doi:10.22364/mmp2017.36

VIII International Scientific Colloquium
Modelling for Materials Processing
Riga, September 21 - 22, 2017

Mathematical Modeling on Electromagnetic field Control of the Combustion Process

H. Kalis, M. Marinaki, L. Ozola, U. Strautins, I. Barmina, M. Zake

Abstract

The present paper considers a mathematical model of 2 D compressible, laminar, axial symmetric flame flow taking into account the Lorentz force action on the development of fuel combustion in a cylindrical pipe. The combustion process is modeled with Arrhenius kinetics using a single step exothermic chemical reaction between fuel and oxidant. The analysis of non-stationary PDEs system with 7 unknown functions is carried out.

For the inviscid flow approximation the implicit finite difference scheme in time with upwind differences in space is used. The results of numerical simulation are confirmed by the results of the experimental study of the electromagnetic field effect on the thermo-chemical conversion of biomass mixture (straw+wood).

Introduction

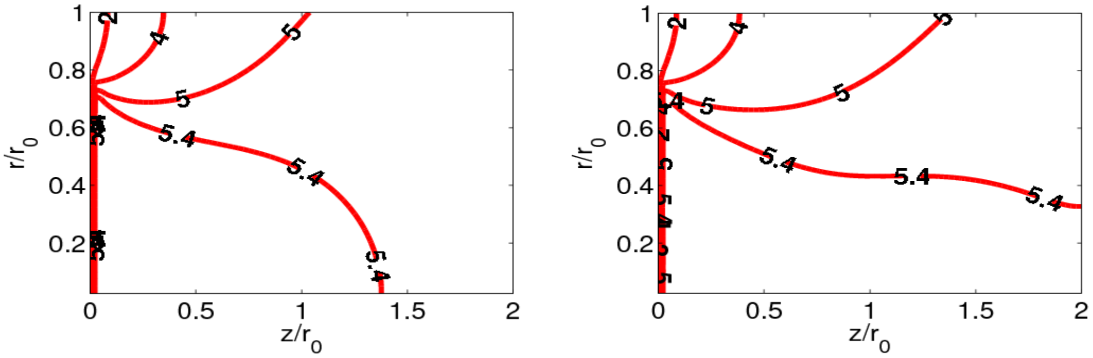
The electric and magnetic field effects on the flames, which can be related to the ionic wind, magnetic wind and Lorentz force effects makes it possible to provide control of the flame shape, size and main combustion characteristics [1,2]. This research aims to give insight on applicability of these effects to provide control of the combustion dynamics at thermo-chemical conversion of biomass mixture (straw+wood) combining the mathematical modelling and experimental study of the field effects on the main flame characteristics. In [3] the results of numerical simulation evidence that formation of the flame reaction zone is influenced by the electric field-induced variations of the local vortices and mixing of the reactants by increasing the reaction rate.

1. Mathematical modelling

For mathematical modelling, we considered a system of 7 partial differential equations describing an axially symmetric compressible reacting swirling flow and the temperature with a simple chemical reaction in a cylindrical pipe-combustor with the radius r = 0.05 [m], length z = 0.1 [m] [3,4].

The applied electric field with a current I of uniform density between the positively biased walls of the combustor and the negatively biased axially inserted electrode determines the formation of the azimuthally induced magnetic field, which was scaled to $B_0 = 0.4\ 10^{-5}$ I [N/(A m)].

For the numerical calculation, the implicit finite difference scheme and the ADI method were applied providing the estimation of the effects of the variation of the molecular diffusivity D, thermal conductivity λ and electric field on the main flame characteristics, i.e. on the minimum value of flow density ρ, on maximum values of the flow velocity components, the reaction rate, the pressure gradient and flow vorticity. For the fixed length of the axially inserted electrode, the decrease in thermal conductivity resulted in the correlating increase of the maximum velocity, pressure gradient, flame temperature, reaction rate and flow vortices with the decrease in density, whereas the decrease of the molecular diffusivity resulted in the increase of the maximum density and in the decrease of the velocity, pressure gradient, temperature, reaction rate and flow vortices. With the fixed values of D and λ, the electric field affects the flow dynamics, the local and average values of the flow velocity, the density and pressure in the flame reaction zone. The application of the electric field to the flame reaction zone leads to an increase in length of the flame reaction zone (Fig. 1 –a, b).



a **b**

Fig. 1. Isotherms (Max temperature = 5.99x300[K]); without electric field (a), with electric field I=0.1 [mA] (b)

For the external magnetic field the mathematical model is similar to [3,4], but has a different form of the radial (F_r) and axial (F_z) components of the Lorentz force. The goal was to illustrate a qualitative difference between the velocity distributions in cases when the external magnetic field induced by a permanent magnets wrapped around the computational domain was applied. Simulations were made using the Matlab and FEMM software simultaneously [5].
The FEMM software provides a finite element solution of the Maxwell equations formulated for the magnetostatic case. The software considers the vector potential formulation in the case of two dimensions. Zero vector potential boundary condition was applied to the symmetry part of the boundary for the case of axial symmetry. For magnetic flux density, two magnetization directions, perpendicular to the flow direction and aligned with the flow direction, were considered (see Figs. 2,3).

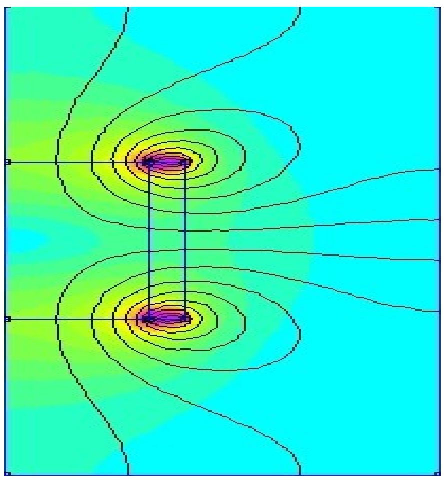


Fig. 2. Magnetic flux density plot: the magnetization direction perpendicular to the flow direction

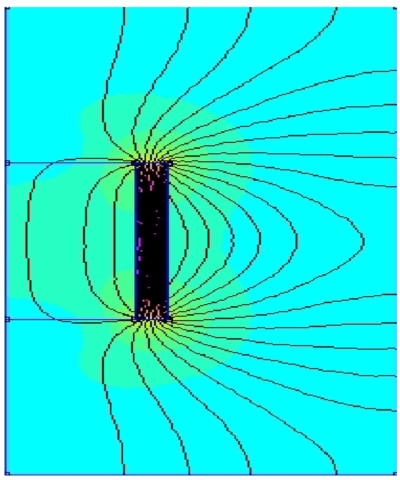


Fig. 3. Magnetic flux density plot: the magnetization direction aligned with the flow direction

The flux density varies between 0.001 T and 0.1 T. For the calculations, a mean value of 0.03 T was considered. After the magnetic field with the two components B_r, B_z is obtained, we use the Matlab built-in differentiation commands to calculate the Lorentz force terms F_r, F_z. For the inviscid flow approximation, we used the implicit FDS in time with upwind differences in space. To solve the discrete problem, we applied the ADI method of Douglas and Rachford, similarly as in [3, 4]. Here some graphs are presented which allows to compare the stream function distributions when the source term is applied. One can see two vortices in Fig.4 and the disappearance of vorticity in Fig. 5.

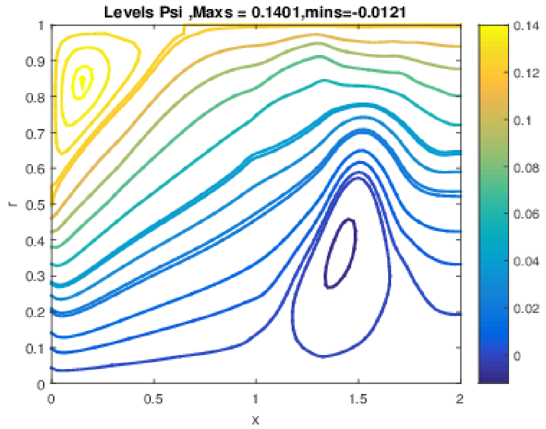


Fig. 4. Stream function; the magnetization direction perpendicular to the flow direction

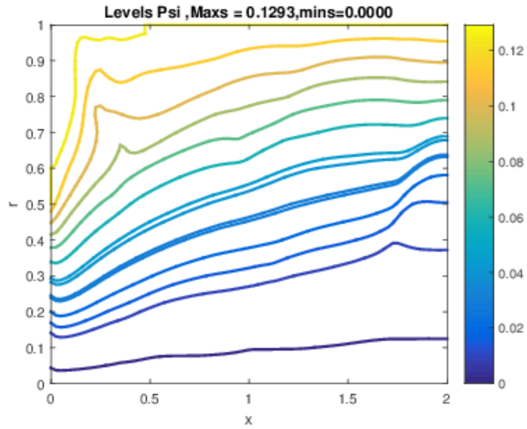


Fig. 5. Stream function; the magnetization aligned with the flow direction

2. Experimental studies.

The experimental studies of the electric field effect on the combustion dynamics at thermo-chemical conversion of biomass mixture (straw+wood) is carried out using a batch-size experimental device which is described in [6,7].

The effect of electric field on the combustion dynamics was studied using a nichrome electrode, 3 mm in diameter and 35 mm in length, which was placed at the bottom of the flame reaction zone and was positive with respect to the grounded walls of the inlet nozzle and to the water-cooled walls of the combustor Fig. 6-b.

Therefore, the axially inserted electrode acts as the anode, whereas the inlet nozzle of the combustor and the grounded water-cooled walls of the combustor act as the cathode by collecting the ion current. To prevent a discharge, the current between the axially inserted electrode and the grounded walls of the combustor was limited to 5-7 mA at a voltage supply of 0.6-2.4 kV. The electrode voltage and the current were monitored by the high voltage equipment. To provide the experimental study of the magnetic field effects on the swirling flow dynamics at thermo-chemical conversion of the biomass mixture, the upper part of the gasifier was inserted into a transversal magnetic field that was created by the two pairs of permanent magnets (Fig.6-a) determining the formation of the axial and radial magnetic field gradients above and between the poles up to dB/dz≈2.7-3.8 T/m; dB/dr≈ 0.7-2.7 T/m.

The positive bias voltage of the axially inserted electrode first of all shows the influence on the flow dynamics (Fig. 7-a) promoting the radial and reverse axial heat/mass transfer of the neutral flame species (ion wind effect). This leads to enhanced thermal decomposition of the biomass mixture with enhanced release of combustible volatiles (Fig. 7-b) and enhanced mixing of volatiles with an air swirl. As a consequence, more complete combustion of volatiles is observed (Fig. 7-c) with an increase of produced heat energy per mass of burned biomass mixture (wood +20%straw) (Fig. 7-d).

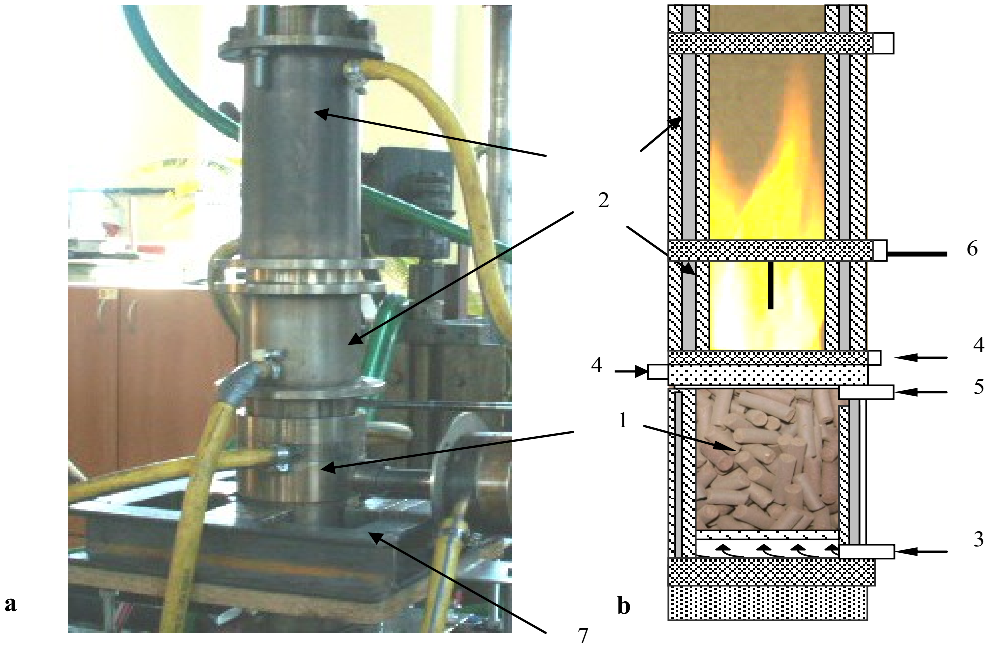


Fig. 6. Digital image and principal schematic of the experimental device: 1 – gasifier with a biomass pellets; water-cooled sections of the combustor; 3 –primary air supply; 4- secondary air supply; 5- propane flame inlet; 6 – positively biased electrode; 7- permanent magnet

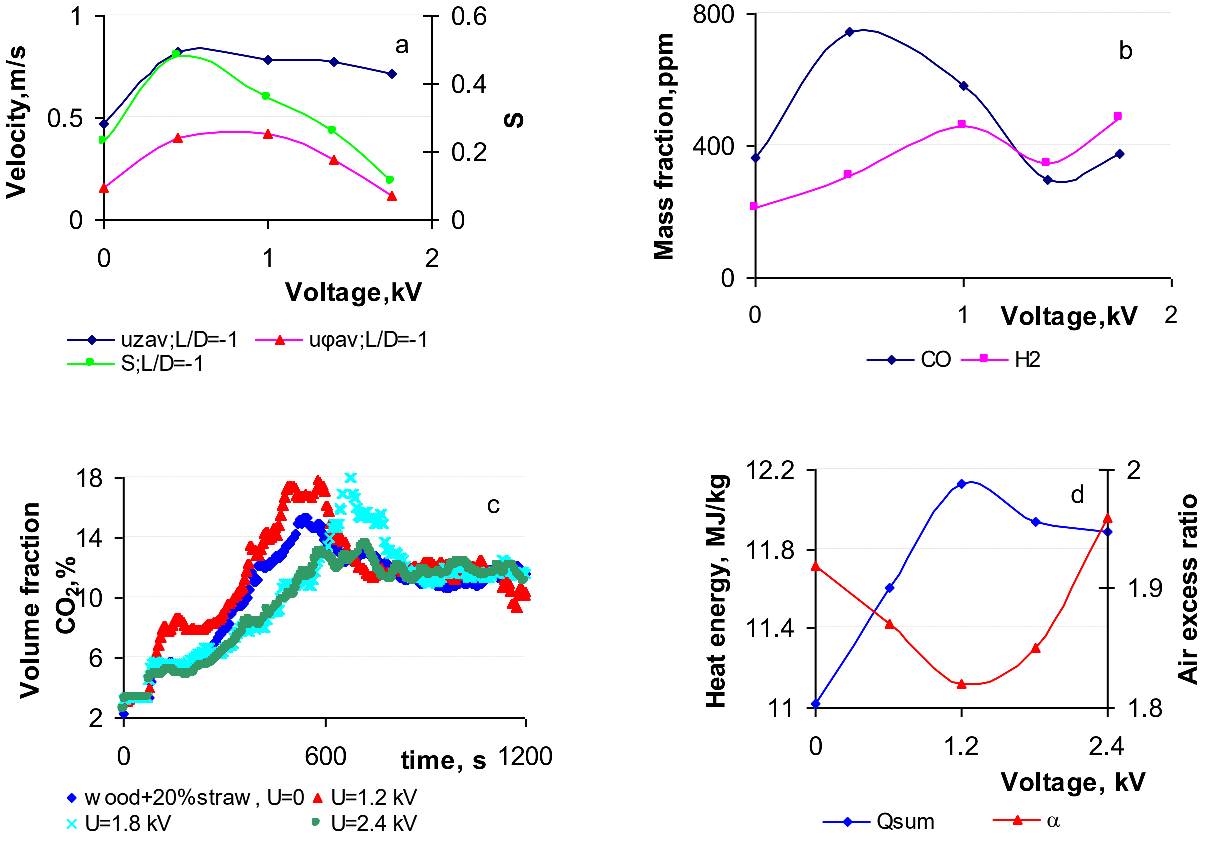


Fig. 7. The electric field effect on the flow velocity components (a), release of volatiles (b), ignition and combustion of volatiles (c) and heat energy production (d)

If the magnetic field is applied to the flame base (Fig. 6-a) the field-enhanced reverse axial heat/mass transfer of the paramagnetic oxygen upstream to the biomass layer promotes the enhanced thermal decomposition of the mixture of biomass pellets (wood +20% straw) by increasing the average weight loss of pellets from 0.135 g/s to 0.143 g/s with faster release of the combustible volatiles (CO, H_2). Moreover, the upstream mass transfer of the paramagnetic oxygen provides the enhanced mixing of the volatiles with air promoting the enhanced ignition and combustion of volatiles with faster increase of the CO_2 volume fraction and the heat output from the device up to the peak values.

Conclusions

The mathematical modelling has shown that for the negatively biased axially inserted electrode the electric field exhibits its influence on the flow dynamics, on the local, average and maximum values of the flow velocity, density and pressure in the flame reaction zone, thus advancing the formation of small vortices with anti-clockwise rotation direction and increasing the flame length at the pipe inlet, and the radial velocity change the sign.

The field influence on the flame characteristics depends on the length of the electrode, i.e. increasing the length of the axially inserted electrode leads to the increase in maximum velocity and in pressure gradient.

The application of an external magnetic field induced by permanent magnets affects the velocity distributions and does not affect much the temperature and the concentration distribution if we stay at the chosen model's bounds. The effect of magnetization perpendicular to the flow direction results in appearance of an additional vortex in the computational domain and in disturbance of the stream lines. The influence of magnetization aligned with the flow direction results in removal of the vortex in the upper left corner and in disturbance of the stream lines.

The experimental study of the electric and magnetic field effects on the thermo-chemical conversion of the mixture of wood with 20% of straw suggest that the both the electric and magnetic fields promote enhanced thermal decomposition of biomass mixture with enhanced formation, ignition and combustion of volatiles by increasing the produced heat energy per mass of burned biomass pellets and the heat output from the device.

With the positive bias voltage of the axially inserted electrode, the electric field body force leads to enhanced thermal decomposition of the biomass mixtures, to the field-enhanced combustion of the volatiles, with the correlating increase of the ion current, combustion efficiency, CO_2 volume fraction in the products and of the heat output from the device up to their peak values during the flaming combustion of volatiles, with the rapid decrease of the field effect on the combustion characteristics during the after-flame smouldering stage.

The voltage dependence of the main flame characteristics suggests that the electric field-enhanced thermo-chemical conversion dominates at $U < 1.2$ kV and starts to decrease at $U > 1.2$ kV, when the radial acceleration of the flame ions along with the field-induced radial mass transfer of the neutral flame species slows down the swirl intensity which is highly responsible for the mixing of the flame components and for the formation of the flame reaction zone.

Acknowledgements

The authors would like to express their gratitude for the financial support from European Regional Funding for project SAM 1.1.1.1./A/16/004 and Latvian Research Cooperation Project of the Latvian Concil of Science Nr. 623/2014.

References

[1] Lawton, J., Weinberg, F.: *Electric Aspects of Combustion.* Clarendon Press. Oxford, England, 1969, 650 p.

[2] Wakayama N. I.: *Behavior of Gas Flow under Gradient Magnetic Fields*, .Journal of Applied Physics, Vol. 69, No. 4, 1991, pp. 2734-2736.
[3] Kalis H., Barmina I., Zake M., Koliskins A. *Mathematical Modelling and Experimental Study of Electrodynamic Control of Swirling Flame Flows,* Engineering for Rural Development, 2016, pp. 134–141.
[4] Kalis H., Marinaki M., Strautins U., Lietuvietis O. *On the numerical simulation of the combustion process with simple chemical reaction,* Proc. the 7-th Baltic Heat Transfer conf. "Advances in Heat Transfer", August 24-26, 2015,pp. 175–180.
[5] Meeker D. *Finite Element Method Magnetics,* Version 4.2, User's Manual, 2015.
[6] Barmina I., Purmalis M., Valdmanis R., Zake M.: *Electrodynamic control of the combustion characteristics and heat energy production*. Combustion Science and Technology, 2016, vol. 188 (2), pp. 190-206.
[7] Barmina I., Valdmanis R., Zake M., Kalis H., Marinaki M., Strautiņš, U.: *Magnetic field control of combustion dynamics*. Latvian Journal of Physics and Technical Science, 2016, Vol. 53, N4, pp. 36-47.

Authors

Dr. hab. Math.&Phys. Kalis Harijs
harijs.kalis@lu.lv
Dokt. Marinaki Maksims
maksims.marinaki@lu.lv
Dokt. Ozola Liva
ozola.liiva@gmail.com
Dr. Math. Strautins Uldis
uldis.strautins@lu.lv
Institute of Mathematics and Computer Science
University of Latvia
Boulevard Raina 29
LV-1459, Riga, Latvia

Dr. Sci. ing.Barmina Inesa
inesa.barmina@lu.lv
Dr. Phys. Zake Maija
maija.zake@lu.lv
Institute of Physics
University of Latvia
Miera Street 32,
LV-2469, Salaspils, Latvia