Modelling of Gasification of Wooden Particles by Steam Plasma Jet in Thermal Plasma Reactor.

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Abstract: Three-dimensional CFD modelling of gasification of wooden particles by steam plasma jet in thermal plasma reactor has been carried out. The modelling simulates conditions in experimental reactor for biomass gasification where syngas is produced. Standard k-ε model was used for the simulation. Steam plasma properties used in the computation were determined under the assumption of existence of LTE.

Key words: numerical modelling, gasification, crushed wood, turbulence, plasma reactor

1. Introduction

Utilization of thermal plasmas for destruction of waste materials and gasification of organic waste and biomass has been in the focus of interest of scientists as well as industrial companies in recent decade. Production of harmful substances, which is main problem of non-plasma technologies for destruction of waste materials and biomass gasification, can be efficiently suppressed in plasma treatment.

Gasification of biomass in plasma generated from water was studied in experiments with plasma-chemical reactor PLASGAS with hybrid gas/water-stabilized torch with arc power up to 160 kW [1, 2]. The process offers possibility of simple control of composition and quality of produced gas. Synthesis gas with high caloric value, high content of hydrogen and carbon monoxide and low concentration of carbon dioxide, was produced. Production of higher hydrocarbons was suppressed due to higher temperatures and high level of uv radiation in the reactor volume.

Material is treated in the reactor volume that is heated by the high enthalpy steam plasma jet. Plasma torch is characterized by very low plasma mass flow rate and high plasma enthalpy and temperature. Relatively large reactor volume is heated by very low mass flow rate, constricted plasma jet with nozzle exit diameter 6 mm and the length of the potential core several centimeters. Despite of these characteristics the heating of the whole reactor volume (cca 200 l) was homogeneous and the differences in the wall temperatures found in the experiments in various positions within the reactor were below 150 K for average temperature 1600 K [1, 2].

This paper presents results of modeling of the process of reactor heating by steam plasma jet for conditions corresponding to the experiments. The modeling studied interaction of the jet with the atmosphere in the reactor volume during pre-heating period when the reactor volume is heated to the operation temperature by plasma jet. Heat transfer to the parts of the reactor close to the jet inflow position was studied by the model computations. As the composition of produced syngas is controlled in the experiments by addition of gases into the reactor, the model calculations simulated interaction of the plasma jet with the cold gas flow within the reactor volume. The aim of the paper is to analyze distributions of physical properties (temperature, density, mass fractions of gases) within the reactor volume and effect of addition of cold gases on these distributions.

2. Computing Procedure

3D simulation was made using computer code FLUENT. Standard k-ε turbulence model was used in the computation. This model is two-equation model that consist of transport equation for turbulent energy k and of transport equation for its dissipation rate ε. Net time of the computation performed on single core 3 GHz Pentium 4 processor with 1 GB RAM (used CFD software: Fluent, version: 6.3.26; operating system: Windows XP Professional) was 5 days and so we used single precision.

Following assumptions were applied in the computation: the plasma flow into the reactor is turbulent (Reynolds number at jet exit is Re = 786) and subsonic. Gravity, radiation effects and magnetic field are neglected. Steam plasma is considered to be in local thermodynamic equilibrium.

Pressure based solver with implicit formulation and energy equation that encompasses heat transfer due to conduction and convection were used in the computation. Mixture of species in the reactor consisted of 5 fluid substances: steam plasma, hydrogen, nitrogen, carbon monoxide and wood volatiles. The computation models the situation when crushed wood in a form of solid state enters the reactor after what it is heated up and volatilized. Simplified description of wood volatilization was used in the paper. We assumed that solid wooden particles are directly transformed to “wood volatiles” with composition corresponding to stoichiometric composition of used wood ($C_{1.61}H_{2.241}O$) when their temperature reaches 600 K. This gas reacts chemically with steam plasma and syngas (mixture of CO and H_2) is produced. This chemical endothermal reaction is represented by a source term in the computations. As the real flow in the reactor is only mildly compressible we decided to neglect the compressibility effects on the flow and also on chemical kinetics and to use incompressible approach. Chemical reaction was treated in each computational cell as turbulent or finite-rate depending on which effect is dominant at that cell: turbulence or laminar flow. Eddy dissipation model was used if turbulence is dominant and finite rate model was used in laminar flow regions. Physical properties of all gas species used in the computations, namely: density, heat capacity, thermal conductivity and viscosity were computed assuming existence of LTE by methods described in [3, 4]. These properties were defined in all calculations in piece-wise linear form and they are only temperature dependent as we employ incompressible flow. No other user defined sources were implemented to governing equations. Physical properties of solid wood were based on values commonly available in tables and properties of wood volatiles were evaluated as for ideal gas consisting of molecule $C_{1.61}H_{2.241}O$ at a temperature of 600 K. Wooden particles injected to hot steam plasma flow were treated as inert droplets and they were subject to heating, melting, boiling and evaporating. These processes were caused by the heat given from steam plasma to the droplet via thermal conduction. Nitrogen that is present in the reactor is inert but it must be taken into account, because in real experiments it is present in free spaces among crushed wood.

The dimension of calculation domain that is presented in Fig. 1 and in Figs. 3-5 is h = 1.102 m (y-coordinate, height); w = 0.793 m (x-coordinate, width); d = 0.57 m (z-coorinate, depth). Inner total volume of the calculation domain (reactor chamber) is $V = 0.206\ m^3$.

Plasma jet characteristics at the input into the reactor correspond to the experimental conditions in [1, 2] and are as follows: mean velocity v=2635 m/s; centerline velocity v_c=4407 m/s; mean temperature T=14500 K; centerline temperature T_c=23000 K; mean enthalpy H=185 MJ/kg; mean density $\rho=3.64\times10^{-3}\ kg/m^3$; centerline density $\rho_c=1.23\times10^{-3}\ kg/m^3$. Wall temperature of the reactor was constantly set to 1300 K which corresponds to the conditions in the experiment [1, 2].

Wooden particles characteristics are as follows: total mass flow rate Q_m= 2 g/s; initial temperature of wooden particles: T_i=285 K; velocity magnitude: v_m= 0.5 m/s; minimum diameter: d_1=1 mm; mean diameter d_m=2 mm; maximum diameter d_2=3 mm. Rossin–Rammler diameter distribution was used for the particles at their entrance to the reactor.

Grid used in all our simulations contained approximately 1.2 million nodes and was of variable node density. It means that close to plasma jet input (where velocity of steam plasma approaches the value of 2635 m/s) the node density is ten times higher than it is in areas of low velocity magnitudes (e.g. in lower parts of the reactor chamber and in exhaust pipe). Third-order MUSCL scheme was applied to the the grid to reduce numerical diffusion and due to the use of this scheme the computation possess third-order of accuracy for diffusive and conductive terms.

Computation reached good convergence level. It means that at the end of every computation the values of all monitored residuals (i.e. specific measures of convergence) were below the value of 1/1000.

3. Results and discussion

All results are presented as a 2D cut (namely xy plane, z=0) of 3D distribution of each particular physical property. In Fig. 1 the temperature distribution within the reactor is given. Temperature distribution in the reactor is not homogeneous but average temperature

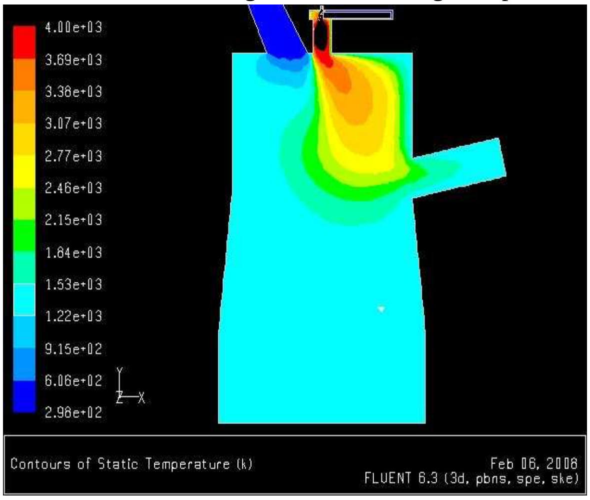

Fig. 1. Temperature distribution
in the reactor (global view)
(Range 298 K – 4000 K)

(about 1600 K) is sufficient for efficient gasification. In lower parts of the reactor chamber the temperature equals 1250 K what is close to measured temperature of reactor walls. It is also positive that there is a non-negligible area with higher temperature (about 2500 K - 3000 K) located at upper right corner of the reactor chamber in positions where wood comes into first contact with plasma. Black areas within the reactor in its upper part correspond to physical values that are out of range according to actual scale that is always given in left side of a corresponding figure.

In Fig. 2 we see the shape and dimensions of plasma jet close to the plasma torch exit nozzle. The black region corresponds to temperatures higher than 4 000 K.

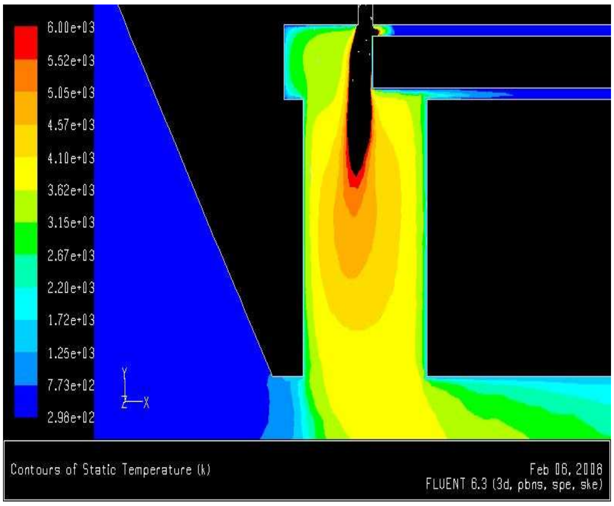

Fig. 2. Plasma Jet
(Temperature range 298K-6000K)

In Fig. 3 there are contours of mass fraction of hydrogen. It is clearly visible that the highest concentration of hydrogen is at the central part of the reactor chamber where it is produced as a result of interaction of wood with plasma.

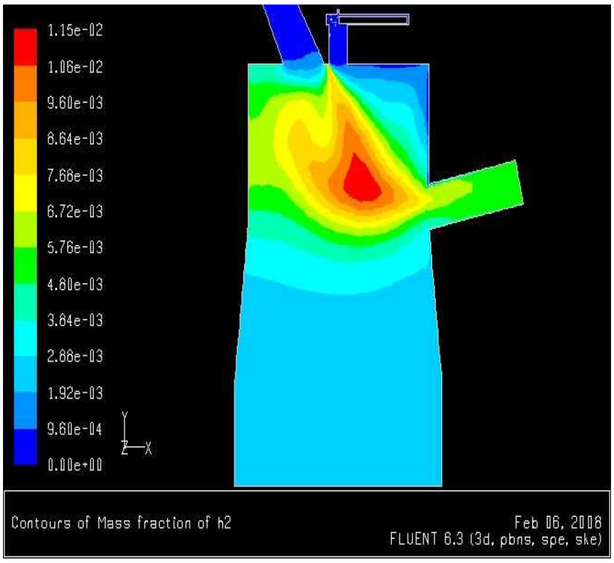

Fig. 3. *Contours of mass fraction of* H_2
(Range 0-0.0115)

In Fig. 4 we can see that in the right upper part of the reactor there is higher mass fraction of steam plasma what is caused by not ideal mixing of flows.

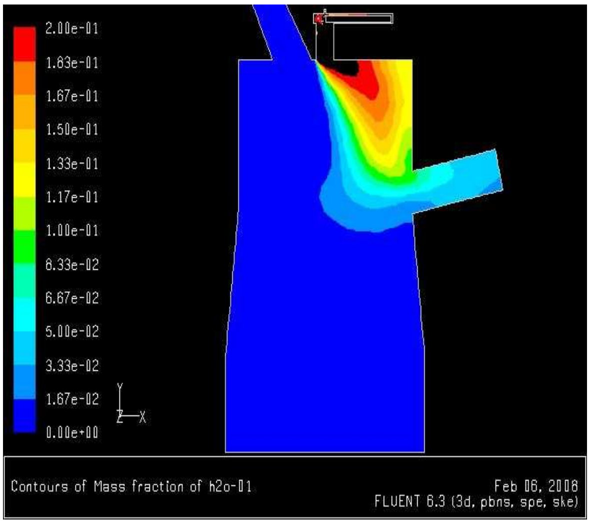

Fig. 4. *Contours of mass fraction of steam*
(Range 0-0.2)

In Fig. 5 the density of gas mixture in whole reactor is given. We can see that the highest density is located at the entrance tube for wooden particles and

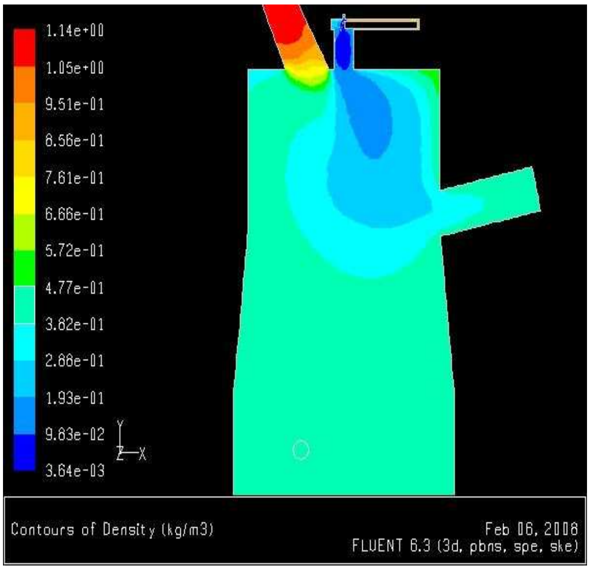

Fig. 5. Distribution of density
(Range 0.00364 kg/m^3*- 1.14* kg/m^3)

the lowest density is at plasma entrance because temperature is highest at that region.

4. Conclusion

Results published in the paper gave us satisfactory preview of processes that take place in the reactor during the process of gasification of wooden particles because they were in relatively good agreement with experiment. It means that for example temperature distribution of gas mixture is modeled on satisfactory level (according to good correspondence with experimental data). Further improvement of the model will be concentrated on more detailed description of heat and mass transfer between gasified particles and surrounding hot gas.

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