A MATHEMATICAL MODEL OF GASEOUS FUEL COMBUSTION IN SWIRL CHAMBER

by

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In this paper a mathematical model for prediction of velocity, temperature and concentration fields of axisymmetrical confined swirl, turbulent flame was presented. Model consists of few mutualy coupled segments related to basic processes in turbulent flows with combustion. Turbulent flow is specified by time averaged Navier-Stokes equations and the k-e model of turbulence. For the evaluation of convective heat and mass transfer the energy equation and the conservation equations for the relevant components of the gas mixture were solved. The radiation heat transfer was modeled by six flux method. Processes of the single-phase combustion were described by conservation equations for the relevant components of the combustion, and by modelling the source term which represents reaction rate. The original combustion rate model based on the ideal reacting hypothesis within the fine structure of turbulence was applied. In the proposed model, both the chemical kinetics and turbulent effects, were considered at the same time. For the numerical solution of the model equations a control volume method with SIMPLE algorithm was applied. The parallel analysis of experimental and calculation results showed satisfactorily agreement between the model and the experiment. The analysis also showed significance of the proposed combustion rate model with simultaneous influence of both the chemical kinetics and turbulent effects.

Introduction

For the purpose of computer simulation of gaseous fuel burners and combustion chambers a mathematical model and numerical solution procedure, for the prediction of the turbulent swirl flow with heat and mass transfer and combustion in two-dimensional plane and axisymmetrical geometries was developed. In this work the model was applied to the analysis swirl combustion chamber.

The problems of flow and heat transfer in boiler furnaces and combustors are of a multidisciplinary nature, and hence attention must be focused on the general principles which govern the behaviour of the flow in such complex configurations.

According to this the mathematical model of processes in the combustion chamber consists of three basic segments:

- Turbulent swirl flow;
- Convective heat and mass transfer;
- Chemical reactions;
- Radiative heat transfer.

Turbulent swirl flow modeling

In this paper a turbulent recirculating swirl flow is described by time-averaged elliptic Navier-Stockes equations and a k-ε model of turbulence for the determination of turbulent stress components. The effective viscosity hypothesis connects the Reynolds stresses to the mean velocity gradients. Reynolds stresses for cylindrical, axisymmetrical conditions can be expressed as follows:

$$\begin{aligned} -\rho\overline{uv} &= \mu\left(\frac{\partial U}{\partial r}+\frac{\partial V}{\partial x}\right) \\ -\rho\overline{uw} &= \mu_t \frac{\partial W}{\partial x} \\ -\rho\overline{vw} &= \mu_t \frac{\partial}{\partial r}\left(\frac{W}{r}\right) \end{aligned} \tag{1}$$

Turbulent and effective viscosities, according to k-ε model, are given by:

$$\mu_t = C_\mu \rho k^2/\varepsilon, \quad \mu_{eff} = \mu + \mu_t \tag{2}$$

Obviously, to calculate Reynolds stresses the values of k and e must be known. Those values are obtined from the solution of their respective transport equations.

Model of turbulent swirl flow, thus, consists of: mass conservation equation, momentum equations for velocities in axial (U), radial (V) and tangential (W) direction and transport equations for k and ε. All equations can be given in standard form for the conservation of a general variable ϕ:

$$\frac{\partial}{\partial x}(\rho U_\phi)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho V\phi) = \frac{\partial}{\partial x}\left(\Gamma_{eff}\frac{\partial}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_{eff}\frac{\partial \phi}{\partial r}\right)+S_\phi \tag{3}$$

Dependent variables (ϕ), diffusion coefficients (Geff) and sources (S_ϕ) for all conservation equations which describe the turbulent flow, as well as convective heat and mass transfer are listed in Table 1.

Table 1. Dependent variables, diffusion coefficients and source terms in equation (3)

Equation	Dependent variable [ϕ]	Coefficient [Γ_{eff}]	Source term [S_ϕ]
Continuity	1	0	0
Axial momentum	U	μ_{eff}	$\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial U}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\mu_{eff} r\frac{\partial}{\partial x}\right)-\frac{\partial p}{\partial x}$
Radial momntum	V	μ_{eff}	$\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial U}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\mu_{eff} r\frac{\partial V}{\partial r}\right)-2\mu_{eff}\frac{V}{r^2}+\rho\frac{W^2}{r}-\frac{\partial p}{\partial r}$
Tangential momentum	W	μ_{eff}	$-\left(\frac{\mu_{eff}}{r^2}+\frac{\rho V}{r}+\frac{1}{r}\frac{\partial \mu_{eff}}{\partial r}\right)W$
Kinetic energy of turbulence	k	μ_{eff}/σ_k	$G_{k_1}-\rho\varepsilon$
Dissipation of turbulence energy	ε	$\mu_{eff}/\sigma_\varepsilon$	$\frac{\varepsilon}{k}(C_1 G_{k_1}-C_2\rho\varepsilon)$
Stagnation enthalpy	h	μ_{eff}/σ_h	S_R

$$G_{k_1}=\mu_t\left\{2\left[\left(\frac{\partial U}{\partial x}\right)^2+\left(\frac{\partial V}{\partial r}\right)^2+\left(\frac{V}{r}\right)^2\right]+\left(\frac{\partial W}{\partial x}\right)^2+\left[r\frac{\partial}{\partial r}\left(\frac{W}{r}\right)\right]^2+\left(\frac{\partial U}{\partial r}+\frac{\partial V}{\partial x}\right)^2\right\}$$

Constants of model	C_μ	C_1	C_2	σ_k	σ_ε	σ_h	σ_m
Values	0.09	1.44	1.92	1.0	1.3	0.9	0.9

Heat transfer modeling

For determination of convective heat transfer it is necessary to solve the energy equation defined trough the conservation of the gas stagnation enthalpy:

$$h=\sum_k m_k c_{p_k} T+\sum_k m_k H_{R_k}+\frac{1}{2}(U^2+V^2+W^2) \qquad (4)$$

where mk denotes mass fractions of combustible components of the mixture and H_{Rk} their corresponding combustion heats. Energy equation can also be given in form (3) where the sorce term represents radiation heat transfer (Table 1).

For the evaluation of radiative heat transfer the flux model of De Marco and Lockwood [2] was applied. This model has shown good accuracy and computation economy and has been successfully used for the modeling of pulverized coal combustion.

When the six-flux model of De Marco and Lockwood is reduced to the axisymmetrical case, the equations for the mean radiation fluxes in axial (F_x) and radial (F_r) directions are:

$$\frac{\partial}{\partial x}\left(\frac{1}{K_a}\frac{\partial F_x}{\partial x}\right)+K_a\left(-\frac{8}{3}F_x+\frac{4}{3}F_r+\frac{4}{3}E_B\right)=0$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{1}{K_a}r\frac{\partial F_r}{\partial r}\right)+K_a\left(-\frac{8}{3}F_r+\frac{4}{3}F_x+\frac{4}{3}E_B\right)=0 \tag{5}$$

where K_a denotes the gas absorption coefficient and $E_B = \sigma T^4$ stands for the black body emissive power, with σ being the Boltzmann constant. The equations (5) are coupled with the set of basic equations of the model (3), which describe the gas flow and convective heat and mass transfer through the coefficients in the equations (5) and the radiation source term S_R in the fluid stagnation enthalpy conservation equation. The expression for the radiation source term was derived from the model of De Marco and Lockwood:

$$S_R = \frac{16}{9}K_a(F_x+F_r)-\frac{32}{9}K_aE_B \tag{6}$$

The radiative heat transfer flux on the wall perpendicular to the x-direction is:

$$q_{wx} = 2\frac{\varepsilon_w}{2-\varepsilon_w}(E_{Bw}-F_{xw}) \tag{7}$$

where ε_w denotes the wall emissivity. The wall flux in the radial direction is determined by the expression analogous to (7).

It is important to note that radiation flux equations (5) have the same form as the equations (3) which govern the fluid flow and convective heat and mass transfer (3), so that the same numerical method can be used for the solution of all combustion chamber model equations.

Convective mass transfer and combustion

The convective transfer of mass can be described by the conservation equations for the relevant components of the gas mixture, whose form corresponds to the standard form (3). Combustion model, proposed in this paper, is also based on the set of the conservation equations for the chemical species, where it is important to evaluate the source term that is determined by the combustion rate. Proposed concept for the combustion modeling is useful for complex chemical reactions (consecutive, parallel, *etc.*) description. In this work, for example, the two-step combustion was analyzed.

The source terms in conservation equations for the chemical species of the two-step propane – butane mixture combustion are listed in Table 1. These source terms are given in dependance of rate of fuel conversion. Thus, the source terms evaluation in species conservation equations reduces to combustion rate determination.

Combustion rate model

Proposed model of combustion rate is based on an eddy dissipation concept and k-ε model of turbulence, including simultaneous influence of chemical kinetics and turbulent mixing. Basic assumption of the model is that chemical reactions take place when reactants are mixed at molecular scale in isolated regions whose entire volume is a small fraction of the fluid elements. These regions are occupied by fine structures that represents end of cascade of eddy dissipation process, whose characteristic dimensions are of the same magnitude as the Kolmogorov microscale [1]. Consideration of the contact probability of fluctuating reactants, existing in PDF modeling concept, was substituted by consideration of mixing on molecular level inside fine turbulent structures. Calculation of the overall combustion rate is thus reduced on the determination of participation fine structures in turbulence, and afterwards on the analysis of processes in fine structures. In the proposed model both, the chemical kinetics and molecular mixing, are considered at the same time, while in similar models (EBU, C/D, *etc.*) the chemical kinetics is treated separately, or is neglected at all. Simultaneous influence of chemical kinetics and turbulent effects on the combustion rate is attained by treating fine structures like ideal chemical reactors (Fig. 1).

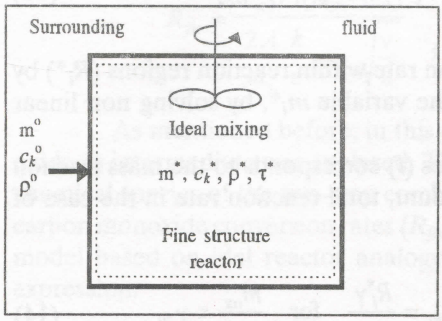

Figure 1. Schematic illustration of the reacting zones.

On the basis of the mass balance for species i in fine structures and surrounding fluid, and including chemical kinetic rate, the conversion rate of species i can be expressed as:

$$R_i^* = \frac{c_i^\circ \frac{\rho^*}{\rho^\circ}}{\tau^*} = k_\circ e^{-\frac{E_a}{RT^*}} c_i^{*b_i} c_j^{*b_j} \qquad (8)$$

where c_i° and c_i^* are mass concentrations of species i, outside and inside the fine structures respectively.:

$$m_i = c_i/\rho, m^*_i = c^*_i/\rho^*, m^\circ_i = c^\circ_i/\rho^\circ \qquad (9)$$

Right side of the equation (8) represents chemical reaction rate for fine structure conditions, where are k° is the constant of chemical kinetics, b_i and b_j order of chemical conversion reaction.

Equation (8) represents mass conversion rate of the species i within existing time of smallest eddies. It is equaled with the chemical kinetic rate for the fine structure conditions, analogously to ideal chemical reactore processes.

If the total mass m is equal to sum of masses in fine structures m^* and surrounding m°: $m = m^* + m^\circ$, then mass fraction occupied by fine structures is defined as: $\gamma^* = m^*/m$. The relation between mean mass fraction and mass fraction for fine

structure and surrounding fluid conditions of deficient species i in control volume is given by:

$$m_k = (1-\gamma^*)m_k^\circ + \gamma^* m_k^* \tag{10}$$

Taking into account (9) and (10) the left side of the relation (8) takes the form:

$$R_i^* \frac{\rho^*(m_i - m_i^*)}{\tau^*(1-\gamma^*)} \tag{11}$$

The equation (11) represents conversion rate within reaction regions (fine structure).

Taking into account stoichiometric relation for chemical reaction, mass fraction of the second (overplus) reactant – j in the turbulent fine structures is defined by: $m_j^* = m_j^\circ - s_{j_i}(m_i^\circ - m_i^*)$, and applying (10) it can be expressed as:

$$m_j^* = m_j - s_{j_i}(m_i - m_i^*) \tag{12}$$

where – $s_{j_i} = (n_j M_j)/(n_i - M_i)$ is stoichiometric ratio of the overplus j and deficient i species.

Considering these relations the species i mass balance within fine structure regions reads as follows:

$$\frac{\rho^*(m_i - m_i^*)}{\tau^*(1-\gamma^*)} = k_\circ \rho^{*(b_i+b_j)} e^{-\frac{E_a}{RT}} m_i^{*b_i} [m_j - s_{j_i}(m_i - m_i^*)]^{b_j} \tag{13}$$

Now it is possible to calculate combustion rate within reaction regions (R_i^*) by equation (11), bat it is necessary to determine the variable m_i^*, by solving non linear equation (13).

Reaction rate R_i^* for the deficient species (i) corresponds to the mass fraction occupied by fine structures. Taking this into account, total reaction rate in the case of finite chemical reaction rate can be expressed by:

$$R_{fu} = R_i^* \gamma^* \quad \text{for} \quad \frac{m_{ox}}{s_{fu}} \geq m_{fu} \quad \wedge \quad R_{fu} = \frac{R_i^* \gamma}{s_{fu}} \quad \text{for} \quad \frac{m_{ox}}{s_{fu}} < y_{fu} \tag{14}$$

where $s_{fu}=(n_{ox}M_{ox})/(n_{fu}M_{fu})$ is stoichiometric oxygen requirement.

As mentioned, time scale for the fine structures corresponds to the Kolmogorov time scale:

$$\tau^* = a_\tau \sqrt{\nu/\varepsilon} \tag{15}$$

Mass fraction occupied by fine structures (γ^*) can be obtained as the ratio between Kolmogorov microscale and bulk mixing time scale: $\gamma^* = \tau^*/\tau_m$. If we suppose that bulk mixing time scale is proportional to the turbulent macroscale, the ratio of micro and macro scales τ^*/τ_m is proportional to $\sqrt{\nu/\varepsilon}/(l/u)$, where $u = \sqrt{2/3k}$ and $\varepsilon = Au^3/l$. Therefore the mass fraction of the fine turbulent structures can be written by the expression:

$$\gamma^* = a_\tau \frac{3a_\gamma}{2A} \sqrt{\frac{\nu\varepsilon}{k^2}} \tag{16}$$

Taking into account that the fine structures, as well as Kolmogorov microscale, are responsible for the dissipation of turbulent energy, it can be assumed a_τ. Proposed values for constant A in literature are among 0.1 and 1, but authors mainly recommend 0.6. Taking into account the results of EDC interstructural energy transfer modeling [1] it was assumed $a_\gamma = 0.18$.

Fluid density in fine structures was determined on the same way as for mixture of ideal gases for conditions in reaction zones, using values of static pressure and temperature for surrounding fluid:

$$\rho^* = \frac{P}{RT^*}\left[\underbrace{\frac{m_i^*}{M_i}}_{\substack{\text{deficient}\\ \text{reagent}}} + \underbrace{\frac{m_j - s_{j_i}(m_i - m_i^*)}{M_j}}_{\text{reagent in excess}} + \sum_l \underbrace{\frac{m_l + s_{l_i}(m_i - m_i^*)}{M_l}}_{\text{combustion products}}\right]^- \tag{17}$$

Combining equations: (11), (14), (15) and (16) combustion rate can be expressed as:

$$R_{fu} = \frac{C_{st}\rho^*(m_i - m_i^*)}{\frac{2A}{3a_\gamma}\frac{k}{\varepsilon} - a_\tau\sqrt{\frac{\nu}{\varepsilon}}} \quad \begin{array}{ll} i = fu \ \wedge \ C_{st} = 1 \Rightarrow \dfrac{m_{ox}}{s_{ox_{fu}}} \geq m_{fu} \\ i = ox \ \wedge \ C_{st} = \dfrac{1}{s_{ox_{fu}}} \Rightarrow \dfrac{m_{ox}}{s_{ox_{fu}}} < m_{fu} \end{array} \tag{18}$$

As mentioned before, in this work the two-step combustion, with carbon monoxide as intermediate was analyzed. The source terms in conservation equations for the chemical species of the two-step combustion are given (Table 1) in function of fuel and carbon monoxide conversion rates (R_{fu}, R_{CO}). Accordingly the proposed combustion rate model based on idel reactor analogy CO conversion rate can be determined by the expression:

$$R_{CO} = k_{CO}^{\circ}\rho^{*(b_{CO}+b_{O_2})} e^{\frac{E_{aCO}}{RT}} m_{CO}^{*bCO} m_O^{*bO_2} \gamma^* \tag{19}$$

The proposed submodel for calculation of combustion rate can be easily coupled with the other combustion chamber model equations, by appropriate formulation of the source and sink terms in conservation equations for the reactants and products. Thus, reaction model parameters (τ^*, γ^*, ρ^*, m_i^*), by which R_{fu}, and R_{CO} can be obtained, were calculated for each control volume.

Influence of the kinetic rate on total combustion rate is performed through the insufficient species (m_i^*) mass fraction in combustion region (fine structures). The combustion rate, determined from (18) depends on temperature through m_i^*. That model property can be illustrated by diagrams of Fig. 2.

The combustion rate can be also brought into the connection with the fluctuation characteristics that are result of the combustion and turbulence effects. It can be illustrated by comparison between equation (18) and the corresponding equation of the advanced "eddy – break up" (EBU) model, by Spalding:

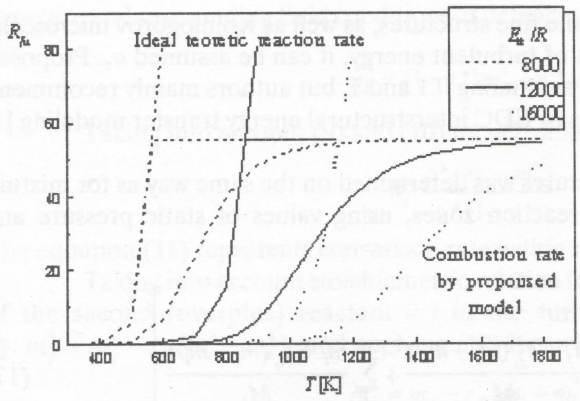

Figure 2. Reaction rate temperature dipendence

$$R_{EBU} = \frac{\rho\sqrt{\overline{m'^2_{fu}}}}{\frac{1}{C_R}\frac{k}{\varepsilon}} \qquad (20)$$

where m'_{fu} represents mass concentration fluctuations of fuel. Thus, we could assume the following relation:

$$m_i - m_i^* = (\overline{m_i'^2})^{1/2}$$

Differences between equation (18) and (20) in the denominators are result of various turbulent combustion modeling approach. EBU reaction rate modeling is based on consideration of the rate of break-up of the large eddies, while proposed model is based on chemical species balance within smallest eddies.

Test case

In this paper the mathematical modeling of the homogenous reactions in confined turbulent flows with swirl was applied on simulation of processes in water cooled combustion chamber with gas swirl flow, and calculation results were compared with experimental data. The schematic presentation of the experimental combustior is given in Fig. 3. The experimental apparatus consists of four basic parts: the experimental burner (2), (6), (7), (21) with the combustion chamber that consists of six segments (1), (4); a measurement and an acquisition equipment (8), (9), (10), (11), (18), (19), (20); a fuel (16), (17) and an air (14), (15) supplying line and the water cooling line (12), (13).

The swirl burner (2) consists of: the swirler (3), the air distributive chamber (6), the fuel pipe (7) and the diffuser (21). The swirler is a removable disk with inclined plates where the air annular flow gets tangential velocity component, and with an axial pipe for the introduction of fuel. Three swirlers with three plates inclination angles, were used, in this manner it had providing three different swirling regimes.

The temperature and concentration measurements were carried out using the combined probe consisted of a thermocouple and a tube for gas sampling. Besides temperature fields these experiments have provided data for CO_2, O_2 and CO concentration fields, for three swirl regimes.

Fig. 4 shows schematic sight of burner and combustion chamber working area with measurement points and numerical calculation nods. Numerical solution of the given system of equations has been obtained using the control volume method with iterative procedure of solution convergence. Non-uniform numeric grid, with 23 control nodes in axial and 22 nodes in radial direction, has been used in calculations.

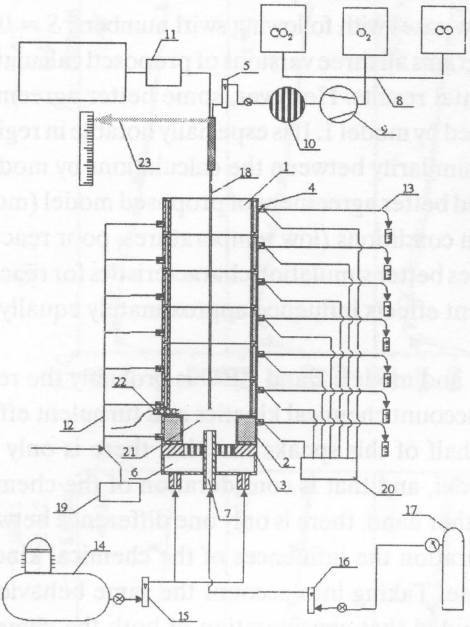

Figure 3. Schematic presentation of the experimental combustior

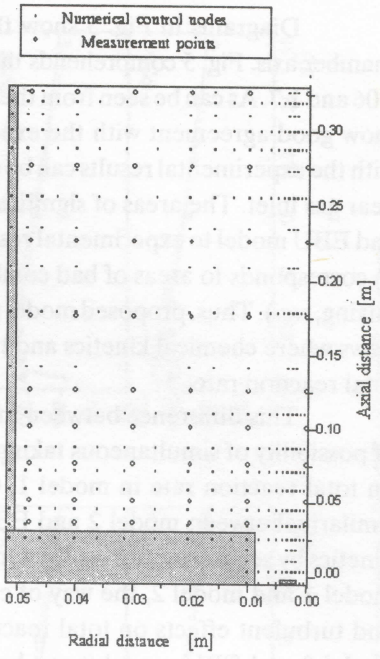

Figure 4. Measurement points and numerical control nods

Results of predictions

The aim of this work is to analyze feasibility of the prediction of swirling reactive flow in cylindrical chamber, based on the comparison of the experimental results with the results obtained using mathematical model. Calculation results (model 1) were compared (beside with experimental data) with the version of model that comprises simplified proposed combustion rate model (model 2) and with the calculation that uses broadly applied version of EBU combustion rate model. In simplified version of the proposed model (model 2) the assumption that in combustion regions the kinetic rate is always infinitely fast ($m_i^* = 0$ and $\rho^* = \rho$) is implied. Hence, in this version it is not possible to take into account turbulent and kinetic effects simultaneously. Instead, the special criterion for determination of the the minimum of chemical reaction kinetics rate and the turbulent diffusion rate was applied.

$$R_{fu} = \min\left\{R_{ch}, R_{fu}\right\} \tag{28}$$

In the applied version of the EBU model, instead variance: $\sqrt{m'^2_{fu}}$ (20), mean mass fraction of fuel mfu has been used. For taking into account chemical kinetic effects was criterion (28) applied.

Diagrams in Fig. 5 show the axial temperature profiles at five distances from chamber axis. Fig. 5 comprehends three flow cases with following swirl numbers: $S = 0.83$, 1.06 and 1.7. As can be seen from these diagrams all three versions of proposed calculation show good agreement with the experimental results. However, some better agreement with the experimental results can be obtained by model 1. It is especially notable in regions near gas inlet. The areas of significant dissimilarity between the calculations by model 2 and EBU model to experimental results and better agreement of proposed model (model 1) corresponds to areas of bad combustion conditions (low temperatures, poor reactant mixing, *etc.*). Thus, proposed model provides better simulation characteristics for reacting flows where chemical kinetics and turbulent effects influence approximately equally the total reaction rate.

This difference between model 1 and models 2 and EBU is probably the result of possibility of simultaneous taking into account chemical kinetics and turbulent effects on total reaction rate in model 1. On behalf of this speaks fact that there is only one similarity between model 2 and EBU model, and that is consideration of the chemical kinetics by separate criteria (38). On the other hand, there is only one difference between model 1 and model 2, the way of consideration the influences of the chemical kinetics and turbulent effects on total reaction rate. Taking into account the same behavior of model 2 and EBU model it can be concluded that consideration of both the chemical kinetics and turbulent effects at the same time is crucial for these calculations.

Same conclusions can be obtained by comparative analysis of the results of measurement and calculation of the chemical species distribution. Figures 6. and 7. show the axial CO_2 and O_2 concentration profiles respectively for dry combustion products, at five distances from chamber axis and for three different swirl regimes. In these figures it can also be seen the better agreement of model 1 then model 2 and EBU model with the experimental data, especially in intensive reaction zones.

Figs. 5, 6 and 7 show good agreement of model 1 with experimental data. As can be seen in these figures the proposed model good describes an influence of the swirl intensity on combustion configurations. Flows with higher swirl number provides a smaller intensive combustion zones that are placed near the gas inlet regions. Thus, flow regimes with a more intensive swirl produce better reaction conditions and more combustion efficiency.

Influence of flow regimes on a shape of the intensive combustion regions can be better seen in the temperature filed diagrams (Fig. 8). Each of diagrams on Fig. 8. is split on two parts, where the upper part represents experimental results and the lower one the calculated temperature distribution. As can be seen in this figure the intensive combustion zones (with highest temperatures) get a torus shape, according both experimental results and model calculation. The experiments as well as model, show that for more intensive swirl regimes these high temperature regions are placed closer to the burner and to the wall.

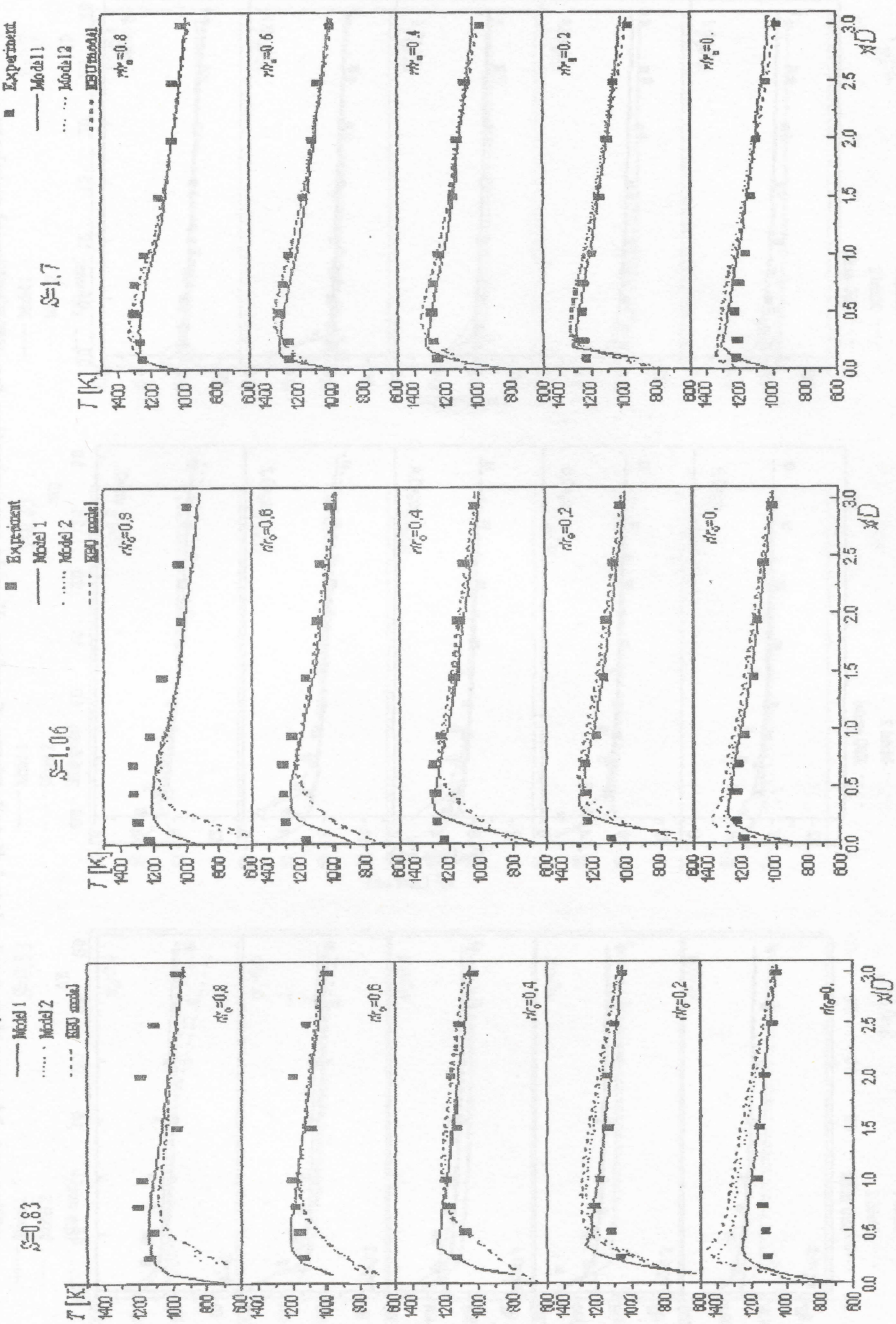

Figure 5. Measured and calculated distributions of temperature for different swirl numbers

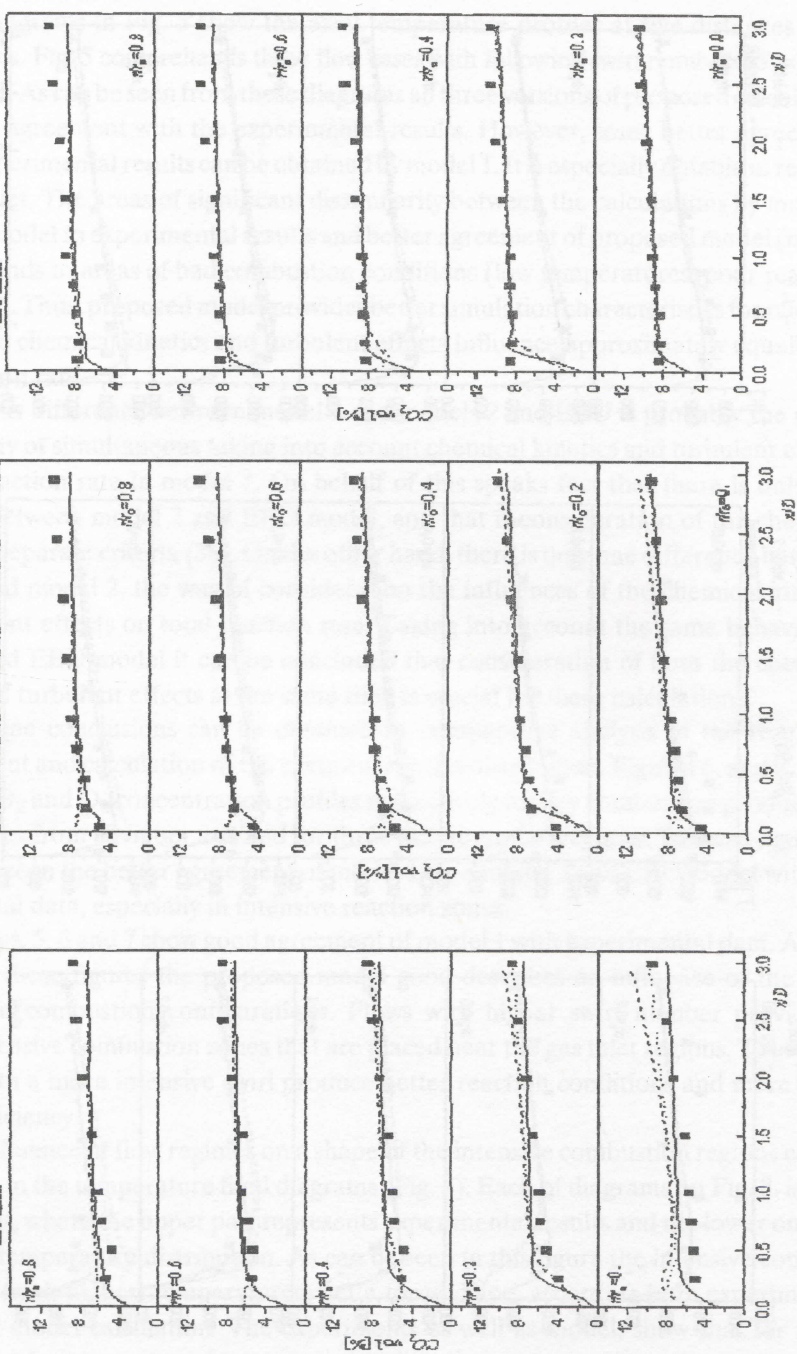

Figure 6. Measured and calculated distributions of carbon dioxide concentration for different swirl numbers

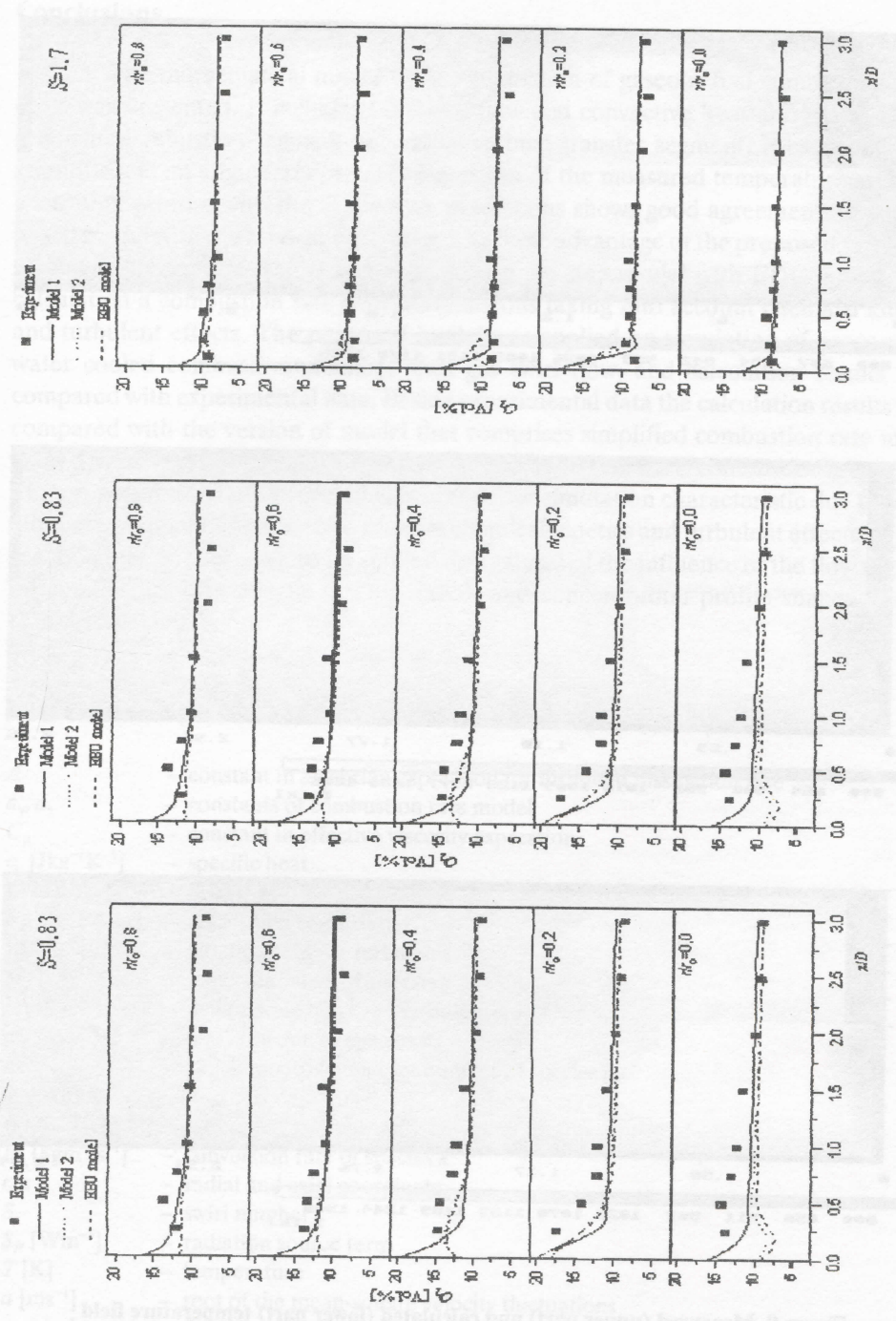

Figure 7. Measured and calculated distributions of oxygen concentration for different swirl numbers

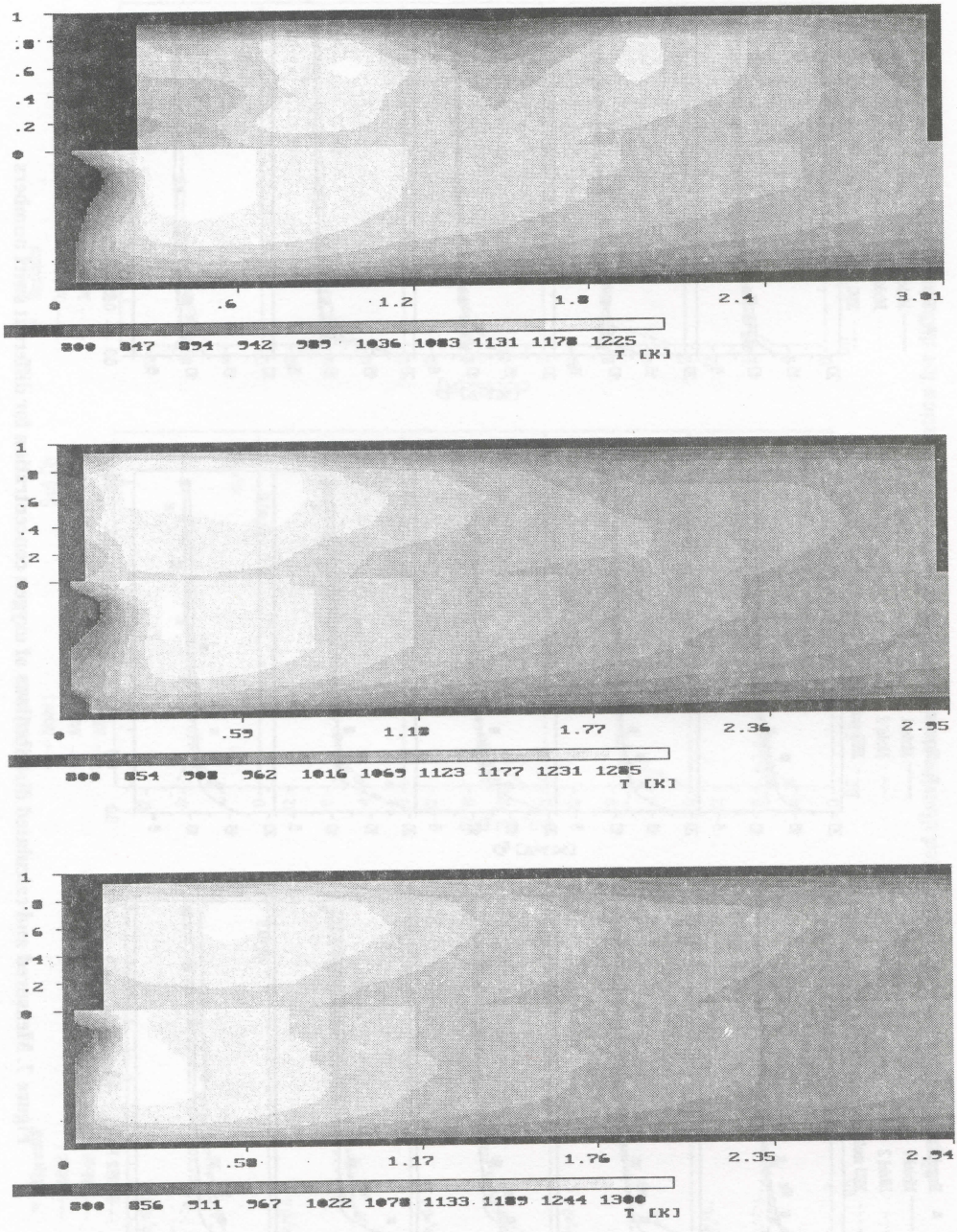

Figure 8. Measured (upper part) and calculated (lower part) temperature field distribution for different swirl number

Conclusions

The mathematical model for the prediction of gaseous fuel combustion processes was presented. It includes turbulent flow and convective heat and mass transfer segment, combustion segment and radiative heat transfer segment. It can be used as scientific and an engineering tool. Comparison of the measured temperature and concentration profiles with the calculation predictions shows good agreement of the proposed model with the experimental data. The basic advantage of the proposed numerical simulation procedure is application of the combustion model with EDC approach to calculation a combustion rate with simultaneous taking into account chemical kinetics and turbulent effects. The proposed model was applied on simulation of processes in water cooled combustion chamber with gas swirl flow, and calculation results were compared with experimental data. Beside experimental data the calculation results were compared with the version of model that comprises simplified combustion rate model and with the calculation that uses broadly applied version of EBU combustion rate model. The proposed simulation concept provides better simulation characteristic due to possibility of simultaneous taking into account chemical kinetics and turbulent effects on total reaction rate. Model can also be applied on analyzes of the influence of the flow regimes on combustion efficiency and temperature and concentration profile shapes in swirl combustion chamber.

Nomenclature

A – constant in algebrian expression for turbulent dissipation rate
a_γ, a_τ – constants of combustion rate model
C_μ – constant in effective viscosity expression
c_p [$Jkg^{-1}K^{-1}$] – specific heat
E_a [$Jmol^{-1}$] – activation energy
K_a [m^{-1}] – absorption coefficient
k [Jkg^{-1}] – kinetic energy of turbulence
M_k [$kgmol^{-1}$] – molecular mass of species k
l [m] – macro-scale length of turbulencem
m_k – mass fraction of species k
n_k – stoichiometric molecule number of species k
q_w [Wm^{-2}] – heat flux on a wall
R [$Jmol^{-1}K^{-1}$] – universal gass constant
R_k [$kgm^{-3}s^{-1}$] – conversion rate of species k
r, x – radial and axial coordinate
S – swirl number
S_R [Wm^{-3}] – radiation source term
T [K] – temperature
u [ms^{-1}] – root of the mean-square velocity fluctuations
u, v, w [ms^{-1}] – fluctuating component of an axial, radial and tangential velocity

Greek symbols

ε [m^2s^{-3}] – dissipation rate of turbulence
ν [Pas] – viscosity
ρ [kg^{-3}] – density
τ^* [s] – time micro-scale

Subscripts

fu – fuel
k – fluctuation
* – fine structures

Superscripts

" – fluctuation
* – fine structures
° – surrounding fluid

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