanja. Praktična uporaba modelov, kakor tudi predstavljena analiza, pa kažeta, da je treba opraviti še vrsto eksperimentalnih raziskav, da bi lahko določene vplivne parametre natančneje ocenili in tako dosegli boljše ujemanje rezultatov.

Med modeli, ki vključujejo vpliv vbrizgavanja goriva, smo izpeljali in ocenili Janikijev model ter ga dopolnili z lastnimi predlogi (J-1, J-2, J-3). Naši predlogi nekoliko podrobneje obravnavajo dieselsko zgorevanje, seveda pa še vedno le na makroskopski ravni. Prednost teh modelov je, da za opis medsebojne povezave parametrov vbrizgavanja in sproščanja toplote ne potrebujejo empiričnih ali polempiričnih korelacij. Izkazalo se je, da dosežemo najboljše ujemanje izračunanih diagramov tlaka z izmerjenimi vrednostmi z modelom J-3, in to v širokem področju delovnih režimov, kar je značilno za motorje vozil.

Raziskave so tudi pokazale, da bi v modele, ki vključujejo značilnice vbrizgavanja goriva, kazalo uvesti (preproste) korelacijske povezave med parametri vbrizgavanja in trajanjem zgorevanja φ_z. Tako bi z neposredno metodo lahko omogočili študij možnosti zmanjšanja emisije NO_x brez povečanja porabe goriva. Načrtno krmiljeni proces značilnice vbrizgavanja goriva je namreč prvi pogoj za učinkovito, okolju prijazno gorevanje v dieselskem motorju.

Za konec želimo poudariti še naslednje: dandanes obstaja veliko število metod računalniškega simuliranja, ki so nedvomno velikega pomena pri razvoju in projektiranju motorjev. Stopnja, do katere lahko računalniško simuliranje vpliva na ceno, kakovost in čas za izvedbo izboljšave, je odvisna od vrste dejavnikov. Med njimi je zelo pomembna zmožnost projektanta, da izbere in uporabi najprimernejšo metodo, kar pa ni preprosta odločitev. Zavedati se moramo namreč, da so zaradi našega pomanjkljivega znanja o procesih zgorevanja v motorju prav vse, doslej razvite, simulirne metode do neke mere nepopolne in netočne [30].

3. CONCLUSIONS

During the last 30 years, since 1960 when Viebe's burning law appeared, a number of authors have proposed several models of a similar type. Only a few of them have been presented here and most of them have found application in PTM as submodels primarily used to solve current engineering problems, during the lead-cycle when a design engineer is searching for a quick answer, and when the details of combustion phenomena are not of interest.

The mathematical simplicity of these models has been the greatest challenge for their development, although an estimation of critical parameters controlling the ROHR is required in all models. There has been a permanent trend to include in the models also factors determing the engine operating regime and/or those controlling several stages of diesel combustion. The practical application and the analysis presented here has shown that more experimental work is needed in order to estimate more accurately the critical parameters and to obtain better accuracy in prediction.

Among models including the influence of IR we have derived and discussed Janikiev's model and our three proposals (J-1, J-2, J-3) considering in more detail diesel combustion, although still on a macroscopic level. The advantage of these models is that no additional empirical or/and semi-empirical correlation is needed to describe the interrelationship between fuel injection parameters, ambient air state and ROHR. Model J-3 has proved to give the best agreement of predicted pressure diagrams with those obtained from experiments at the crucial operating points typical for a vehicular diesel engine.

However, our investigation has shown that it will be worth finding a simple relationship between injection parameters and combustion duration φ_z, the value of which must now be estimated, for further improvement of the ROHR model including IR. This will enable direct study to decrease NO_x emission, without an increase in fuel consumption. Namely, a well controled IR history is the main prerequisite for efficient diesel combustion.

Finally, let us stress the following idea [30]: A large number of engine simulation methods are available today, and they are, without doubt, an important step in engine development and design technology. The degree to which the simulation can affect the time, price and quality of improvement depends on a variety of factors, among which the designer's ability to choose and apply the most appropriate one with regard to his engineering objective at hand, plays a dominant role. This is not an easy task, bearing in mind that, because of our lack of understanding all engine simulations are, so far, to some degree incomplete and inexact [30].

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OZNAČBE

a — odstotek goriva, ki zgori med zgorevanjem
C — koncentracije, integracijska konstanta,
CA — kot zavrtitve ročične gredi (RG),
D — premer bata,
EVO— izpušni ventil odprt,
g_e — specifična poraba goriva,
h — specifična entalpija,
H_f — spodnja kurilnost goriva,
IR — značilnica vbrizgavanja goriva,
IVC — polnilni ventil zaprt,
J-1 — Janikiev model, predlog avtorjev št. 1,
J-2 — Janikiev model, predlog avtorjev št. 2,
J-3 — Janikiev model, predlog avtorjev št. 3,
k — konstanta,
k_f — konstanta kemične reakcije,
l_0 — masno stehiometrijsko razmerje,
L_0 — molsko stehiometrijsko razmerje,
M — število molov,
m — masa, faktor oblike zgorevanja,
n — število vrtljajev,
p — tlak,
Q — toplota,
q — prostorninska količina vbrizganega goriva,
R — plinska konstanta,
ROHR — značilnica sproščanja toplote,
s — gib bata,
SUB— računalniški podprogram,
T — temperatura,
TC — tlačno polnjen,
TDC— zgornja mrtva lega,
t — čas,
u — specifična notranja energija,
V — prostornina,
W — delo, med IVC-EVO,

NOMENCLATURE

a — degree of fuel burnt during combustion,
C — concentration, integration constant,
CA — crank angle (RG),
D — piston diameter,
EVO— exhaust valve opens,
g_e — brake specific fuel consumption,
h — enthalpy per unit mass,
H_f — fuel lower heating value (heat of combust.),
IR — rate of injection,
IVC — intake valve closes,
J-1 — improvement of JM - authors proposal 1,
J-2 — improvement of JM - authors proposal 2,
J-3 — improvement of JM - authors proposal 3,
k — constant,
k_f — reactivate constant,
l_0 — stoichiometric mass air-fuel ratio,
L_0 — stoichiometric mole air-fuel ratio,
M — number of moles,
m — mass, ROHR shape factor,
n — rotational speed,
p — pressure,
Q — heat,
q — fuelling by volume,
R — gas constant,
ROHR — rate of heat release,
s — piston lift,
SUB— subroutine,
T — temperature,
TC — turbo-charged,
TDC— top dead center,
t — time,
u — internal energy per unit mass,
V — volume,
W — indicated work during IVC-EVO,

x – relativna količina zgorelega goriva: $x = m_{Fb}/m_{FC}$,
y – relativni čas zgorevanja: $y = t/t_z = \varphi/\varphi_z$,
$\alpha(\varphi)$ – trenutna vrednost relativnega razmernika zrak/gorivo med zgorevanjem,
α_0 – povprečna vrednost relativnega razmernika za celoten cikel, definicija,
$\alpha_0(\varphi)$ – trenutna vrednost relativnega razmernika zrak/gorivo med vbrizgavanjem,
γ – koeficient zaostalih plinov,
Θ – kot zavrtitve ročične gredi,
μ_0 – teoretični koeficient molekularne spremembe med zgorevanjem,
ρ – gostota,
σ – standardna deviacija,
φ – kot ročične gredi (samo med zgorevanjem, $0 \leq \varphi \leq \varphi_z$).

Indeksi

a – zrak,
b – zgoreli,
C – na cikel,
ce – konec zgorevanja,
cs – začetek zgorevanja,
d – difuzijski,
F – gorivo,
ID – zakasnitev vžiga,
IS – začetek vbrizga,
P – produkti zgorevanja,
p – poprej pomešani reaktanti,
r – zaostali,
s – stehiometrični,
t – celoten,
z – zgorevanje.

x – relative amount of fuel burnt: $x = m_{Fb}/m_{FC}$,
y – relative time of burning: $y = t/t_z = \varphi/\varphi_z$,
$\alpha(\varphi)$ – equivalence air/fuel ratio - instant value during combustion,
α_0 – average equivalence air/fuel ratio during the whole cycle,
$\alpha_0(\varphi)$ – equivalence air/fuel ratio, instant value during injection period,
γ – coefficient of residual gases,
Θ – crank angle,
μ_0 – coefficient of mole quantity change during combustion,
ρ – density
σ – standard deviation,
φ – crank angle (during combustion only, $0 \leq \varphi \leq \varphi_z$).

Subscripts

a – air,
b – burnt,
C – per cycle,
ce – combustion end,
cs – combustion start,
d – diffusion,
F – fuel,
ID – ignition delay,
IS – injection start,
P – combustion products,
p – premixed, reactants,
r – residual,
s – stoichiometric,
t – total,
z – combustion.

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