Strojniški vestnik - Journal of Mechanical Engineering 51(2005)6, 280-303
UDK - UDC 662.92:536.46
Izvirni znanstveni članek - Original scientific paper (1.01)

Analiza pogojev zgorevanja v sekundarni komori pilotne sežigalnice na podlagi računske dinamike tekočin

An Analysis of the Combustion Conditions in the Secondary Chamber of a Pilot-Scale Incinerator Based on Computational Fluid Dynamics

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Predstavljena je numerična analiza zgorevanja v sekundarni komori (termoreaktorju) dvostopenjske pilotne sežigalnice z uporabo računske dinamike tekočin (RDT-CFD). Z raziskavo smo se osredotočili na analizo fizikalnih pogojev popolnega zgorevanja, kakor so temperatura, čas zadrževanja in turbulentno mešanje. Uporabili smo več izvedb programov vrste CFX za RDT, ki omogočajo uporabo različnih modelov zgorevanja v odvisnosti od vrste in načina zgorevanja. Izbira ustreznega modela zgorevanja je potekala na podlagi primerjave numeričnih rezultatov z izmerjenimi vrednostmi nekaterih makroparametrov zgorevanja v termoreaktorju. Uporabili smo modele na temelju enostopenjske bimolekularne kemijske reakcije in modela večstopenjskih reakcij, ki omogočata bolj natančno napoved dogajanja v sekundarni komori pilotne sežigalnice. Z večstopenjskima modeloma lahko izračunamo lokalne koncentracije ostankov nepopolnega zgorevanja, kar je izrednega pomena za primerno oblikovanje in optimiranje kurilnih naprav. Na podlagi izbranega modela zgorevanja je izvedena temeljna analiza zgorevanja v termoreaktorju z vidika doseganja pogojev popolnega zgorevanja pri različnih obratovalnih razmerah, ki so posledica spremenljive količine, sestave in kurilne vrednosti plinov iz primarne komore. Prišli smo do pomembne ugotovitve, da na kakovost zgorevanja v termoreaktorju v največji meri vplivata način dovoda sekundarnega in terciarnega zraka ter njuno razmerje.

(Ključne besede: zgorevanje, analize numerične, modeli zgorevanja, računska dinamika tekočin)

A numerical analysis of the combustion in the secondary chamber (thermoreactor) of a two-stage pilot-scale incinerator using computational fluid dynamics (CFD) is presented. The focus of the research was on those physical conditions that ensure complete combustion, i.e., temperature, residence time and turbulent mixing. Various versions of the CFD program package CFX were used; they offer different combustion models for specific types and forms of combustion processes. The selection of an appropriate combustion model was based on a comparison of the numerical results and experimental values of some combustion macro parameters in a thermoreactor. Combustion models based on a one-step bimolecular chemical reaction and models based on multi-step reactions were used; this enabled a more detailed prediction of the combustion conditions in the secondary chamber of a pilot-scale incinerator. The products of incomplete combustion that are very important for the designing and optimization of combustion devices can be predicted by applying multi-step reaction models. An ultimate analysis of the complete combustion conditions was made based on a selected combustion model by considering those different operating conditions, causing variations in the quantity, composition and heating values of the gases coming from the primary chamber. The important conclusions are that the secondary and tertiary air intakes and the relationship between them have the greatest influence on the combustion quality in the thermoreactor.

(Keywords: combustion, numerical analysis, combustion models, computational fluid dynmics)

0 UVOD

Postopki toplotne obdelave odpadkov, ki omogočajo energijsko izrabo odpadkov, so dandanes

0 INTRODUCTION

Nowadays, thermal waste-treatment techniques and technologies enabling energy recovery

zelo razvite tehnologije. Ena takšnih tehnologij je tudi sežig oziroma zgorevanje odpadkov. Njegova glavna naloga je toplotni razkroj organskih snovi in proizvodnja energije iz odpadkov. Pri postopku sežiga lahko pride tudi do nastanka onesnaževal, katerih količina v dimnih plinih je v veliki meri odvisna od kakovosti zgorevanja.

Z vidika navedenega je zelo pomembno poznavanje fizikalno-kemijskih pojavov v zgorevalnem prostoru, ki jih je mogoče dokaj natančno simulirati in analizirati z ustreznimi modeli računske dinamike tekočin (RDT) ([16], [8] in [7]). Rezultati numeričnih simulacij postopkov zgorevanja v različnih razmerah obratovanja omogočajo veliko podporo pri oblikovanju zgorevalnega prostora z vidika učinkovitega doseganja pogojev popolnega zgorevanja [12]. Nadalje zagotavljajo dobro oceno makroparametrov postopkov zgorevanja, ki jih je mogoče razmeroma preprosto preveriti na podlagi meritev [6]. Z numeričnimi simulacijami postopkov zgorevanja lahko ocenimo tudi obratovalno območje sežigalnice, predvsem z vidika različnih količin in kurilne vrednosti odpadkov, količine dimnih plinov in dodanega zraka.

Težišče prispevka je namenjeno numerični analizi pogojev zgorevanja na temelju:

- zagotovitve homogenosti temperaturnega polja (izogniti se področjem najbolj nizkih in visokih temperatur, ki pomenijo jedra za mogoč nastanek onesnaževal),
- učinkovitosti zgorevanja na osnovi koncentracij produktov zgorevanja in
- dovajanja sekundarnega in terciarnega zraka pod različnimi pogoji

v sekundarni komori sežigalnice. Na podlagi modeliranja zgorevanja v sekundarni komori pilotne sežigalnice je podana primerjava različnih modelov zgorevanja v okviru programa CFX. Nadalje je podana ocena, kateri model zgorevanja je najbolj natančen, stabilen in omogoča hiter izračun.

Praktično uporabnost numeričnega modeliranja in simulacij zgorevanja v sežigalnicah so do sedaj potrdili številni raziskovalci ([5], [7], [8] in [10]). Skupna ugotovitev vseh je, da je uporaba numeričnih orodij modeliranja in simulacij zgorevanja lahko zelo koristna in praktično uporabna, če uporabljeni ustrezni numerični modeli dovolj natančno opisujejo dejanske fizikalne razmere v zgorevalnem prostoru ([12], [13] in [4]). S tega vidika je velika pozornost namenjena prav izbiri ustreznega modela zgorevanja, ki

from waste are highly developed. One of these techniques is incineration, also known as waste combustion. Its aims are the thermal destruction of organic compounds and the production of energy from the waste. Some pollutants can be formed during the incineration process, whose quantity in the flue gasses depends on the quality of the combustion.

Based on the above facts, it is of key importance to have the necessary knowledge of the physical and chemical processes in a combustion chamber in order to accurately simulate and analyze them using the appropriate CFD packages ([16], [8] and [7]). Results from numerical simulations of combustion processes under various operating conditions provide important support in the design of a combustion chamber to the stage of complete combustion-condition fulfilment [12]. Furthermore, they ensure good estimations regarding some macro parameters of combustion processes and can be fairly easily examined by measurements [6]. A numerical simulation of the combustion process also enables a review of an incinerator's operating conditions, especially the amounts and calorific values of the input waste stream, the amount of flue gases and the quantity of added combustion air.

The main concern of this paper is focused on the numerical analyses of combustion conditions based on:

- assurance of a homogenous temperature field (to avoid low and high peak temperature areas presenting cores of possible pollutant formation),
- combustion efficiency when considering combustion products' compositions,
- various intake conditions of secondary and tertiary combustion air,

in the secondary chamber of an incinerator. A comparison of different combustion models involved in the CFX program was done based on combustion simulation in the secondary chamber of the pilot-scale incinerator. Furthermore, an assessment will be presented as to which of the combustion models is the most accurate, stable and fast.

The practical values of combustion modelling and incineration simulation have so far been confirmed by many investigators ([5], [7], [8] and [10]). The common denominator of their findings is that the application of numerical modelling tools and combustion simulation can be very useful and have practical applications if the chosen numerical models closely resemble, in physical terms, the actual conditions in the combustion chamber ([12], [13] and [4]). From this point of view, great attention was placed on the selection of an adequate com-

omogoča najbolj natančno analizo sežiga v termoreaktorju.

1 OPIS PILOTNE PREIZKUSNE SEŽIGALNICE

V naši raziskavi je uporabljena pilotna sežigalnica (sl. 1), katere tehnologija zgorevanja sodi v skupino dvostopenjskih oziroma dvokomornih sežigalnic, ki so bile prvotno razvite za sežig industrijskih, bolnišničnih in drugih nevarnih odpadkov. Takrat je zakonodaja za sežig teh odpadkov predpisovala strožja merila obratovanja kakor za sežig komunalnega (gospodinjskega) odpada. Glavni namen uporabe sekundarne komore je bil izboljšati kakovost zgorevanja in kolikor je le mogoče zmanjšati emisije strupenih onesnaževal [1].

Delovanje tovrstnih sežigalnic temelji na primanjkljaju zraka v primarni komori in na presežku zraka v sekundarni komori. To zagotavlja dobro zgorevanje, majhne emisije in manjšo porabo dodatnega goriva, če je kurilna vrednost odpadkov prenizka za samostojno zgorevanje [13].

Postopek zgorevanja dvokomornih sežigalnic je zasnovan na dveh fizikalno-kemijskih pojavih:

- segrevanju, sušenju in semipirolitičnem uplinjanju odpadkov v primarni komori in

bustion model, which would enable the most accurate analyses of incineration in the thermoreactor.

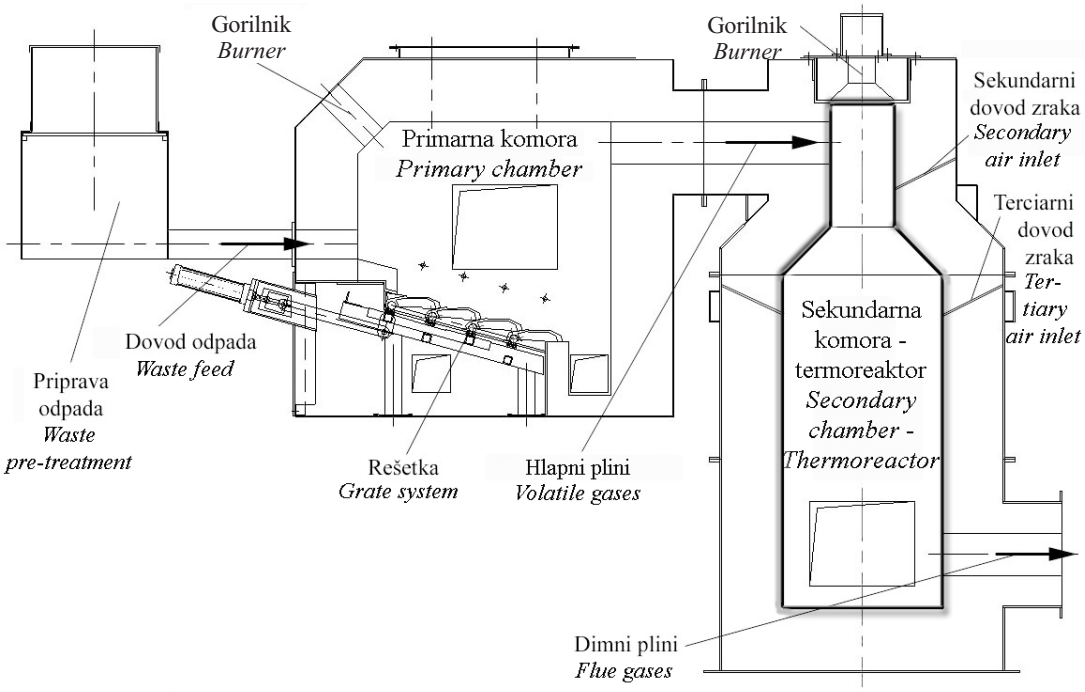
1 DESCRIPTION OF AN EXPERIMENTAL PILOT-SCALE INCINERATOR

This study was conducted on a pilot-scale incinerator (Figure 1); its combustion technology belongs to the group of two-stage or two-chamber incinerators, originally developed for the incineration of industrial, hospital and other hazardous waste. At that time the legislation demanded that the treatment of such waste was stricter than for municipal (household) waste incineration. The main purpose of the secondary chamber was to improve the combustion quality in order to reduce emissions of toxic pollutants as much as possible [1].

The function of these incinerators is based on primary-chamber starved-air and secondary-chamber excess-air conditions. This enables good combustion, low emissions and lower consumption of additional fuel when the calorific value of the waste is too low to enable self-combustion [13].

The combustion process in two-chamber incinerators is based on two groups of physical–chemical processes:

- warming, drying, semi-pyrolitic gasification of the waste in the primary chamber,



Sl. 1. *Shema pilotne dvostopenjske sežigalnice*
Fig. 1. *Schematic representation of a two-stage pilot-scale incinerator*

- mešanju gorljivih plinov z zrakom, vžig in popolno zgorevanje v sekundarni zgorevalni komori.

Nepopolno zgorevanje v primarni komori predstavlja pirolitično uplinjevalne postopke, ki potekajo v razmerah pomanjkanja zraka. Količina dovedenega zraka znaša okrog 70% stehiometrično potrebnega zraka. Temperatura v primarni komori je odvisna od sestave odpada in se spreminja med 650 °C in 850 °C. Višje temperature kažejo na to, da zgori v primarni komori več plinov, zato pa gredo potem v sekundarno komoro plini z nižjo kurilno vrednostjo. Zagotavljanje stabilnih obratovalnih razmer v celotni sežigalnici je vezano na strukturo odpadkov, ki prihajajo v primarno komoro. Sestava odpadkov v veliki meri vpliva tudi na količino in kakovost plinov, ki se sproščajo v primarni komori.

Termoreaktor je fizično ločen od primarne komore. Opremljen je z gorilnikom, ki zagotavlja zagon in stabilno obratovanje tudi v primeru nižjih kurilnih vrednosti plinov iz primarne komore. Na postopke v termoreaktorju v veliki meri vplivata količina in smer dovoda sekundarnega in terciarnega zraka. Ta mora zagotoviti ustrezno mešanje plinov in učinkovito zgorevanje. Predvsem je pomembno doseganje velike homogenosti zmesi reaktantov in temperaturnega polja, da ne pride do nastanka neželenih produktov nepopolnega zgorevanja.

2 MODELIRANJE TURBULENTNEGA REAKTIVNEGA TOKA

Zgorevanje v termoreaktorju je dokaj natančno popisano s sistemom diferencialnih enačb (Navier Stokesove enačbe - NSE) reaktivnega toka. Sistem enačb sestavljajo zakon o ohranitvi snovi, gibalne količine in energije. NSE lahko rešimo neposredno za laminarni kakor tudi za turbulentni reaktivni tok, za kar pa porabimo veliko računske moči in časa. Zato se je uveljavila Reynoldsova zamisel o dekompoziciji trenutne vrednosti poljubne makroskopske veličine toka na časovno povprečno vrednost in njej pripadajoči oscilirajoči del za simulacijo turbulentnih reaktivnih tokov:

- mixing of the volatile gases with air, ignition and complete combustion in the secondary combustion chamber.

Incomplete combustion in the primary chamber represents the pyrolitic and gasification processes and takes place during air shortage. The quantity of air added is around 70% of the stoichiometric air needed. The temperature in the primary chamber depends on the waste's composition and varies from 650 to 850°C. Higher temperatures indicate that more gases have been burnt in the primary chamber and consequently lower-calorific-value gases then pass to the secondary chamber. Stable operating conditions for the whole incinerator depend on the waste composition introduced into the primary chamber. Waste composition greatly influences the quantity and quality of the volatile gases released in the primary chamber.

The thermoreactor is physically separated from the primary chamber. It is equipped with a burner that ensures start-up and stable operation, even in the case of lower calorific gas values coming from the primary chamber. The amount and direction of the secondary- and tertiary-air induction in the thermoreactor play an important role in the thermoreactor processes. It has to ensure proper mixing of the gases and efficient combustion. Crucially, it is important to achieve a high homogeneity of the reactant mixture and the temperature field to prevent the formation of undesirable products due to incomplete combustion.

2 TURBULENT – REACTING FLOW MODELLING

The combustion in a thermoreactor is described quite accurately by a system of differential equations (Navier Stokes equations – NSEs) of the reacting flow. It is composed of continuity-, momentum- and energy-conservation equations. The NSEs can be solved directly for laminar, as well as for turbulent reacting flow, by spending a lot of computational power and time. Therefore, the Reynolds idea of the arbitrary macroscopic value of fluid flow decomposition being on the time-averaged value and its variable part, has been widely used for turbulent reacting flow simulations:

$$\phi(x_i,t)=\bar{\phi}(x_i)+\phi'(x_i,t) \quad (1),$$

kjer je:

which is:

$$\bar{\phi}(x_i)=\frac{1}{\Delta t}\int_{t}^{t+\Delta t}\phi(x_i,t)\mathrm{d}t \quad (2).$$

To povprečenje je dalo Reynoldsove povprečene NSE (RPNS), predstavljene v naslednji obliki:

This transformation produces the Reynolds' averaged NSEs (RANS), as presented in the following form:

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{\rho}\overline{\upsilon}_j\right) = 0 \tag{3}$$

$$\frac{\partial}{\partial t}\left(\overline{\rho}\overline{\upsilon}_j\right) + \frac{\partial}{\partial x_j}\left(\overline{\rho}\overline{\upsilon}_j\overline{\upsilon}_i\right) = -\frac{\partial p}{\partial x_i} + \overline{f_{vi}} - \frac{\partial}{\partial x_j}\left(\overline{\tau}_{ij} + \overline{\rho\upsilon'_j\upsilon'_i}\right) \tag{4}$$

$$\frac{\partial}{\partial t}\left(\overline{\rho}\overline{h}\right) + \frac{\partial}{\partial x_j}\left(\overline{\rho}\overline{\upsilon}_j\overline{h}\right) - \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{q}_j + \overline{\rho\upsilon'_j h'}\right) = \overline{I_T} + \overline{I_R} \tag{5}.$$

$\overline{\rho}$, $\overline{h}$ in $\overline{\upsilon_j}$ so srednje vrednosti gostote, entalpije in hitrosti tekočine, $\overline{f_{vi}}$ je vsota vseh prostorninskih sil, p je tlak, $\overline{I_T}$ zgorevalni in $\overline{I_R}$ sevalni izvirni/ponorni člen, $\overline{\tau}_{ij}$ in $\overline{q}_j$ sta viskozni napetostni tenzor in toplotni tok. Z uporabo RPNS nastanejo dodatni členi, ki jih imenujemo Reynoldsove napetosti ($\overline{\rho\upsilon'_j\upsilon'_i}$) in tokovi ($\overline{\rho\upsilon'_j\phi'}$). Modelirani so z uvajanjem turbulentne viskoznosti η_t. Reynoldsov napetostni tenzor je določen z Boussinesqovim modelom turbulentne viskoznosti η_t:

$\overline{\rho}$, $\overline{h}$ and $\overline{\upsilon_j}$ are the mean values of density, enthalpy and fluid velocity, $\overline{f_{vi}}$ is the sum of all the volume forces, p is the pressure, $\overline{I_T}$ is the combustion and $\overline{I_R}$ is the radiation source/sink terms. $\overline{\tau}_{ij}$ and $\overline{q}_j$ are the viscous stress tensor and the heat flux, respectively. Applying RANS, some additional terms have been produced named the Reynolds' stresses ($\overline{\rho\upsilon'_j\upsilon'_i}$) and fluxes ($\overline{\rho\upsilon'_j\phi'}$). They are modelled by the introduction of the turbulent viscosity η_t. The Reynolds' stress tensor is expressed with the Boussinesq model of turbulent viscosity η_t:

$$\overline{\rho\upsilon'_j\upsilon'_i} = \frac{2}{3}\delta_{ij}\left(\rho k + \eta_t\frac{\partial \upsilon_k}{\partial x_k}\right) - \eta_t\left(\frac{\partial \upsilon_i}{\partial x_j} + \frac{\partial \upsilon_j}{\partial x_i}\right) \tag{6}.$$

Turbulentno viskoznost lahko izračunamo z uporabo različnih turbulentnih modelov za sklenitev sistema Reynoldsovih enačb. Za potrebe modeliranja predstavljenega reaktivnega toka smo uporabili dvoenačbni turbulentni model k - ε. Uporabo turbulentnega modela k - ε je v primerih modeliranja reaktivnih tokov pokazalo več avtorjev ([5], [7], [8], [10] in [16]) kot zelo uspešno. Turbulentna viskoznost se izračuna z uporabo:

Turbulent viscosity can be determined using various turbulent models to closedown the system of Reynolds' equations. The two-equation k - ε turbulent model is used for the purpose of the presented reacting flow modelling. The application of the k - ε turbulent model in the modelling of reacting flows has already been proven by many authors ([5], [7], [8], [10] and [16]) as a very successful one. The turbulent viscosity is computed using:

$$\eta_t = \rho C_\eta \frac{k^2}{\varepsilon} \tag{7},$$

kjer je k turbulentna kinetična energija – $k = 0{,}5\left(\overline{\upsilon'_i\upsilon'_i}\right)$ in ε njeno razsipanje (nepovračljiva sprememba kinetične energije v notranjo energijo).

where k is turbulent kinetic energy – $k = 0{,}5\left(\overline{\upsilon'_i\upsilon'_i}\right)$ and ε is its dissipation (irreversible transformation of kinetic energy into internal energy).

Lokalne vrednosti k in ε se izračunajo z uporabo naslednjih prenosnih enačb:

Local values of k and ε are computed using the following transport equations:

$$\frac{\partial}{\partial t}\left(\rho k\right) + \frac{\partial}{\partial x_j}\left(\overline{\upsilon}_j k\right) - \frac{\partial}{\partial x_j}\left[\left(\eta + \frac{\eta_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] = I_k \tag{8}$$

$$\frac{\partial}{\partial t}\left(\rho\varepsilon\right) + \frac{\partial}{\partial x_j}\left(\overline{\upsilon}_j\varepsilon\right) - \frac{\partial}{\partial x_j}\left[\left(\eta + \frac{\eta_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] = I_\varepsilon \tag{9},$$

izvirna člena sta modelirana kot:

the source terms are modelled as:

$$I_k = \eta_t\left(\frac{\partial \overline{\upsilon}_i}{\partial x_j} + \frac{\partial \overline{\upsilon}_j}{\partial x_i}\right)\frac{\partial \overline{\upsilon}_i}{\partial x_j} - \rho\varepsilon \tag{10}$$

$$I_\varepsilon = C_1 \frac{\varepsilon}{k}\left[\eta_t\left(\frac{\partial \overline{\upsilon}_i}{\partial x_j}+\frac{\partial \overline{\upsilon}_j}{\partial x_i}\right)\frac{\partial \overline{\upsilon}_i}{\partial x_j}\right]-C_2\rho\frac{\varepsilon^2}{k} \quad (11).$$

Reynoldsov entalpijski tok $\overline{\rho\upsilon'_j h'}$ v enačbi (5) je prav tako določen s turbulentno viskoznostjo:

The Reynolds' enthalpy flux $\overline{\rho\upsilon'_j h'}$ in equation (5) is also defined with turbulent viscosity:

$$\overline{\rho\upsilon'_j h'} = -\frac{\eta_t}{\mathrm{Pr}_t} c_p \frac{\partial T}{\partial x_j} \quad (12),$$

kjer je Pr_t turbulentno Prandtlovo število. C_η, C_1, C_2, σ_k in σ_ε so stalnice, katerih vrednosti, ki smo jih uporabili v našem delu, so: C_η=0,09; C_1=1,44; C_2=1,92; σ_k=1 in σ_ε=1,3.

where Pr_t is the turbulent Prandtl number. C_η, C_1, C_2, σ_k and σ_ε are constants, and their values used in the presented work are: C_η=0.09; C_1=1.44; C_2=1.92; σ_k=1 and σ_ε=1.3.

Konvektivno-difuzivna enačba masnega deleža (ξ_k) komponente k ima zaradi Reynoldsovega povprečenja dodatni člen, ki ga imenujemo turbulentni tok masnega deleža:

The convection–diffusive equation of mass species (ξ_k) of the component k has, due to Reynolds' averaging, an additional term called the turbulent mass species flux:

$$\overline{\rho\xi'_k\upsilon'_j} = \frac{\eta_t}{\mathrm{Sc}_t}\frac{\partial \xi_k}{\partial x_j} \quad (13)$$

in ga lahko modeliramo s turbulentno viskoznostjo z uporabo modela k-ε. Celotna konvektivno-difuzivna enačba za masni delež je:

and can be modelled with turbulent viscosity using the k-ε model. The complete advection–diffusive mass species equation is:

$$\frac{\partial}{\partial t}\left(\overline{\rho\xi_k}\right)+\frac{\partial}{\partial x_j}\left(\overline{\rho\upsilon_j\xi_k}\right)-\frac{\partial}{\partial x_j}\left[\left(\rho D_k+\frac{\eta_t}{\mathrm{Sc}_t}\right)\frac{\partial \xi_k}{\partial x_j}\right]=\overline{I_{\xi_k}} \quad (14),$$

kjer je Sc_t turbulentno Schmidtovo število in D_k je molekularna snovska difuzivnost sestavine k. Z novim členom:

where Sc_t is the turbulent Schmidt number and D_k the molecular diffusion coefficient of component k. With the new term:

$$\Gamma_{k,eff} = \rho D_k + \frac{\eta_t}{\mathrm{Sc}_t} = \Gamma_k + \frac{\eta_t}{\mathrm{Sc}_t} \quad (15)$$

lahko enačbo (14) ponovno zapišemo kot:

equation (14) can be rewritten as:

$$\frac{\partial}{\partial t}\left(\overline{\rho\xi_k}\right)+\frac{\partial}{\partial x_j}\left(\overline{\rho\upsilon_j\xi_k}\right)-\frac{\partial}{\partial x_j}\left(\Gamma_{k,eff}\frac{\partial \xi_k}{\partial x_j}\right)=\overline{I_{\xi_k}} \quad (16).$$

Izvorni člen energijske enačbe ($\overline{I_T}$) in enačbe masnega deleža ($\overline{I_{\xi_k}}$) izračunamo z naslednjima enačbama, pri čemer je $\overline{\omega}_k$ izračunana s turbulentnim modelom zgorevanja:

The source terms of the energy ($\overline{I_T}$) and mass species ($\overline{I_{\xi_k}}$) transport equations are computed by the following two equations, where $\overline{\omega}_k$ is computed by the turbulent combustion model:

$$\overline{I_T} = -\sum_{k=1}^{N}\Delta H^o_{f,k}\overline{\omega}_k \quad (17)$$

$$\overline{I_{\xi_k}} = M_k\overline{\omega}_k \quad (18),$$

kjer sta $\Delta H°_{f,k}$ standardna tvorbena entalpija in M_k molska masa sestavine k. V enačbah (17) in (18) predstavlja $\overline{\omega}_k$ stopnjo nastanka/porabe komponente k in je definiran z naslednjim izrazom:

where $\Delta H°_{f,k}$ is the standard formation heat and M_k the molecular mass of the component k . In equations (17) and (18) the $\overline{\omega}_k$ stands for the formation/consumption rate of component k and is defined by the following expression:

$$\overline{\omega}_k = \frac{d[X_k]}{dt} = (\nu''_k - \nu'_k)\overline{R}_k \quad (19),$$

ki je zapisan za splošno obliko kemijske reakcije:

which is written for the general form of the chemical reaction:

$$\sum_{k=1}^{N} \nu'_k X_k \xrightarrow[k_b]{k_f} \sum_{k=1}^{N} \nu''_k X_k \tag{20},$$

kjer ν'_k in ν''_k označujeta stehiometrične koeficiente komponente k za reaktante oziroma produkte. Hitrost kemijske reakcije $\overline{R}_k$ v enačbi (19) računamo z ustreznimi modeli zgorevanja. Izpostaviti velja, da je dandanes v praktični uporabi veliko število turbulentnih modelov zgorevanja. Njihova uporabnost je odvisna od tipa zgorevanja (difuzijski, kinetični, mešani), vrste goriva (trdno, kapljevito, plinasto) in kurilne naprave (peči, kotli, motorji). Večina modelov vsebuje različne empirične stalnice in jih je treba določiti za vsak primer posebej. Pri tem pa je treba poudariti, da zaradi velike nelinearnosti povprečna vrednost hitrosti kemijske reakcije ni enaka vrednosti, katerih osnova so povprečne vrednosti temperature in koncentracije sestavin reaktivnega toka:

where ν'_k and ν''_k designate the stoichiometric coefficients of component k for the reactants and products, respectively. The chemical reaction rate $\overline{R}_k$ in equation (19) is calculated using appropriate combustion models. It has to be pointed out that nowadays many turbulent combustion models are in practical use. Their application depends on the type of combustion (diffusion, kinetic, mixed), fuel type (solid, liquid, gaseous) and combustion device (furnace, boiler, engine). Most of the models include various empirical constants that need to be individually determined case by case. It needs to be pointed out that, due to the high non-linearity of the problem, the average value of the chemical reaction rate is not equal to the reaction-rate value based on the average values of the temperature and mass species

$$\overline{R}_k \neq R_k\left(\overline{T}, \overline{\xi}_k\right) \quad k = 1,\ldots, N \tag{21},$$

ki jih dobimo z reševanjem RPNS. Uporaba povprečnih vrednosti lahko v posameznih primerih vodi do napačnih izračunov reakcijskih hitrosti [9]. V takih primerih je treba uporabiti primernejše statistične modele zgorevanja na podlagi porazdelitvenih verjetnostnih funkcij (PVF). V primerih modeliranja postopkov zgorevanja z nižjimi oscilacijami temperature v zgorevalnem prostoru, kar je značilno tudi za naš predstavljen primer, dajejo empirični modeli sprejemljive rezultate ([8] in [10]).

Izvorni sevalni člen $\overline{I_R}$ modeliramo z različnimi sevalnimi modeli, ki pomenijo poenostavitev sevalne prenosne enačbe [4]. Izvirni člen je divergenca skupnega sevalnega toplotnega toka q^R, ki ga dobimo z integracijo spektralnega sevalnega toplotnega toka q_ν po celotnem spektru:

that are achieved by solving the RANS equations. The use of the average values in certain instances can lead to false computation results of the reaction rate [9]. In such instances it is reasonable to apply more appropriate statistical combustion models based on probability density functions (PDFs). In the case of combustion modelling at lower temperature oscillations in the combustion chamber, as in the presented case, the empirical models provide acceptable results ([8] and [10]).

The radiation source term $\overline{I_R}$ is modelled with different radiation models that represent a simplification of the Radiation Transport Equation [4]. The source term is a divergence of the total radiative heat flux q^R, obtained by integrating the spectral radiative heat flux q_ν over the spectrum:

$$\overline{I_R} = \frac{\partial}{\partial x_j}\left(q_j^R\right) = \int_0^\infty q_\nu{}^R d\nu \tag{22},$$

kjer je spektralni sevalni toplotni tok $q_\nu{}^R$ enak:

where the spectral radiative heat flux $q_\nu{}^R$ is:

$$q_\nu{}^R(r_j, n_j) = \int s_j n_j I_\nu(r_j, s_j) d\Omega_s \tag{23}.$$

V enačbi (23) r_j označuje vektor lokacije, n_j normalni vektor, s_j smerni vektor in I_ν je spektralni sevalni prenos v določeni smeri, prostoru in spektru na temelju emisije, absorbcije in razpršitve po prenosnem sredstvu.

In Equation (23) r_j designates the vector location, n_j is the normal vector, s_j is the direction vector and I_ν is the spectral radiative transfer in a fixed direction, location and spectrum based on emitting, absorbing and medium scattering.

Obravnavali smo tudi sevalni model za bolj natančen popis fizikalnega dogajanja, ki se odvija v termoreaktorju. Kratka analiza različnih sevalnih modelov je pokazala le manjše razlike v numeričnih rezultatih ob uporabi privzetih nastavitev programskega paketa. Zato je sevalni model vpet v računsko analizo, vendar ne bo predmet podrobnejše razprave v tem prispevku.

V našem predstavljenem primeru gre za difuzijsko obliko zgorevanja plinov (zmes CO in CH_4) v valjastem zgorevalnem prostoru (sl. 1) s protitočnim vplivom vzgona. Gre za specifičen primer, značilen za sežigalnice z ločeno sekundarno komoro, za katerega ni na voljo splošno uporabnega modela zgorevanja. V ta namen smo preizkusili in ovrednotili različne modele zgorevanja, ki so na voljo v programu CFX: mešalni (imenovan MIB), vrtinčni (im. EBU), vrtinčno-disipacijski model (im. EDC), model končne hitrosti kemijskih reakcij (im. FRC) in kombiniran model slednjih dveh (im. COMBINED). Nekateri modeli dodatno omogočajo tudi izračun večstopenjske kemijske kinetike, ki omogoča podrobnejšo analizo pogojev nastanka škodljivih snovi.

The radiation model was also considered for describing more accurately the physical events presented in a thermoreactor. A brief analysis of different available radiation models showed only minor differences in terms of the achieved numerical results, using the program package's default settings. Thus the radiation model is included in computational analysis but will not be discussed in more detail in this paper.

In the presented case there is a diffusion type of gaseous combustion (CO and CH_4 mixture) in the cylindrical combustion chamber (Figure 1), with a cross flow buoyancy influence. It is a specific case problem, common for incinerators with a separated secondary chamber for which there is no available combustion model, in general. For this purpose different combustion models available in the CFX program: Mixed is burnt (MIB), Eddy break up (EBU), Eddy dissipation combustion (EDC), Finite rate chemistry (FRC) model and the combined (COMBINED) model of the last two, were tested and evaluated. Some models additionally enable the computation of multistep chemical kinetics, providing more detailed numerical analyses of the pollutant formation conditions.

3 MODELI TURBULENTNEGA ZGOREVANJA

3.1 Mešalni model (MIB)

Model zgorevanja MIB predpostavlja hitre kemijske reakcije zgorevanja. To pomeni, da pride do trenutne reakcije, če so na istem mestu navzoči reaktanti in ob tem nastanejo produkti zgorevanja. Predpostavimo, da se gorivo in oksidant vežeta pri stalnem razmerju *i*, ki ga imenujemo stehiometrično razmerje, tako da je:

3 TURBULENT COMBUSTION MODELS

3.1 Mixed IS Burnt Model (MIB)

The MIB combustion model presumes infinitely fast chemical reactions of combustion. Thus, if reactants are present at the same place and time, instantaneous reaction occurs and produces combustion products. Assuming that the fuel and oxidant react at a constant ratio *i*, also called the "stoichiometric ratio", such that:

$$1\ kg\ \text{goriva} + i\ kg\ \text{oksidanta} \rightarrow (1+i)\ kg\ \text{produktov}$$
$$1\ kg\ \text{fuel} + i\ kg\ \text{oxidant} = (1+i)\ kg\ \text{products} \quad (24),$$

potem lahko delež zmesi *f* (reakcijska koordinata) za reakcijo definiramo kot [4]:

then the mixture fraction *f* for the reaction can be defined as[4]:

$$f = \frac{\chi - \chi_O}{\chi_F - \chi_O} \quad (25),$$

kjer je:

where:

$$\chi = \xi_F - \frac{\xi_O}{i} \quad (26)$$

in ξ je masni delež in indeksa *F* in *O* pomenita gorivo in oksidant. Tako sta χ_O in χ_F uporabljena v enačbi (25) enaka $\chi_O = -1/i$ in $\chi_F = 1$.

and ξ is the mass fraction and the indices *F* and *O* stand for the fuel and the oxidant. The χ_O and χ_F applied in equation (25) are $\chi_O = -1/i$ and $\chi_F = 1$.

Srednja vrednost deleža zmesi *f* je označena kot *F* in jo računamo z naslednjo obliko prenosne enačbe [4]:

The mean value of the mixture fraction *f* is designated with *F* and is computed with the following form of transport Equation [4]:

$$\frac{\partial}{\partial t}\rho F + \frac{\partial}{\partial x_j}(\rho \upsilon F) - \frac{\partial}{\partial x_j}\left(\left(\eta + \frac{\eta_t}{\mathrm{Pr}_t}\right)\frac{\partial F}{\partial x_j}\right) = 0 \quad (27),$$

kjer so ρ gostota tekočine, υ srednja hitrost tekočine, η in η_t sta molekularna in turbulentna viskoznost tekočine in Pr_t je ekvivalentno turbulentno Prandtlovo število.

where ρ is the fluid density, υ is the mean velocity of the fluid, η and η_t are the molecular and turbulent viscosities of the fluid and Pr_t is the equivalent turbulent Prandtl number.

Stopnja nastanka/porabe $\overline{\omega}_k$ komponente *k* v enačbi (19) se izračuna na podlagi deleža zmesi:

The formation/consumption rate $\overline{\omega}_k$ of the component *k* in Equation (19) is based on the mixture fraction:

$$\begin{aligned} &\text{če je/if } F > F_{ST}\text{, potem/then: } \xi_F = \frac{F - F_{ST}}{1 - F_{ST}},\ \xi_O = 0,\ \xi_P = 1 - \xi_F \\ &\text{če je/if } F < F_{ST}\text{, potem/then: } \xi_O = 1 - \frac{F}{F_{ST}},\ \xi_F = 0,\ \xi_P = 1 - \xi_O \end{aligned} \quad (28),$$

kjer je $F_{ST} = \frac{1}{1+i}$ (χ=0) in ξ_P označuje masni delež produktov zgorevanja.

where $F_{ST} = \frac{1}{1+i}$ (χ=0) and ξ_P designates the combustion products' mass fraction.

Ta model je pogosto uporabljen za modeliranje čistega difuzijskega plamena, za kar sta potrebna dva ločena vhodna tokova reaktantov. Pomanjkljivost modela je v enostopenjski neskončno hitri kemijski reakciji, kar onemogoča napovedovanje ostankov nepopolnega zgorevanja in vmesnih radikalov.

This model is frequently used for modelling a pure diffusion flame requiring two separate intakes of reactants. The deficiency of the model is in its one-step infinitely fast chemical reaction that prevents products of incomplete combustion and intermediate radical predictions.

3.2 Vrtinčni model (EBU)

Model zgorevanja EBU se uspešno uporablja za modeliranje odprtega plamena in modeliranja v industrijskih pečeh in zgorevalnih napravah [4] z različnimi gorivi.

Pri simulacijah z uporabo modela zgorevanja EBU se rešuje prenosna enačba za srednji delež zmesi in masni delež goriva. Masna deleža oksidanta in ostankov se izračunata z uporabo algebraičnih in ne diferencialnih enačb. Vsota vseh teh treh masnih deležev (gorivo, oksidant, ostanki) je v vsaki posamezni končni prostornini enaka ena. To omogoča sočasni obstoj goriva, oksidanta in produktov v zmesi, kar je blizu dejanskim razmeram zgorevanja v večjih kurilnih napravah s stalnim dovodom goriva.

Hitrost kemijske reakcije je sorazmerna:

3.2 Eddy Break-up Model (EBU)

The EBU combustion model is successfully applied for open-fire modelling and industrial-furnace and combustion-device modelling [4] for various fuels.

The transport equation for mean-mixture fraction and fuel-mass fraction is solved by applying the EBU combustion model. The mass fractions of the oxidant and the products are computed using algebraic equations instead of differential equations. The sum of all three mass fractions (fuel, oxidant and products) equals one in every single finite volume. This enables the simultaneous existence of fuel, oxidant and products in a mixture that is close to combustion conditions, in larger combustion devices with a continuous fuel supply.

The chemical reaction rate is proportional to:

$$\overline{R}_k \approx \frac{1}{t_t} \quad (29),$$

pri čemer je t_t odvisen od turbulentnega polja in pomeni dobo trajanja vrtinčka oziroma čas njegovega razpada:

where t_t depends on the turbulent field and represents the eddy lifetime or its decay time:

$$\frac{1}{t_t} = \frac{\varepsilon}{k} \tag{30},$$

kjer sta k turbulentna kinetična energija in ε njeno razsipanje. Hitrost kemijske reakcije je skladno s hipotezo tega modela tudi sorazmerna oscilacijam masnega deleža sestavin:

where k is the turbulent kinetic energy and ε its dissipation. According to the hypothesis of this model the chemical reaction rate is also proportional to the oscillations of the component mass fraction:

$$\overline{R}_k \approx \overline{\xi_k'^2} \tag{31}.$$

Nazadnje lahko zapišemo tudi formulacijo hitrosti kemijske reakcije [4]:

Finally, the formulation of the chemical reaction rate can be written as [4]:

$$\overline{R}_k = -C_{EBU}\rho\frac{\varepsilon}{k}\overline{\xi_k'^2} \tag{32}.$$

Stalnico C_{EBU} je treba skladno s priporočili in izkušnjami prilagoditi specifični simulaciji zgorevanja. V okviru naše raziskave je imela stalnica vrednost C_{EBU}=4.

Model je primeren le za simulacije, kjer ima mešanje oziroma tokovno dogajanje odločilno vlogo pri zgorevanju. Ne vključuje pa tudi členov, ki v tokovnem smislu pomenijo omejitve zgorevanja (npr. ugasnitev plamena, hladne cone, slabo mešanje). Model tudi ne omogoča napovedi koncentracij produktov nepopolnega zgorevanja.

The constant C_{EBU} needs to be adjusted for a specific combustion simulation, in accordance with recommendations and experience. In our investigation the constant value was C_{EBU}=4.

The model is convenient for simulations where mixing or flow conditions are crucial for combustion. It does not include terms limiting combustion in the case of flow disturbances (i.e., flame extinguishing, cold zones, improper mixing). Product concentrations of incomplete combustion cannot be predicted using this model.

3.3 Vrtinčno disipacijski model (EDC)

Model EDC temelji na predpostavki, da so kemijske reakcije hitrejše od difuzijskih pojavov v reaktivnem tokovnem polju. Ko se reaktanti premešajo na molekularnem nivoju, dobimo produkte zgorevanja. Pri turbulentnih tokovih je čas mešanja v glavnem odvisen od karakteristik vrtincev. Zato je hitrost reakcije sorazmerna času mešanja:

3.3. Eddy-Dissipation Model (EDC)

The EDC model is based on an assumption that chemical reactions are faster than diffusion processes in a reacting flow field. The products of combustion are produced when reactants are mixed at the molecular level. In turbulent flows the mixing time basically depends on the eddy's properties. The reaction velocity is, therefore, proportional to the mixing time:

$$\text{hitrost reakcije / reaction rate} \propto \frac{\varepsilon}{k} \tag{33}.$$

V modelu EDC je hitrost kemijske reakcije določena z manjšo vrednostjo naslednjih izrazov z upoštevanjem [4]:

- reaktantov:

$$\overline{R}_k = A\frac{\varepsilon}{k}\min\left(\frac{[X_k]}{\nu'_k}\right) \tag{34},$$

kjer je $[X_k]$ molska koncentracija komponente k in vključuje samo reaktante, A pa je stalnica modela, katere vrednost se razlikuje od primera do primera; v našem primeru je bila A=4;

- produktov:

The chemical reaction rate in the EDC model is determined by the lower value of the following expressions by considering [4]:

- reactants:

where $[X_k]$ is the molar concentration of component k, including only the components of the reactants, A is a constant and its value varies from case to case, and in this case it was A=4;

- products:

$$\overline{R}_k = AB\frac{\varepsilon}{k}\left(\frac{\sum_{k=1}^{P}[X_k]M_k}{\sum_{k=1}^{P}\nu''_k M_k}\right) \quad (35),$$

kjer P obsega vse sestavine produktov v elementarni reakciji (enačba 20), B pa je dodatna stalnica modela (v našem primeru B=-1). Pri večstopenjskih reakcijah (2 ali 5 reakcijskih stopenj) je v uporabi samo izraz (34).

Podobno kakor drugi modeli tudi ta vsebuje stalnice, ki jih je treba določiti na podlagi preizkusov in priporočil. Hitrost kemijske reakcije je odvisna od jakosti tokovnega polja ($f(k)$). Uporaba večstopenjske kinetike omogoča napoved koncentracij pomembnejših vmesnih produktov zgorevanja (radikalov) in koncentracij produktov nepopolnega zgorevanja.

where P includes all the components of the products in the elementary reaction (Equation 20) and B is an additional model constant (B =-1 for our application). Applying multi-step reactions (2 or 5 reaction steps) only expression (34) is in use.

Like others, this model includes constants that have to be determined based on experiments and recommendations. The chemical kinetic rate depends on the flow-field intensity ($f(k)$). The use of multi-step kinetics enables the prediction of important intermediate combustion products (radicals) and the concentrations of incomplete combustion products.

3.4 Model končne hitrosti kemijskih reakcij (FRC)

Model FRC predstavlja kinetični model zgorevanja, ki se večinoma uporablja za simulacijo laminarnega zgorevanja. Splošno je uporaben tudi za turbulentno zgorevanje v primeru reševanja NSE z neposrednim simuliranjem. V nekaterih primerih, ko nihanja temperatur niso prevelika, pa je uporaben tudi v primeru reševanja RPNS. Še posebno je uporaben v primeru sestavljenih modelov z reševanjem področij šibke turbulence reaktivnih tokov. Hitrost kemijske reakcije lahko zapišemo za nasprotujočo kemijsko reakcijo (20) na podlagi zakona o delovanju mas v naslednji obliki [4]:

3.4 Finite-Rate Chemistry Model (FRC)

The FRC model represents a kinetic combustion model applied mostly for a laminar combustion simulation. In the general case of turbulent combustion it is applicable for solving NSE by a direct simulation method. In specific circumstances when the temperature oscillations are not too high it can also be used in the case of RANS equations. It is especially applicable for the case of combined models solving low turbulence issues regarding reacting flows. The chemical reaction rate can be written for the opposite chemical reaction (20) based on the law of mass interaction in the following form [4]:

$$\overline{R}_k = k_f \prod_{k=1.}^{N}[X_k]^{\nu'_k} - k_b \prod_{k=1}^{N}[X_k]^{\nu''_k} \quad (36),$$

kjer je $[X_k]$ molska koncentracija komponente k, k_f in k_b pa stalnici hitrosti kemijskih reakcij (naprej in nazaj), ki jih izračunamo z Arheniusovo enačbo:

where $[X_k]$ is the molar concentration of component k, k_f and k_b are chemical reaction rate constants (forward and backward) computed by the Arrhenius equation:

$$k_{f,b} = A_k T^{\beta_k} \exp\left(-\frac{E_k}{R_m T}\right) \quad (37),$$

kjer so:
A_k ..... predeksponencialni faktor,
β_k ..... temperaturni eksponent (brezrazsežni),
E_k ..... energija aktiviranja,
T ..... temperatura,
R_m ..... splošna plinska stalnica.

Vrednosti koeficientov A_k, β_k in E_k so podane v preglednicah [2], [3] in [11] za različne tipe kemijske reakcije v smeri naprej in nazaj.

where:
A_k ..... pre-exponential factor,
β_k ..... temperature exponent (dimensionless),
E_k ..... activation energy,
T ..... temperature,
R_m ..... general gas constant.

The values of the coefficients A_k, β_k and E_k are listed in Tables [2], [3] and [11], for different types of chemical reactions for forward and backward rates, separately.

Model FRC je uporaben predvsem za področja reaktivnega toka, kjer ima kemijska kinetika zgorevanja prevladujoč vpliv v primerjavi s turbulentnim mešanjem. S tega vidika za celotno področje reaktivnega toka model samostojno ni uporaben, ampak skupaj z nekaterimi drugimi modeli, običajno EDC.

3.5 Sestavljeni model (COMBINED)

V okviru programa CFX prestavlja model COMBINED sestavo modelov EDC in FRC. V primeru uporabe tega modela se ločeno računajo reakcijske hitrosti po obeh modelih. V modelu EDC je hitrost kemijske reakcije povezana s turbulenco in v primeru šibke turbulence bo vrednost reakcijske hitrosti velika zaradi majhne vrednosti turbulentne kinetične energije (enačbi (34) in (35)), medtem ko bo vrednost reakcijske hitrosti po modelu FRC manjša. V primeru močne turbulence so razmere nasprotne, zato za nadaljnji izračun uporabimo manjšo vrednost reakcijske hitrosti, izračunane z obema modeloma, kar bolje opisuje dejanske razmere. Enak postopek se odvija v vsakem računskem koraku. Tako je lahko v prvem koraku zgorevanje omejeno s kemijsko kinetiko, v drugem pa s turbulentnim mešanjem na istem kraju.

Model je uporaben za različne tipe turbulentnega reaktivnega toka s širokim območjem Damköhlerjevih števil, ki podaja razmerje med hitrostjo kemijske kinetike in jakostjo turbulence. Pomanjkljivost modela je daljši čas računanja, ki je potreben zaradi dvojnega računanja izvornih členov z različnima modeloma zgorevanja.

4 ROBNI POGOJI IN NUMERIČNI MODEL

Robne pogoje termoreaktorja (sl. 2) smo določili na podlagi dejanskih obratovalnih razmer v pilotni sežigalni napravi:

- hitrost plinov iz primarne komore: 0,25 m/s (≈ 30 m^3/h),
- temperatura plinov iz primarne komore: 700 °C,
- hitrost zraka skozi sekundarne dovode: 6 m/s pri 60 % skupne dovedene količine zraka,
- hitrost zraka skozi terciarne dovode: 4 m/s pri 40 % skupne dovedene količine zraka,
- temperatura dovedenega zraka: temperatura okolice sežigalnice (≈ 25 °C),
- smer dovedenega zraka za vsak dovod posebej po načrtu sežigalnice

The FRC model is primarily applicable for reacting flow where combustible chemical kinetics holds a dominant role compared to turbulent mixing. The model is inapplicable itself for a complete range of turbulent reacting flows so it is usually in combination with other models, mostly with the EDC model.

3.5 Combined Model (COMBINED)

The COMBINED model in CFX is composed of the EDC and FRC models. In the application of this model the reaction rates are calculated separately with both models. In the EDC model the reaction rate is linked to turbulence and, in the case of low turbulence, the reaction rate is high due to the low turbulent kinetic energy (Equations (34) and (35)), while the value of the FRC model is lower. In the case of higher turbulence intensity, the conditions are inversed and for further calculation the lower value of both models is used, reflecting the real physical circumstances better. The same procedure is considered at every calculation step. Therefore, the first step can be limited by chemical kinetics and the second step by turbulent mixing at the same place.

This model seems to be applicable for various types of turbulent reacting flows with a wide range of Damköhler numbers that define the relationship between the chemical reaction rate and the turbulence intensity. The model's weakness is a longer computational time because of the double computation of source terms with different combustion models.

4 BOUNDARY CONDITIONS AND NUMERICAL MODEL

The real operating parameters of the pilot-scale incinerator were considered for prescribing the corresponding boundary conditions of the thermoreactor (Figure 2):

- velocity of volatile gases from the primary chamber: 0.25 m/s (≈ 30 m^3/h),
- temperature of volatile gases from the primary chamber: 700°C,
- velocity of air through the secondary air inlets: 6 m/s at 60 % of total air inflow,
- velocity of air through the tertiary air inlets: 4 m/s at 40% of total air inflow,
- temperature of added air: incinerator surrounding temperature (≈ 25°C),
- air directions for every single inlet, based on the blueprint;

Preglednica 1: *Prostorninska sestava plinov na vstopu v termoreaktor*
Table 1: *Volume gas composition at the thermoreactor inlet*

Komponenta / Component	CO	CH_4	CO_2	H_2O	N_2
Pros. vrednost [%] / [%] by vol.	14	50	4	3	29

in jih ohranili nespremenjene ves čas izbire modela zgorevanja.

Preizkus smo izvedli z industrijskim gorivom, proizvedenim iz komunalnih odpadkov (GTO-SRF). Sestava plinov na vstopu v termoreaktor je podana v preglednici 1.

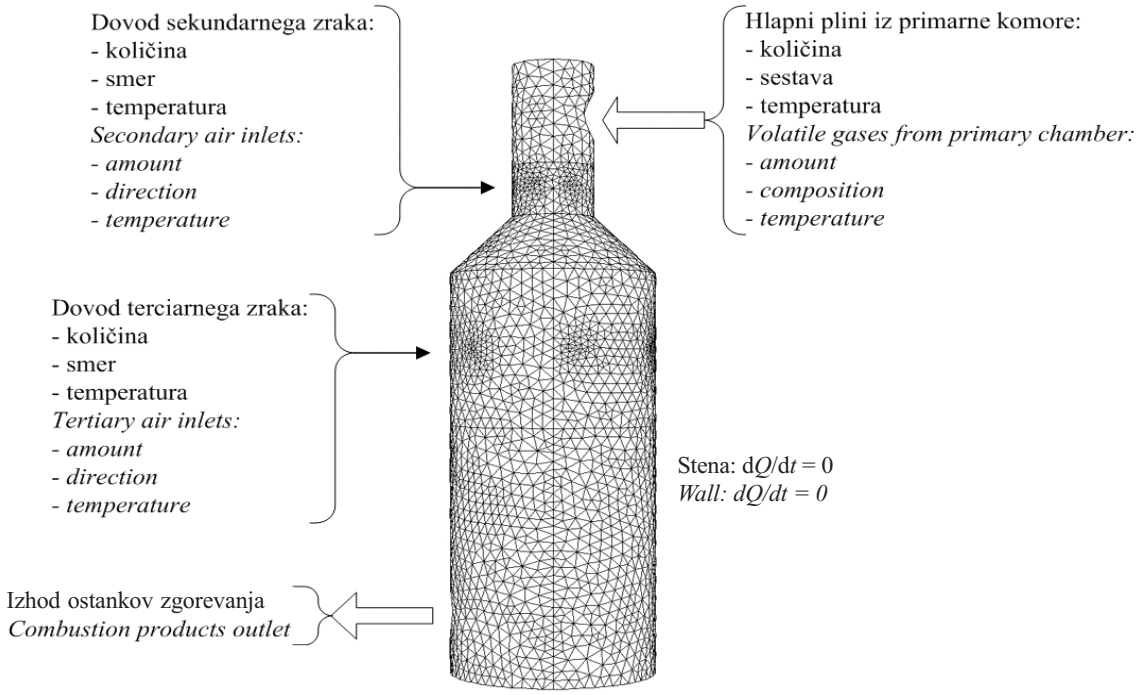
Da bi ugotovili relativni vpliv posameznega obratovalnega parametra na doseganje pogojev popolnega zgorevanja, smo za izračune z izbranim modelom zgorevanja kasneje spremenili mnogo robnih pogojev (npr. količino plina in njegovo sestavo, kurilno vrednost, vstopne hitrosti in količine zraka).

Za izdelavo diskretnega modela in zamrežitve geometrijske oblike termoreaktorja smo uporabili dva programska paketa. Programski paket CFX 4.4, ki vsebuje modela zgorevanja MIB in EBU, omogoča izdelavo le strukturirane zamrežitve. Programski paket CFX 5.7, ki vsebuje preostale modele zgorevanja (EDC, FRC in COMBINED), pa keeping them unchanged during the combustion model selection.

The experiment was conducted on industrial fuel produced from municipal solid-waste (SRF-solid-recovered fuel). The composition of the gas entering the thermoreactor is shown in Table 1.

In order to find the relative influence of the operating parameters on achieving complete combustion conditions, many of the boundary conditions (i.e., amount and composition of the gas, calorific value, air inlet velocities and quantities) changed for the calculations to be done later by the selected combustion model.

The geometry modelling and its meshing were performed using two program packages. The CFX 4.4 program package, involving the MIB and EBU combustion models, enables structured meshing only. The CFX 5.7 program package, which includes other combustion models (EDC, FRC and COMBINED), also enables unstructured meshing of



Sl. 2. *Robni pogoji in zamrežitev termoreaktorja*
Fig. 2. *Thermoreactor boundary conditions and meshing*

omogoča tudi nestrukturirano zamreževanje geometrijske oblike. Test gostote strukturirane mreže je pokazal, da mreže, ki so bolj grobe od 275.674 končnih prostornin, izračunajo rezultate, ki niso dovolj natančni v primerjavi z izmerjenimi vrednostmi (temperatura in sestava dimnih plinov). Bolj gosta zamrežitev pa omogoča praktično enako natančen rezultat kakor z 275.674 končnimi prostorninami, pri čemer se je za izračun porabilo veliko več računskega časa. To število končnih prostornin je omogočilo dobro natančnost in veliko hitrost izračuna in je bilo osnova za nadaljnje delo. Enak test gostote zamrežitve geometrijske oblike je bil ponovljen za nestrukturirano zamrežitev in zamrežitev s 123.273 končnimi prostorninami (sl. 2) je bila izbrana za nadaljnje delo. Za izbiro primernega modela zgorevanja smo uporabili oba programska paketa CFX.

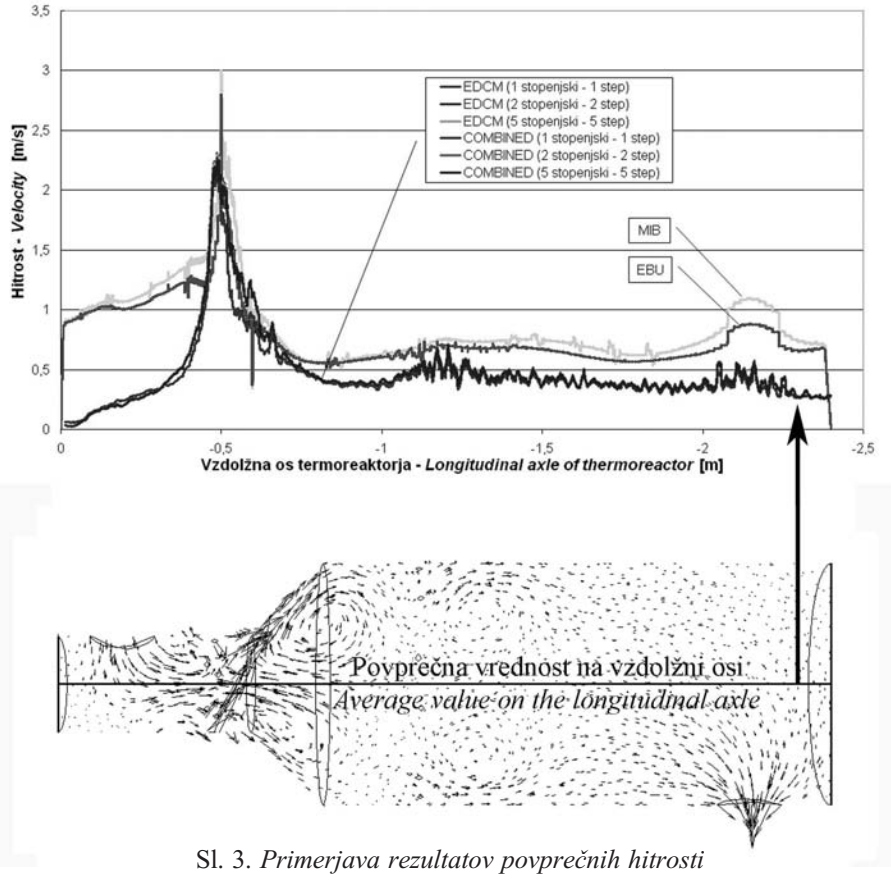
5 IZBIRA MODELA ZGOREVANJA

Opravili smo kakovostno analizo in primerjavo rezultatov, dobljenih z različnimi modeli zgorevanja. Model FRC je bil preizkušen v kombinaciji

the geometry. The mesh dependency testing of the structured geometry meshing showed that meshes coarser than 275,674 finite volumes did not produce results that were accurate enough, compared with the measured ones (i.e., temperature and flue-gas composition). Denser meshes produced results practically the same compared to the 275,674 finite volumes but took up much more computational time. This number of structured finite volumes offered good accuracy and high computational speed, and it was the basis for further work. The same mesh-dependency testing was repeated for unstructured mesh, and the meshing with 123,273 finite volumes (Figure 2) was chosen for further work. Both CFX program packages have been used to select the appropriate combustion model.

5 COMBUSTION MODEL SELECTION

Qualitative analyses and a results comparison obtained using different combustion models were performed. The FRC model was tested in combination



Sl. 3. *Primerjava rezultatov povprečnih hitrosti*
Fig. 3. *Average velocity results comparison*

z modelom EDC (model COMBINED). Zgorevalna modela EBU in MIB sta bila preizkušena z uporabo programskega paketa CFX 4.4. Zaradi velikega števila izračunanih rezultatov, ki so posledica izbranih mrež, smo se pri analizi omejili na vzdolžno sredinsko ravnino termoreaktorja. Vse izračunane vrednosti reaktivnega tokovnega polja v tej ravnini smo povprečili na določeni višini termoreaktorja, da bi lahko nato primerjali vse rezultate ne glede na gostoto in obliko zamrežitve (strukturirana, nestrukturirana) v enem grafu.

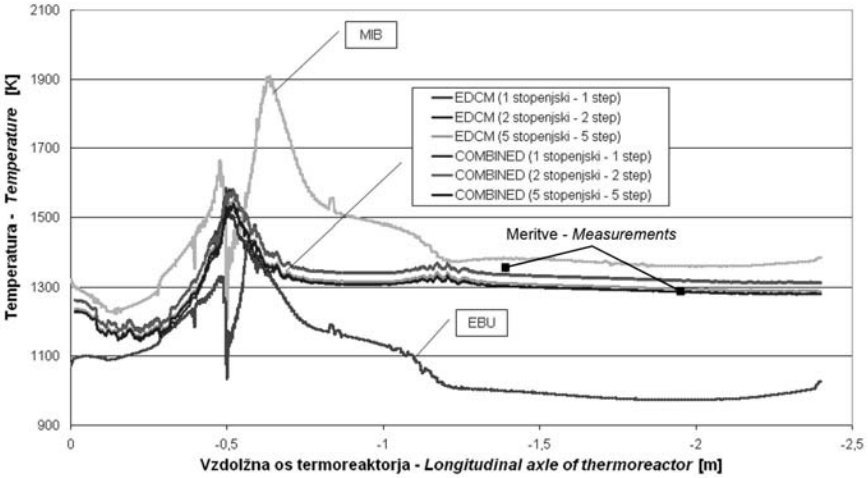
Slika 3 prikazuje primerjavo povprečnih hitrosti vzdolž termoreaktorja, kjer so razvidne očitne razlike med rezultati različnih modelov zgorevanja. Razlik med rezultati modelov EDC in COMBINED praktično ni. Prav tako ni razlik rezultatov pri uporabi enostopenjskih in večstopenjskih modelov. Na sliki 3 je dobro viden vpliv dovoda sekundarnega in terciarnega zraka.

Na sliki 4 je podana primerjava temperatur, izračunanih z različnimi modeli zgorevanja. Z modeloma zgorevanja EDC in COMBINED smo izračunali temperature, katerih vrednosti so v območju med vrednostmi, dobljenimi z modeloma zgorevanja MIB in EBU. Modela EDC in COMBINED izračunata povprečne temperature v termoreaktorju okrog 1300 K. To se ujema s povprečno obratovalno temperaturo v termoreaktorju ob pogojih obratovanja, ki so enaki robnim pogojem pri numeričnem izračunu in po naših meritvah znašajo okrog 1273 K (sl. 5). Ugotovili smo, da različno število stopenj kemijskih reakcij posameznega modela izračuna praktično enake temperature, kar pomeni,

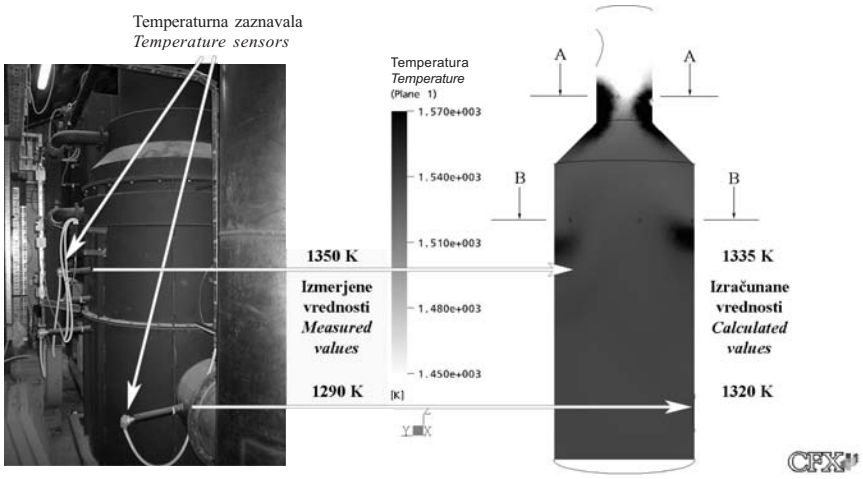
with the EDC model (COMBINED model). The EBU and MIB combustion models were compared applying the CFX 4.4 program package. The analyses were reduced to the longitudinal middle plane of the thermoreactor because of the large number of results produced by the selected meshes. All the computed results of the reacting flow field at this plane were averaged on the single height of the thermoreactor, in order to compare all the results in one graph, regardless of mesh thickness and type (structured, unstructured).

Figure 3 presents a comparison of the average velocities alongside the thermoreactor, showing great differences in the results obtained by different combustion models. However, there are almost no differences between the EDC model and the COMBINED combustion model. There are also no differences between the various single or multi-step reaction models. The secondary and tertiary air inlets and their influences are clearly seen in Figure 3.

Figure 4 shows the temperature values, computed using various combustion models. The temperature results obtained by the EDC and COMBINED combustion models are in a range between the values of the MIB and EBU combustion models. The average temperature values computed by the EDC and the COMBINED combustion models in the thermoreactor are around 1300 K. This is consistent with the measured average values of temperature in the thermoreactor (Figure 5) under operating conditions equivalent to the prescribed boundary conditions applied in the numerical calculations. It was found that single and multi-step chemical reaction models produced practically the same temperature



Sl. 4. *Primerjava rezultatov povprečnih temperatur*
Fig. 4. *Average temperature results comparison*



Sl. 5. *Temperaturna tipala na pilotni sežigalnici in rezultati simulacije*
Fig. 5. *The positions of temperature sensors in the thermoreactor, and the comparison of temperature values*

da dodajanje reakcijskih stopenj ne vpliva bistveno na kakovost rezultatov temperaturnega in tokovnega polja. To pomeni, da je za izračun temperaturnega polja popolnoma zadovoljivo uporabiti enostopenjski model, s čimer prihranimo nekaj računskega časa.

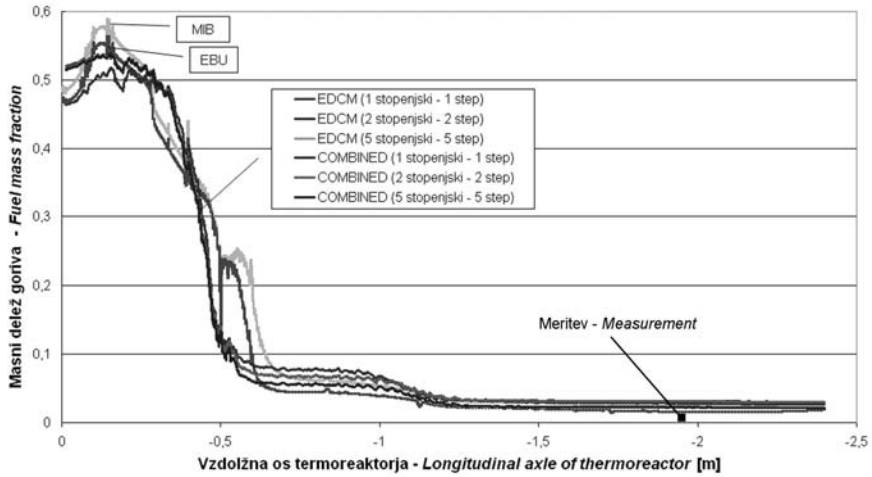
Slika 6 prikazuje vrednosti masnega deleža goriva vzdolž termoreaktorja. Vidimo lahko, da so si rezultati vseh modelov precej podobni. Menimo, da je to posledica majhnih koncentracij produktov nepopolnega zgorevanja, ki tako samo neznatno vplivajo na izračunani masni delež goriva v postopku zgorevanja.

Glavna prednost večstopenjskih modelov se izkaže v primeru izračuna nekaterih produktov nepopolnega zgorevanja, kar je prikazano na sliki 7,

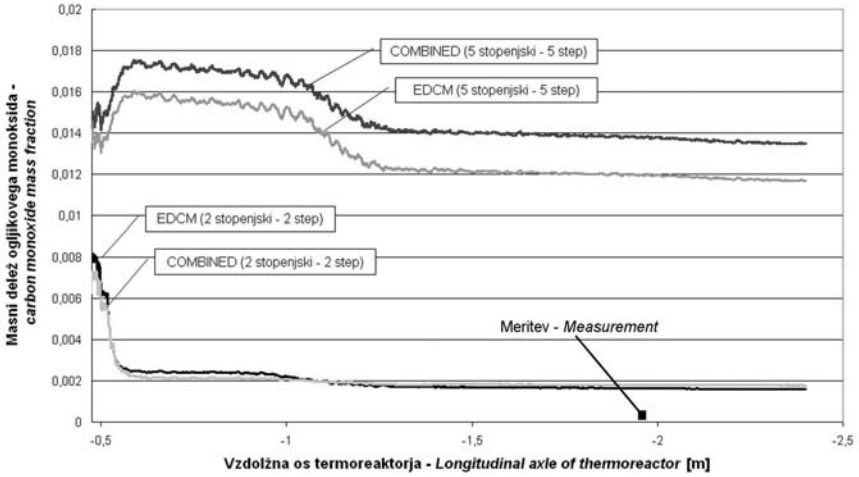
results, meaning that the additional reaction steps do not significantly influence the qualities of the temperature and flow-field results. It means that for the temperature-field calculation, it is sufficient to use single-step models, thus also saving computational time.

Figure 6 shows the values for the fuel mass-fraction along the thermoreactor. It can be seen that the results are quite similar for all the models. It seems to be the consequence of low concentrations of incomplete combustion products insignificantly influencing the computed fuel mass-flow fraction during the combustion process.

The computation ability of the incomplete combustion products' concentrations presents the key advantage of multi-step models, which can be



Sl. 6. *Primerjava rezultatov povprečnega masnega deleža goriva*
Fig. 6. *Average fuel mass-fraction results comparison*



Sl. 7. *Primerjava rezultatov masnega dele□a ogljikovega monoksida*
Fig. 7. *Carbon monoxide mass fraction results comparison*

kjer so predstavljene izračunane koncentracije ogljikovega monoksida.

Rezultati kažejo razliko med dvo- in petstopenjskima modeloma, ne kažejo pa razlike med obema modeloma zgorevanja. Petstopenjski model naj bi izračunal vrednosti bližje izmerjenim povprečnim vrednostim (slika 7) vendar so le-te razmeroma večje od rezultatov, dobljenih z dvostopenjskim modelom. Razlika je verjetno posledica nepravilnega kemijskega mehanizma večstopenjskih modelov glede na specifično sestavo plina na vhodu v termoreaktor z velikim deležem ogljikovega monoksida.

Modele zgorevanja smo ocenili na podlagi primerjave izračunanih in izmerjenih vrednosti temperature in sestave glavnih komponent plina v termoreaktorju. Meritve temperature je bilo mogoče izvesti le v dveh točkah zaradi omejenih možnosti merilnih mest (sl. 5), medtem ko smo sestavo plina merili samo na izhodu iz termoreaktorja. Dodaten kriterij za izbiro modela zgorevanja je bila numerična stabilnost modelov zgorevanja oziroma hitrost konvergence. V teh razmerah se je model EDC izkazal kot najprimernejši za izbrano uporabo. Večstopenjski modeli, vključeni v nekatere modele, omogočajo izračun produktov nepopolnega zgorevanja, na primer ogljikovega monoksida. Zaradi majhnih koncentracij ogljikovega monoksida pa nima pomembnega vpliva na makroparametre zgorevanja. V nadaljnji numerični analizi smo obravnavali in analizirali samo pogoje popolnega zgorevanja (temperatura, turbulenca, čas – 3T parametri) pri različnih obratovalnih pogojih pilotne sežigalnice.

clearly seen in Figure 7 where the calculated carbon monoxide concentrations are presented.

The results demonstrate differences between the two- and five-step models but there is almost no difference between both combustion models. The five-step models should produce results closer to the measured average value (Figure 7), but they are relatively higher than those results obtained by two-step models. The difference seems to be due to the improper kinetic mechanism of the higher-step models regarding the specific gas composition at the thermoreactor inlet, with a high carbon-monoxide fraction.

The combustion models were assessed based on a comparison of the computed and measured values of the temperatures, and the main gas composition in the thermoreactor. However, measurement of the temperature was possible at two points only, because of the limited possibilities regarding measurement locations (Figure 5), while the gas composition was tested at the outlet of the thermoreactor only. An additional criterion regarding the selection of the combustion model was the numerical stability of the combustion models when mainly considering the convergence speed. In these criteria, the EDC model was found to be the most useful for the presented application. The multi-step models included in some models enabled the computation of incomplete combustion products' concentrations, such as carbon monoxide. However, due to its low concentration, it does not significantly influence the combustion macro parameters. In further numerical simulations, just the complete combustion conditions (temperature, turbulence, time – 3T parameters), were considered, and analyzed under different operating conditions for the pilot-scale incinerator.

6 ANALIZA OBRATOVALNIH POGOJEV SEŽIGALNICE

Pri dejanskih pogojih obratovanja sežigalnice se količina, sestava in vzročno kurilna vrednost plinov na vstopu v termoreaktor spreminjajo, kar je posledica spremenljive strukture odpadkov v primarni komori. Različno količino plinov smo, če upoštevamo kontinuitetno enačbo, simulirali s spreminjanjem vstopne hitrosti plinov. Kurilno vrednost plinov smo simulirali s spreminjanjem sestave mešanice metana in dušika. Preverili smo tudi, kako količina, mesto in smer dovajanja sekundarnega in terciarnega zraka vplivajo na dosego 3T parametrov. Vsi nadaljnji izračuni so bili opravljeni z izbranim modelom EDC.

6.1 Spreminjanje kurilne vrednosti plina iz primarne komore

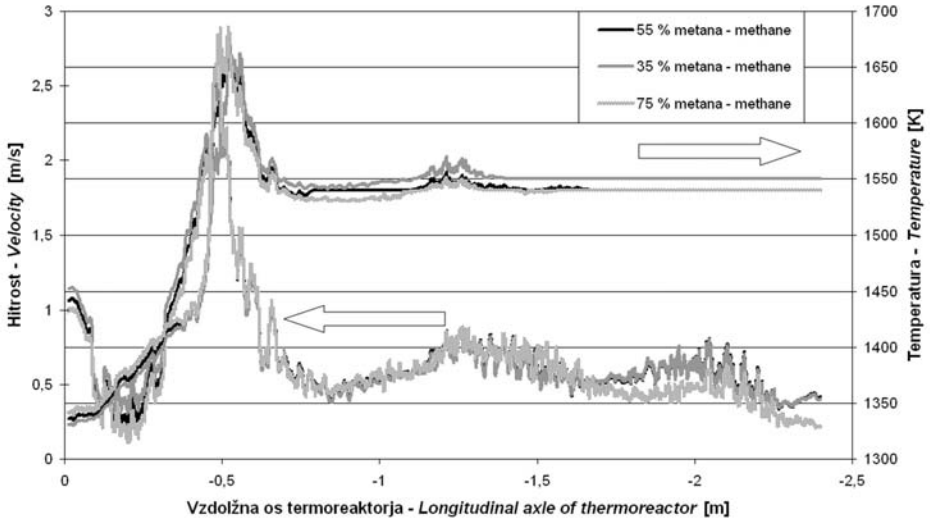
Splošno gledano kurilna vrednost hlapnih plinov močno vpliva na temperaturo v sekundarni komori. Spremembo kurilne vrednosti plinov iz primarne komore smo simulirali z različno količino metana (35%, 55% in 75%), medtem ko so vrednosti preostalih robnih pogojev ostale nespremenjene. Opazili smo samo manj pomembne spremembe. To pomeni, da sprememba kurilne vrednosti ne vpliva pomembno na tokovno polje, če ostane količina zraka stalna. To je razlog, da povečan delež metana ni povzročil

6 ANALYSIS OF THE INCINERATOR'S OPERATING CONDITIONS

Under real operating conditions of the incinerator the amount, composition and, consequently, heating value of the gas entering the thermoreactor always varies because of the waste structure differences in the primary chamber. The gas amount differences were simulated by changing the intake gas velocity, by considering the equation of continuity. The heating value of the gas with a different composition was simulated with the corresponding methane/nitrogen mixture. Additionally, the secondary and tertiary air amounts, their intake positions and the directions into thermoreactor were examined in terms of how they influenced the achievement of the 3T parameters. All further calculations were performed by the selected EDC model.

6.1 Variation in the Primary-Chamber Gas Heating Value

In general, the volatile gases' heating value strongly influences the temperature in the secondary chamber. The primary-chamber gas heating value variation was simulated with various amount of methane (35%, 55% and 75%), while other boundary-condition values remained unchanged. The velocity field structure for all three tested cases (Figure 8) is almost the same. Only differences of minor importance were noticed. In turn, this means that the heating value variation does not essentially influence the flow field, if the amount of combustion air stays constant. For this rea-



Sl. 8. *Vpliv spreminjanja kurilne vrednosti na tokovno in temperaturno polje*
Fig. 8. *Influence of calorific value on the velocity and temperature*

pričakovanega zvišanja temperature v termoreaktorju. Da bi se izognili temu problemu v praksi, je treba izvesti krmiljenje zraka za zgorevanje glede na kurilno vrednost kot podporo običajnem krmiljenju sežigalnic, ki temelji na količini kisika v dimnih plinih, da se zagotovi stalno razmerje zrak/gorivo.

Količino nastalega ogljikovega dioksida za posamezen primer zmesi prikazuje slika 9. Imamo praktično enake vrednosti koncentracije ogljikovega dioksida, dobljene z zgorevanjem hlapnih plinov z različno kurilno vrednostjo. To se ujema z ugotovitvami na temelju rezultatov hitrosti in temperature. V takšnih primerih se zveča koncentracija nezgorelega metana na izstopu iz termoreaktorja (sl. 9). Slednje kaže na nepopolno zgorevanje v termoreaktorju zaradi primanjkljaja zraka za zgorevanje.

6.2 Spreminjanje količine plinov iz primarne komore

Spremenljiva količina plinov iz primarne komore ima poleg drugega vpliv tudi na čas zadrževanja plinov v zgorevalnem prostoru. Razmere smo simulirali s spremenljivo hitrostjo dotoka plinov v termoreaktor, kar ima neposredni vpliv na stopnjo masnega pretoka prek kontinuitetne enačbe: 0,25 m/s (30 m^3/h), 0,38 m/s (45 m^3/h) in 0,5 m/s (60 m^3/h).

S povečanim dovodom plinov pri stalnem masnem deležu metana (55%) iz primarne komore vstopi v termoreaktor tudi večja količina metana.

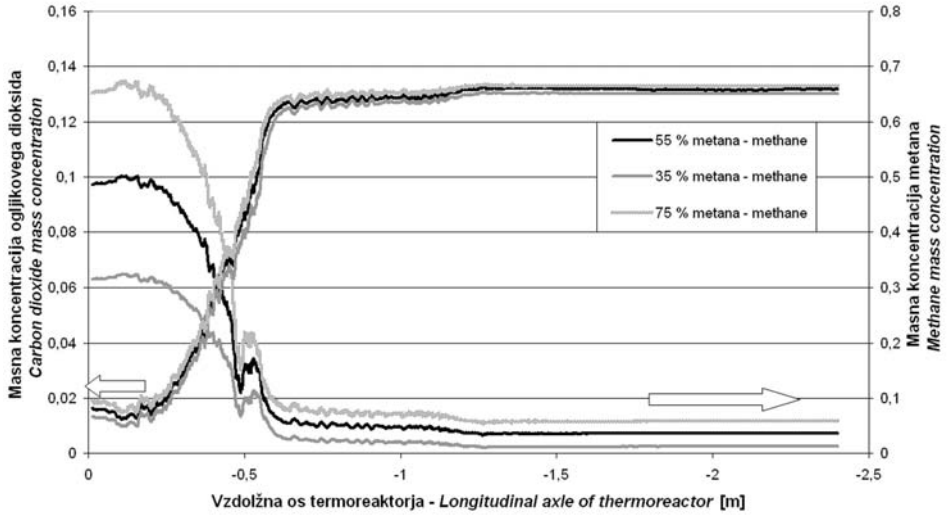
son, a higher methane fraction does not produce the expected temperature rise in the thermoreactor. In order to avoid this problem in practice the combustion air control regarding the gas heating value must be performed to ensure a constant air/fuel ratio as a support to the conventional control of the incinerator based on the oxygen concentration in the flue gases.

The amount of carbon dioxide produced for particular mixtures is shown in Figure 9. There are practically the same values of carbon dioxide concentration produced by the combustion of volatile gases with different calorific values. This is consistent with conclusions made from the velocity and temperature computation results. In such a case the concentrations of unburned methane rise at the thermoreactor exit (Fig. 9). This indicates that undesired, incomplete combustion is present in the thermoreactor because of a shortage of combustion air.

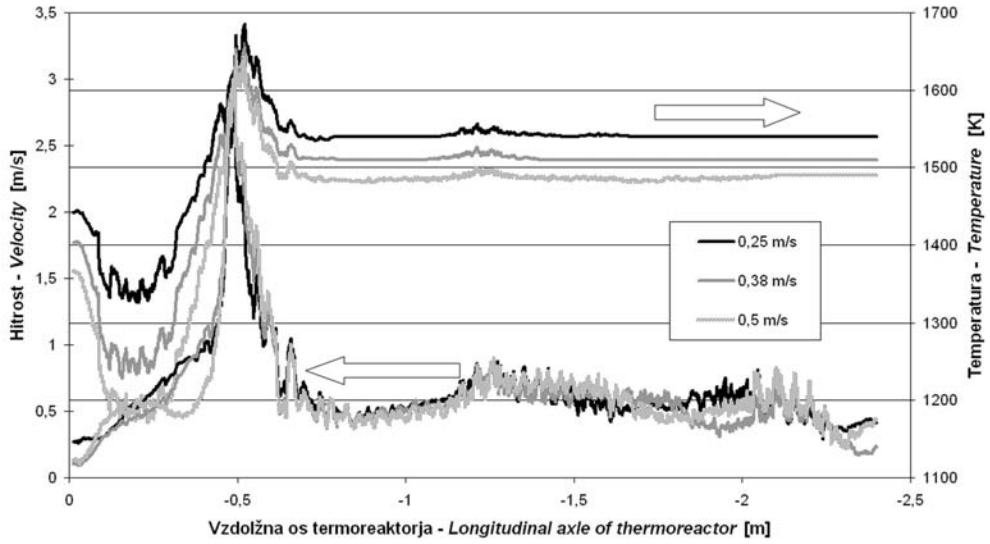
6.2 Primary-Chamber Gas Amount Variation

The gas quantity, in addition to other factors, strongly influences the residence time of the gases in the combustion chamber. The conditions were simulated by changing the intake-gas velocity into the thermoreactor influencing directly on the gas mass-flow rate via the equation of continuity: 0.25 m/s (30 m^3/h), 0.38 m/s (45 m^3/h) and 0.5 m/s (60 m^3/h).

More methane enters into the thermoreactor by increasing the gas amount to a constant methane mass fraction (55%) from the primary chamber. It does



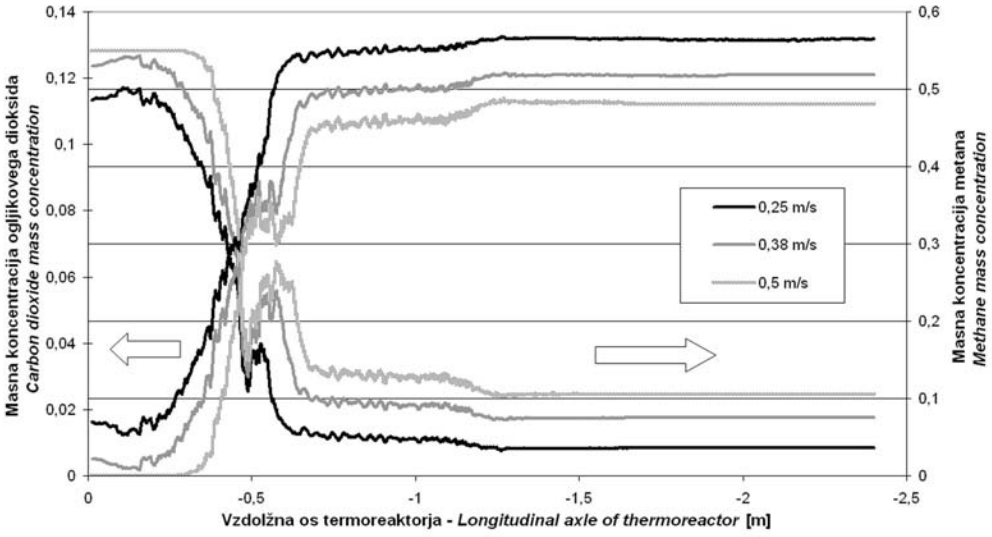
Sl. 9. *Vpliv spreminjanja kurilne vrednosti na porabo metana in nastanek CO_2*
Fig. 9. Calorific-value influencing methane consumption and CO_2 formation



Sl. 10. *Vpliv količine plinov iz primarne komore na temperaturo in hitrostno polje*
Fig. 10. *Primary-chamber gas amounts influencing temperature and flow field*

To pa ne povzroči povečanja največje ali povprečne temperature, temveč jo celo zniža (sl. 10). Povečanje količine hlapnih plinov je povečalo nekatere lokalne hitrosti v termoreaktorju, medtem ko so se povprečne hitrosti vzdolž termoreaktorja le malo spremenile, kar lahko vidimo na sliki 10. To je posledica zmanjšanja zadrževalnega časa zaradi povečane količine plinov in zato nepopolnega zgorevanja v termoreaktorju. Tako se zvečuje delež metana v dimnih plinih in manjša količina ogljikovega dioksida, kakor je prikazano na sliki 11. V praksi moramo s tega zornega kota za

not produce any rise in maximum temperature, or in the average temperature, and even lowers it (Figure 10). The increase of volatile gas amount increased some local velocities in the thermoreactor, while the average velocities along the thermoreactor were only slightly changed, as can be seen form Figure 10. This is a result of a shorter residence time caused by the amount of gas increase and, consequently, incomplete combustion in the thermoreactor. In turn, this increases the amount of methane in the flue gases and the amount of carbon dioxide falls, as demonstrated in Figure 11. This explains the practical experience of maintaining a con-



Sl. 11. *Vpliv količine plinov iz primarne komore na porabo metana in nastanek CO_2*
Fig. 11. *Primary chamber gas amount influencing fuel consumption and CO_2 production*

doseganje pogojev popolnega zgorevanja ohranjati stalno količino hlapnih plinov iz primarne komore. Sicer je treba meriti količino plinov na vstopu v termoreaktor in jih povezati s krmiljenjem zraka za zgorevanje.

6.3 Sprememba smeri in hitrosti dovajanja zraka

Z načinom dovoda in razmerjem sekundarnega in terciarnega zraka lahko pomembno vplivamo na kakovost zgorevanja. S spremembo lege dovodov zraka glede na projektirano stanje smo spreminjali smer in hitrost dovoda zraka. Slika 12 prikazuje mesto dovodov sekundarnega in terciarnega zraka s tlorisa termoreaktorja (prerez A-A in prerez B-B glede na sliko 5). Namen analize je bil ugotoviti učinkovitost projektne rešitve pilotne sežigalnice. Spremenjene hitrosti in smeri dovoda sekundarnega in terciarnega zraka so podane v preglednici 2.

Analizirali smo vpliv spremenjenih smeri in hitrosti dovajanja sekundarnega in terciarnega zraka na temperaturo in kakovost zgorevanja. S slike 13 je razvidno, da se dosežejo najvišje temperature vzdolž celotnega termoreaktorja s projektiranimi vrednostmi dovoda zraka, kar potrjuje projektno rešitev.

Enake ugotovitve lahko vidimo tudi na sliki 14, ki prikazuje vrednost koncentracij ogljikovega dioksida. Skoraj enake rezultate, kakor so projektirani, smo dobili s spremembo razmerja med sekundarnim in terciarnim zrakom, pri čemer je ostala skupna količina zraka stalna.

Po predstavljenih analizah obratovalnih pogojev pilotne sežigalnice lahko ugotovimo, da ima na popolnost zgorevanja največji vpliv predvsem primerna smer dovajanja sekundarnega in terciarnega zraka v termoreaktor, medtem ko njuno razmerje ni tako pomembno. Vendar pa lahko razmerje med sekundarnim in terciarnim zrakom vpliva na

stant volatile gas amount from the primary chamber to establish complete combustion conditions from this point of view. Otherwise, the measurement of gas quantity at the thermoreactor intake should be performed and linked with the combustion air control.

6.3 Air Inlet Directions and Velocity Variation

The intake path and ratio of secondary and tertiary air can significantly influence the combustion quality. The air direction and velocity values were altered by changing the air-inlet position with respect to the projected state. Figure 12 represents the positions of the secondary and tertiary air intakes from the top side of the thermoreactor (cut A-A and cut B-B in Figure 5). The aim of this analysis was to find the efficiency of the pilot-scale incinerator air-intake projecting solution. The variation of velocity and direction of the secondary and tertiary air is listed in Table 2.

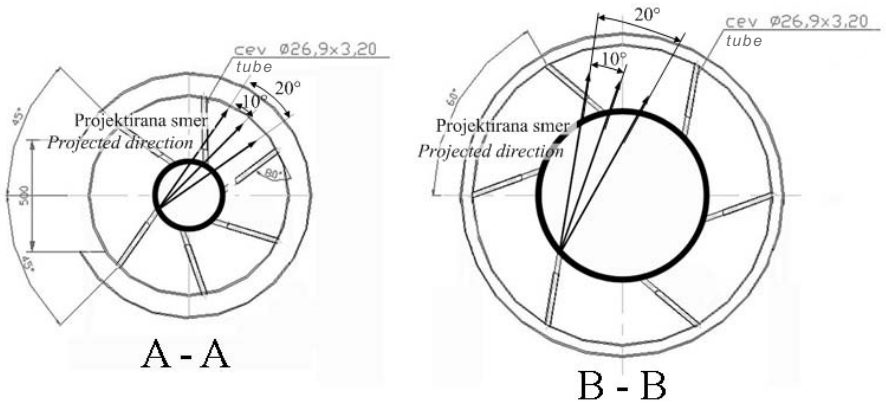
The influence of various directions and velocities of secondary and tertiary air inlets on the temperature and combustion quality was analyzed. Figure 13 shows that the highest temperatures along the whole thermoreactor were produced with the projected values of air intakes confirming the projected solution as correct.

The same findings can be seen in Figure 14, showing carbon dioxide concentration values. Similar results to the projected solution were obtained by varying the ratio of secondary and tertiary air, keeping the total amount of air constant.

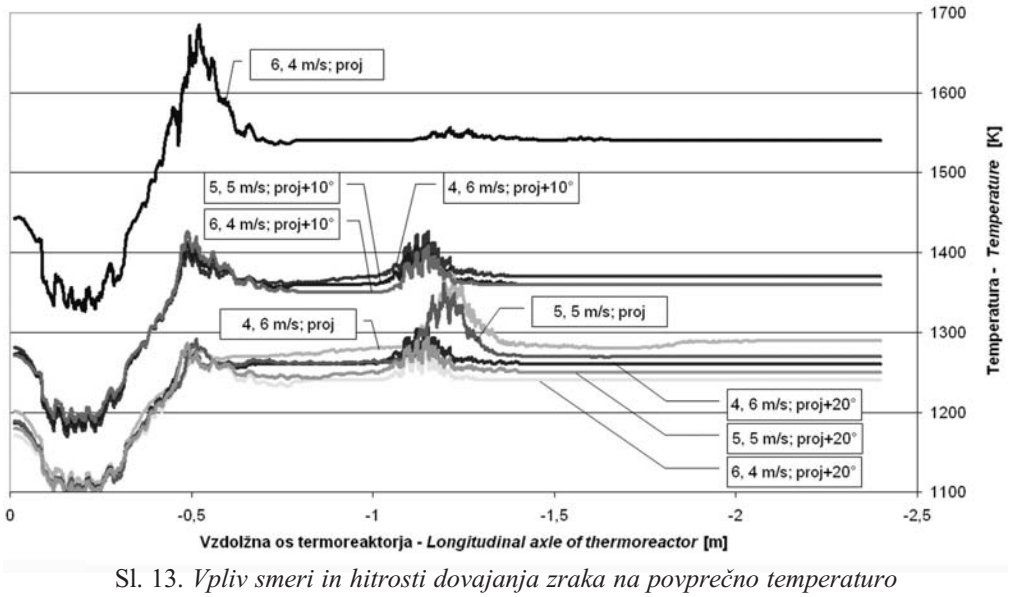
Based on the presented analysis of the pilot-scale incinerator's operating conditions, it can be concluded that the most significant influence on the complete combustion conditions is the appropriate direction of the secondary and tertiary air into the thermoreactor, while their ratio is not as important. However, the secondary/tertiary air ratio can

Preglednica 2. *Projektirane in spremenjene hitrosti in smeri zraka*
Table 2. *Projected and changed air-inlet velocities and directions*

Veličina Quantity	Dovod sekundarnega zraka Secondary air inlets	Dovod terciarnega zraka Tertiary air inlets
hitrost velocity	projektirana = 6 m/s projected = 6 m/s	projektirana = 4 m/s projected = 4 m/s
	4 m/s	6 m/s
	5 m/s	5 m/s
smer direction	projektirana (proj) projected (proj)	projektirana (proj) projected (proj)
	proj + 10^o	proj + 10^o
	proj + 20^o	proj + 20^o



Sl. 12. *Projektirane in spremenjene smeri dovoda sekundarnega in terciarnega zraka*
Fig. 12. *Projected and altered directions of secondary and tertiary air inlets*



Sl. 13. *Vpliv smeri in hitrosti dovajanja zraka na povprečno temperaturo*
Fig. 13. *Air-intake direction and velocity influence on average temperature*

pogoje nastanka določenih onesnaževal, kakor so na primer dušikovi oksidi, kar pa nismo raziskovali v okviru našega dela.

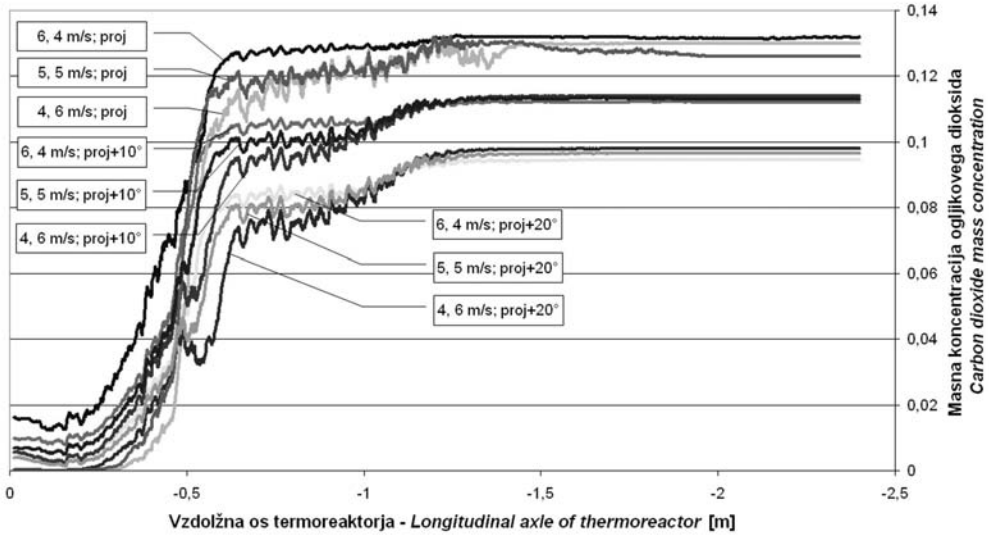
7 SKLEP

Na podlagi dejanskih pogojev obratovanja pilotne dvokomorne pilotne sežigalnice smo preverili in analizirali uporabnost različnih modelov zgorevanja. Primerjava rezultatov je pokazala, da je model EDC izredno zanesljiv in dokaj natančen pri modeliranju specifičnega zgorevanja v termoreaktorju pilotne sežigalnice. Večstopenjski modeli so v takšnih primerih uporabni le za izračun koncentracij produktov nepopolnega zgorevanja, denimo ogljikovega monoksida ali drugih. Omogočajo pa tudi iskanje področij nepopolnega zgorevanja v

influence the conditions of some specific pollutant formations such as nitric oxides, but this was not investigated during the presented work.

7 CONCLUSION

The applicability of various combustion models was examined and analyzed, based on the real operating conditions of a two-stage pilot-scale incinerator. The comparison of results demonstrates that the EDC model is very reliable and quite accurate for modelling the specific combustion processes present in the thermoreactor of the pilot-scale incinerator. Multi-step combustion models are applicable in such cases for the computation of incomplete combustion products' concentrations, such as carbon monoxide, etc. They offer the possibility of locating the regions



Sl. 14. *Vpliv smeri in hitrosti dovajanja zraka na povprečen nastanek CO_2*
Fig. 14. *Air-intake direction and velocity influence on average CO_2 formation*

zgorevalnem prostoru. Vendar pa morajo kinetični mehanizmi večstopenjskih modelov zgorevanja natančno odsevati lastnosti in sestavo goriva, saj sicer lahko povzročijo slabši izračun rezultatov kakor enostopenjski modeli.

V okviru predstavljene raziskave smo ugotovili, da je enostopenjski model EDC najbolj uporaben, še posebej za hitro numerično analizo pogojev obratovanja industrijske zgorevalne naprave, kakor je sežigalnica. Numerična analiza pogojev popolnega zgorevanja ima velik pomen v fazi načrtovanja oblike nove sežigalnice, kakor tudi za nadzor obratovanja že zgrajenih naprav. V našem primeru smo z numerično raziskavo ugotovili, da na pogoje popolnega zgorevanja v največji meri vpliva smer dovoda sekundarnega in terciarnega zraka. Smer dovoda sekundarnega in terciarnega zraka ima neposredni vpliv na jakost mešanja v reaktivni coni plamena.

Povečanje nastale količine plinov v primarni komori, kakor tudi njihove kurilne vrednosti skupaj z nespremenjenim dovodom količine zraka, vodi v nepopolno zgorevanje in nastanek večje količine produktov nepopolnega zgorevanja. V izogib temu, v praksi pogostemu problemu, bi morale sežigalnice imeti poleg običajnega kisikovega krmiljenja še krmiljenje količine zraka za zgorevanje, ki bi temeljila na količini in kurilni vrednosti plinov.

of incomplete combustion in the combustion chamber. However, the kinetic mechanisms of multi-step combustion models should strongly reflect the fuel properties and composition, otherwise they can produce worse results than single-step models.

During the presented investigation it was found that a single-step EDC model seems to be the most useful, especially for a quick numerical analysis of the operating conditions of industrial burning devices, such as incinerators. A numerical analysis of the complete combustion conditions is of great importance for the planning stage of a new incinerator's design, as well as for the operating control of existing devices. In the presented case, using a numerical investigation, it was found that the directions of the secondary and tertiary air inlets present the most important influence on the complete combustion conditions. Secondary and tertiary air-inlet directions have a direct impact on the intensity of the reactant mixing in the flame reaction zone.

The greater amount of gases generated in the primary chamber, as well as their higher calorific value, together with the same amount of air led to incomplete combustion producing a greater amount of incomplete combustion products. To avoid this, which in practise is very often a problem, incinerators should be, besides the standard oxygen control, additionally equipped with combustion-air amount control, depending on the gas amount and its calorific value.

8 LITERATURA
8 LITERATURE

[1] Brunner Calvin R. (1991) Handbook of incineration systems. *McGraw – Hill, Inc.*, New York.

[2] Baulch, D.L., D.D. Drzsdale, O.G.Horne, A.C. Lloyd (1992) Evaluated kinetic data for high temperature reactions, Vol. 1, London.

[3] Brown, N.J. (1991) Rate coefficient calculations for combustion modelling, Numerical approaches to combustion modelling. pp. 37-56, *AIAA Washington*.

[4] CFX 4.4 and 5.7., Users manual (2000, 2004) *AEA Technology.*

[5] Changkook R., S. Donghoon, C. Sangmin (2001) Simulation of bed combustion and gas flow in a grate type waste incinerator. *The 3rd International Symposium on Incineration and Flue Gas Treatment Technologies, Institution of Chemical Engineers*, 2-4 July, 2001, Brussels.

[6] Chen K. S., C. H. Tong (1997) Modelling of turbulent burning flow and performance evaluation of municipal solid incinerator. *Journal of Environmental Engineering*, November 1997, pp. 1150-1157;

[7] Ficarella A., D. Laforgia (2000) Numerical simulation of flow field and dioxins chemistry for incineration plants and experimental investigation, *Waste Management* 20 (2000), pp. 27-49;

[8] Heist D. K., M. Ravichanran, F.C. Gouldin (1994) Experiment and numerical study of an incinerator- and furnace-related flow, *Combustion and Flame*, 99, pp. 339-346, *Elsevier Science Inc.*

[9] Jones W.P., J. H. Whitelaw (1982) Calculation methods for reacting turbulent flows: A Review, *Combustion and Flame* 48: 1-26 (1982).

[10] Kori Y., R. Takeya (2001) Cross jet mixing design and its effect on combustion performance in MSW incinerators with natural gas reburning, *The 3rd International Symposium on Incineration and Flue Gas Treatment Technologies, Institution of Chemical Engineers*, 2-4 July, 2001, Brussels.

[11] Kuo, K.K. (1986) Principles of combustion. *John Wiley & Sons*, New York.

[12] Nasserzadeh V., J. Swithenbank, C. Schofield, D. W. Scott, A. Loader, A. Leonard (1994) Design optimisation of coventry municipal solid waste incinerator. *Journal of Environmental Engineering*, Vol. 120, No. 6, November/December 1994, pp. 1615-1629.

[13] Niessen Walter R. (1995) Combustion and incineration processes: Applications in environmental engineering, Second Edition, Revised and Expanded. *Marcel Dekker, Inc.*, New York.

[14] Peters N., (2004) Turbulent combustion. *Cambridge University Press*, Cambridge.

[15] Škerget L. (1994) Mehanika tekočin. *Univerza v Mariboru, Tehniška fakulteta in Univerza v Ljubljani, Fakulteta za strojništvo*, Ljubljana.

[16] Soongkee K., S. Donghoon, C. Sangmin (1996) Comparative evaluation of municipal solid waste incinerator designs by flow simulation. *Combustion and Flam*e 106: 241-251 (1996).

[17] Warnatz J., U. Maas, R. W. Dibble (1996) Combustion: physical and chemical fundamentals, modelling and simulation, experiments, pollutant formation. *Springer Verlag*, Berlin Heidelberg.

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Prejeto: 29.7.2004
Received:

Sprejeto: 25.5.2005
Accepted:

Odprto za diskusijo: 1 leto
Open for discussion: 1 year