# A Comprehensive CFD Model for Sugar-Cane Bagasse Heterogeneous Combustion in a Grate Boiler System

Daniel J. O. Ferreira, Juan H. Sosa-Arnao, Bruno C. Moreira, Leonardo P. Rangel, Song W. Park

***Abstract*—**The comprehensive CFD models have been used to represent and study the heterogeneous combustion of biomass. In the present work, the operation of a global flue gas circuit in the sugar-cane bagasse combustion, from wind boxes below primary air grate supply, passing by bagasse insertion in swirl burners and boiler furnace, to boiler bank outlet is simulated. It uses five different meshes representing each part of this system located in sequence: wind boxes and grate, boiler furnace, swirl burners, superheaters and boiler bank. The model considers turbulence using standard k-ε, combustion using EDM, radiation heat transfer using DTM with 16 ray directions and bagasse particle tracking represented by Schiller-Naumann model. The results showed good agreement with expected behavior found in literature and equipment design. The more detailed results view in separated parts of flue gas system allows observing some flow behaviors that cannot be represented by usual simplifications like bagasse supply under homogeneous axial and rotational vectors and others that can be represented using new considerations like the representation of 26 thousand grate orifices by 144 rectangular inlets.

***Keywords*—**Comprehensive CFD model, sugar-cane bagasse combustion, sugar-cane bagasse grate boiler.

## I. Introduction

THE thermodynamic analysis like "black box" which variables and parameters in the inlet, outlet and boundaries are already well known for combustion systems such as boilers and furnaces. However, this tool cannot provide local information about what happens with operational variables inside the control volume, it would necessary to know the flue gas flow inside it.

The bagasse or biomass grate boiler operation is composed by a large amount of complex simultaneous processes, but the most important can be considered the bagasse heterogeneous combustion inside furnace under turbulent flue gas flow. The flow motion is mathematically described by Navier-Stokes equations that can be solved numerically by Computational Fluid Dynamics (CFD).

Woodfield [1] presented a 3D modelling to represent the periodic behavior of grate pile combustion which is inserted in few layers of computational cells in furnace bottom of the University of Sidney comprehensive CFD model. The resultant model considers two phase coupling with momentum, mass and heat exchange by Euler-Lagrange approach and the drying and volatilization governed by Arrhenius [1].

A comparison of combustion to bituminous coal and biomass (white straw) evaluating the adaptation of a combustion CFD model to laminar drop-tube furnace was presented in [2]. The simulation strategy to heterogeneous combustion is like coal combustion by analogy considering three steps: raw straw volatilization, and combustion of released volatiles and resulting char.

A CFD was applied to combustion model to simulate and evaluate two different Low-$NO_x$ biomass grate furnaces [3]. The isothermal flow results predicted erosion rates inside boiler and simulations considering three steps reaction, two of the represented by EDM and CO oxidation by FRC model revealed potential to increase CO combustion through geometry furnace and secondary air nozzles modifications.

In 2006 an integrated 3D CFD combustion model with a 2D grate bed model to model was presented by[4] using the same principle of [1] to simulates the quasi-transient operation inside a biomass (straw) boiler. The model considers a complex mechanism to ash formation, transport and deposition in boiler walls and superheaters surfaces. The velocity, temperature and composition of gas continuum phase are simulated under steady state but ash particle deposition is modeled in transient post processing calculations.

Shanmukharadhya and Sudhakar [5] use a CFD model inside the boiler furnace to evaluate and predict the influences of bagasse moisture on pre-ignition zone, flame delay ignition and combustion stability. The work provides a large amount of simulation parameters and methodologies very useful to build a CFD comprehensive model as Arrhenius constants to volatilization, bagasse proximate and ultimate analysis, boundary conditions, etc.

Maier et al. [6] present stationary and transient results to gas-phase combustion in an Australian biomass furnace evaluating different air supply strategies. It was considered turbulent flue gas flow represented by RANS SST model and homogeneous volatiles combustion by Eddy Dissipation Concept using a global mechanism with three equations and a detailed mechanism to $CO/H_2$ combustion with 11 species and 30 reactions.

The majority of previous works have focusing on evaluate and study the flue gas flow just inside boiler furnace, not considering the flow in the rest of combustion system. In the

Daniel J. O. Ferreira and Song W.Park are with the University of São Paulo, São Paulo. Chemical Engineering Department, Av. Luciano Gualberto 380 trv.3.05508-900. São Paulo SP, Brazil (e-mail: chaada@gmail.com, sonwpark@usp.br).
Juan. H. Sosa-Arnao is with the Equipalcool Sistemas Research and Development Department. Rua Sto Onfre 299, Vila Industrial 14177-005, Sertãozinho SP, Brazil (corresponding author phone: +55 16 3513-8000; e-mail: juan@equipalcool.com.br).
Leonardo P. Rangel is with the ESSS Engineering Simulation and Scientific Software–Rua Orlando Phillipi, 100, Saco Grande EdifícioTechplan, 1° andar. 88032-700. Florianópolis SC, Brazil (e-mail: leonardo@esss.com.br).

present work, a comprehensive CFD model to heterogeneous combustion of sugar-cane bagasse is developed to describe the air flow and flue gas flow of the global circuit of a sugar-cane bagasse grate boiler considering geometries from wind boxes below primary air grate, passing by bagasse insertion in swirl burners and boiler furnace, until boiler bank outlet.

## II. Methodology

To the present work, it was done CFD simulations considering isothermal uniform gas phase flow, heat transfer uniform phase flow and heterogeneous two phase flow conditions to five domain geometries in ANSYS CFX 14.5.7.

The circuit simulated in the CFD model is composed by five geometries enumerated below:

1. Windboxes below primary air grate;
2. Swirl burners;
3. Bagasse boiler furnace;
4. Super heaters (external region)
5. Boiler banks (external region)

Fig. 1 shows the strategy used to link the simulations of these geometries.

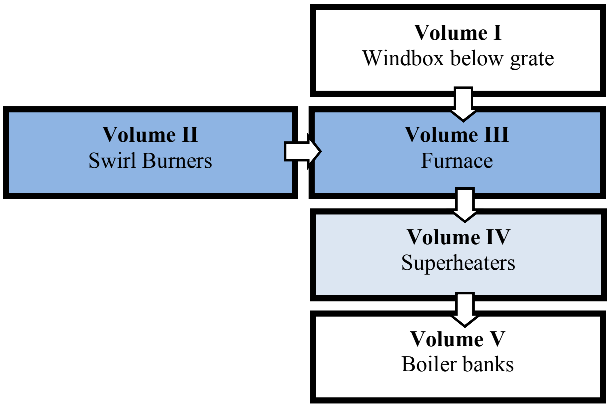



Fig. 1 Sequence of the geometries considered in the CFD model simulation of the sugar-cane bagasse boiler

Due to computational limitation to process a huge amount of mesh elements, this division was necessary. The information about flue gas flow outlet of each geometry was exported as inlet condition to the next one. The geometries of domains 1 and 5 (Windboxes below grate and Boiler banks) are simulated under isothermal conditions. The geometries 2 and 3 (Swirl burners and Furnace) are simulated considering heterogeneous combustion of bagasse particles. The simulation of the geometry 4 (Superheaters) considers homogeneous flue gas flow with heat transfer.

The standard k-ε model was used to represent fluid flow to in the 4 of 5 domains. To simulate the swirl burners, it was used the RNG k-ε model because it presents results more adequate to flow under predominant rotation [7]. The homogeneous combustion inside combustion chamber is represented by the Eddy Dissipation Model (EDM) because the operational conditions inside boiler furnace provides high oxygen and temperature available enough to consider combustion of volatiles be governed by turbulent mixing determined by turbulent time scale, k/ε [8]. To estimate the composition of the volatiles released, it was utilized the proximate and ultimate analysis obtained from University of São Paulo –Ribeirão Preto laboratory and IPT-SP (Institute of Technology Research – São Paulo) to sugar cane bagasse samples from south-eastern Brazil. The chemical mechanism to homogeneous combustion is composed by two reactions:

$$CH_4 + O_2 \rightarrow CO + H_2O \quad (1)$$

$$CO + O_2 \rightarrow CO_2 \quad (2)$$

The $CH_4$ represents the set of light hydrocarbon species released from bagasse particles in volatilization stage. The radiation heat transfer is represented by Discrete Transfer Method (DTM) that considers the isotropic emission, reflection and spreading of the radiation intensity [9] in 16 directions equally spaced for whole computational domain. Despite the one-way coupling is adequate to represent the momentum exchange between disperse and continuous phases due to low particles concentration in the computational domain, the heat exchange between those phases needs to be represented by two-way coupling. By one hand, all gaseous fuel comes from volatilization and char consumption of bagasse particles combustion stages; by the other hand it is necessary heat flux from gas phase to bagasse particles to activate the process of heterogeneous combustion process. Therefore, there is a two-way exchange of influences between the considered phases. The Schiller-Naumann model can be used to represent the bagasse particles dragging inside boiler furnace. It considers each solid particle as rigid sphere.

The size diameter distribution of the particles is obtained from [10] and is presented in Table I.

TABLE I
Bagasse Particle Size Distribution Used in the Simulations of the Swirl Burners

| Size, sieve opening (mm) | Mass fraction |
|---|---|
| 5,660 | 0,0645 |
| 2,830 | 0,0965 |
| 1,190 | 0,1291 |
| 0,590 | 0,3160 |
| 0,297 | 0,2585 |
| 0,149 | 0,1125 |
| 0,050 | 0,0229 |

Table II presents the proximate and ultimate analysis based on [11] and Equipalcool Sistemas data.

TABLE II
Proximate and Ultimate Analysis for Bagasse

| Proximate analysis | | Ultimate analysis | |
|---|---|---|---|
| Material | Mass frac. | Element | Mass frac. |
| Ash | 0.0244 | C | 0.4759 |
| Moisture | 0.0200 | H | 0.0573 |
| Char | 0.1095 | O | 0.4195 |
| Volatiles | 0.8461 | N | 0.0019 |
| LHV | 6.6 MJ/kg | S | 0.0006 |
| Reference | 25°C, 1 atm | Cl | 0.0004 |

The Arrhenius parameters to volatilization rate are from [12]:

$$A = 2{,}13\text{x}10^{6}\ s^{-1} \quad (3)$$

$$E = 92\ 600\ \text{J/mol} \quad (4)$$

*A. Volume I*

The set of windboxes is composed by 6 vertical rectangular pipes and distribution boxes with the same design each one. The outlet of all geometry is referent to the grate, which is the primary air inlet in the boiler furnace, composed by around 140 thousand orifices. As the geometry gas dimensions in order of 101 m and orifices with scales in order of 10-2m, the refined mesh needed next to domain outlet would require an impracticable computational capacity. So, to make it possible, it was simulated just one column corresponding to a 1/6 of whole geometry of Volume I. This simplification reduces the number of orifices from 140,000 to 26,000. The velocity profiles obtained in the orifices are exported to be used in the simulation of the Volume III (Furnace) as primary air inlet. The comparison between the complete geometry and the simplified is shown in Fig. 2.

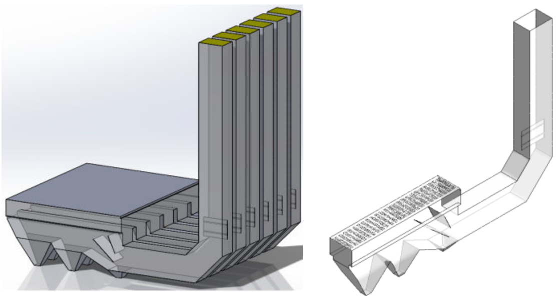


Fig. 2 Geometry simplification of the Volume I

The boundary geometries are presented in Table III.

TABLE III
BOUNDARY CONDITIONS

| Surfaces | Type | Value |
|---|---|---|
| Rectangular pipe | Inlet | 13 kg/s |
| Orifices | Outlet | -49 Pa |
| Lateral next to outlet orifices | Symmetry | - |

*B. Volume II*

The bagasse boiler of this study operates with six swirl burners at alternating rotation directions. So to obtain flow profiles to be exported to Volume III, It is necessary to simulate two cases of swirl burner: clockwise and anti-clockwise directions. As it is necessary to obtain just the velocity and temperature fields to be exported to Volume III simulation in the surface where the flow and particles flows from burner to boiler furnace, the domain is cut in subdomains: swirl burner and farfield. The subdomains and the interface surface are illustrated in Fig. 3. The corresponding boundary conditions are shown in Table IV.

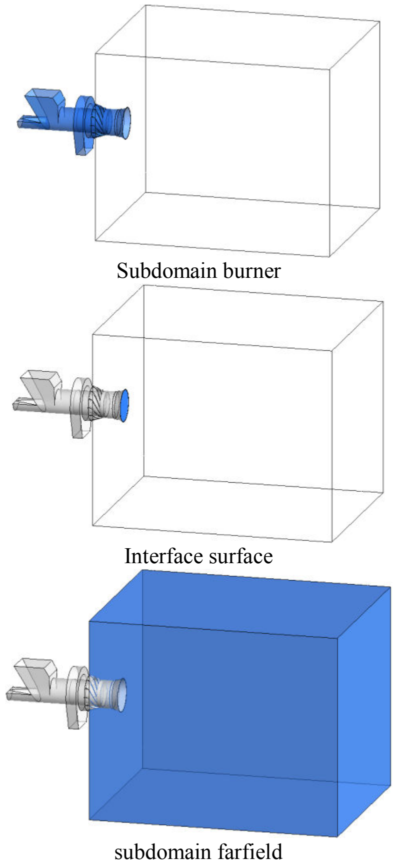



Fig. 3 Subdoamins and interface surface created to simulations of the Volume II

TABLE IV
BOUNDARY CONDITIONS USED IN THE SWIRL BURNER SIMULATIONS

| | | | | |
|---|---|---|---|---|
| Domain | Ref. Pressure | 1atm | | |
| | Ref. Density | 0.66 kg/m$^3$ | | |
| | Turbulence | RNG k-ε | | |
| | Phase coupling | 2 way, Schiler-Naumann | | |
| | Gravity | X (m/s$^2$) | Y (m/s$^2$) | Z (m/s$^2$) |
| | | 0 | -9.81 | 0 |
| Inlet | | Mass flow | Temperature | $O_2$* |
| | Axial | 0.620 kg/s | 25°C | 0.232 |
| | Bagasse (air) | 0.070 kg/s | 60°C | 0.232 |
| | *particles* | *4.130 kg/s* | *60°C* | *0.232* |
| | Tangenctial | 0.690 kg/s | 25°C | 0.232 |
| | Ascendent | 2.000 kg/s | 600°C | 0.232 |
| Walls | Temperature | Adiabatic | | |
| Outlet | Opening | Pressure | Temperature | $O_2$* |
| | | -49 Pa | 600°C | 0.232 |

* mass flow

*C. Volume III*

The furnace can be considered the most important part of this work. Its geometry considers the imported air supply from Volume I as primary air and six profiles imported from Volume II as swirl burner air supply. It was used 3 copies of clockwise simulation profiles and 3 copies of anti-clockwise simulation profiles, in alternated order. Additionally it was considered all secondary air inlets in lower level (in the rear wall next to grate surface) and in superior level (interlaced in both front and rear walls). It does not consider the superheaters region and the outlet surface is divided in two because it was not possible to simulate all pipes, only half of them. The strategy of simulation of Volume IV is discussed in the next section. The geometry and the main boundary conditions are illustrated in Fig. 4. The boundary conditions specifications for Volume III are presented in the Table V.

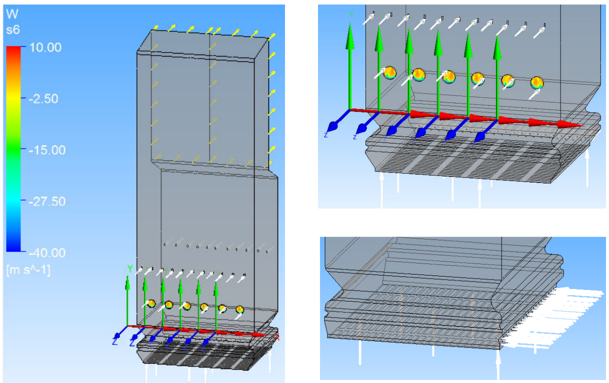



Fig. 4 Geometry and main boundary conditions used in the simulations of the Volume III

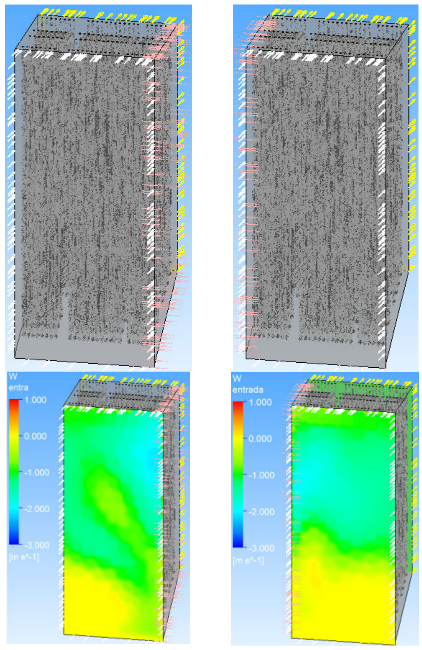
TABLE V
BOUNDARY CONDITIONS USED IN THE VOLUME III SIMULATIONS

| Boundary condition | Specification | Observations |
|---|---|---|
| Inlet | | |
| ar1 | Vol. I* | velocity and temperature |
| ar2FT | 22.4 kg/s, 150 °C | upper level secondary air |
| ar2G | 6.06 kg/s, 50 °C | lower level secondary air |
| s1, s3, s5 | Vol. II clockwise* | velocity and temperature |
| s2, s4, s6 | Vol. II anti-clockwise* | velocity and temperature |
| Particles supply | s1- s6 | |
| Bagasse | 4,13 kg/s, 150 °C | |
| Particles | 10000 | |
| Walls | No slip wall, 285 °C | |
| Radiation | Emissivity: 0.85 | |
| | Diff. Fraction: 1.0 | |
| Outlet | Type: Open | |
| outlet_L | - 49 Pa | |
| outlet_R | - 49 Pa | |

*imported profiles

### D. Volume IV

Due to computational limitation to represent the all superheaters pipes, it was necessary simulate half of Volume IV domain. Despite it is not simulated combustion in this domain, the heat transfer is considered in these simulations. The two geometries with respective boundary conditions are shown in Fig. 5. The boundary conditions specifications are presented in Table VI.



Left side Right side

Fig. 5 Geometry and main boundary conditions used in the simulations of the Volume IV

TABLE VI
BOUNDARY CONDITIONS USED IN THE VOLUME IV SIMULATIONS

| Boundary condition | Specification | Observation |
|---|---|---|
| Simulation | left side | Imported velocity and temperature profiles |
| inlet | Vol. IIIL | |
| symmetry | right surface | |
| outlet | -49 Pa | |
| Simulation | right side | Imported velocity and temperature profiles |
| inlet | Vol. IIIR | |
| symmetry | left surface | |
| outlet | -49 Pa | |

### E. Volume V

The geometry of the boiler banks is more complex and has more small details than other domains. So, even with the domain cut in right and left sides, the geometry had to be divided in the two subdomains in forward direction to allow the construction and processing of the computational mesh. For this domain, the simulations consider isothermal flue gas flow. The first part of Volume V is called *Volume VA* and the last one is called *Volume VB*. The inlet boundary condition for the Volume VB imports the outlet velocity profile from Volume VA. The division strategy to right side and the respective boundary conditions are illustrated in Fig. 6 and Table VII.

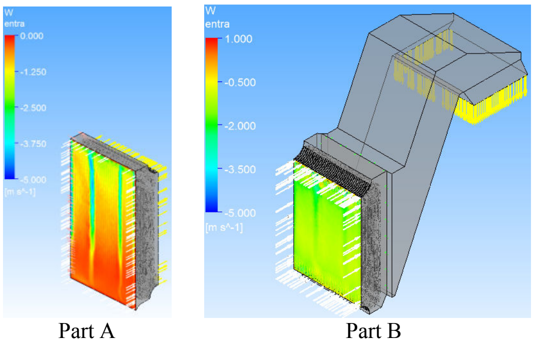



Fig. 6 Geometry, subdomains and main boundary conditions used in the simulations of the Volume V

TABLE VII
BOUNDARY CONDITIONS USED IN THE VOLUME V SIMULATIONS

| Boundary condition | Specification | Observation |
|---|---|---|
| Volume VA | 1st part | Imported velocity and temperature profiles |
| inlet | Vol. IV | |
| outlet | -49 Pa | |
| Simulation | 2nd part | Imported velocity and temperature profiles |
| inlet | Vol. VA | |
| outlet | -49 Pa | |

## III. RESULTS

As presented in the methodology, all results are presented for each domain.

### A. Volume I

The velocity profiles obtained are showed to isometric and superior views in Fig. 7:

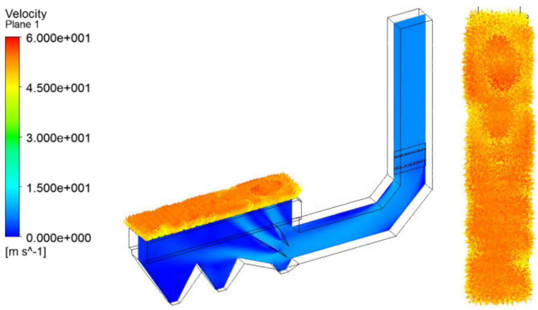



Fig. 7 Velocity profiles obtained to windboxes below primary air grates of Volume I.

The defector plates and the pressure drop produced by orifices promotes an uniform primary air flow to be delivered in the furnace. To evaluate the behavior of flow downstream the grate orifices the volume rendering to velocity profile is showed in Fig. 8.

### B. Volume II

As expected, the flow behavior obtained is similar to the two rotation directions, which evidences that the obtained flow is symmetrical about the rotational direction. So, the showed results correspond to anti-clockwise direction geometry. The big particles penetrate more inside far field than medium and small ones. The small particles are dragged by ascendant flow near the burner exit. The vertical velocity and $O_2$ consumption profiles and the trajectories of 90 bagasse particles plotted with char mass fraction are illustrated in Fig. 9.

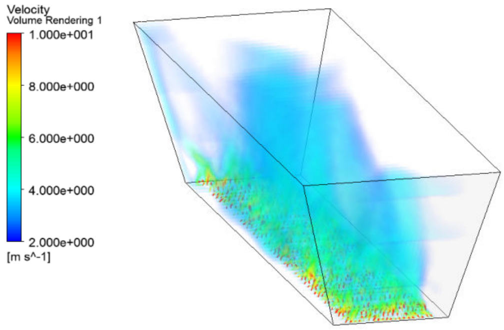
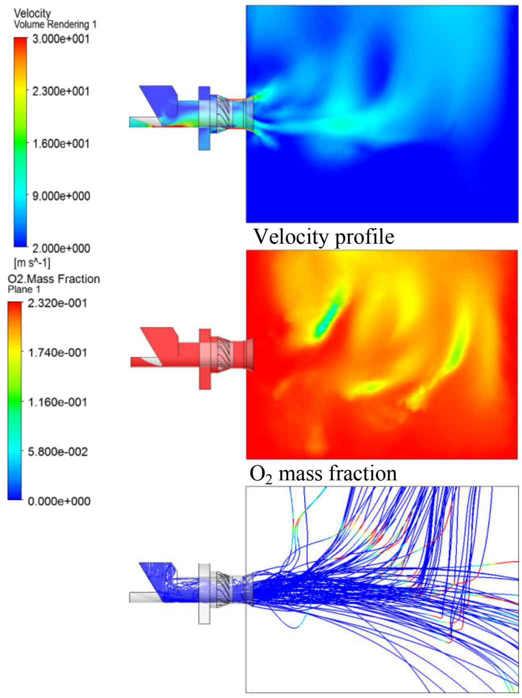



Fig. 8 Volume rendering to velocity profile obtained downstream the grate orifices of Volume I.




Char in particle trajectories

Fig. 9 Vertical profiles of velocity and $O_2$ mass fraction and char concentration plotted in 90 bagasse particle trajectories

It can be observed that the combustion and, consequently, the combustion and temperatures are governed by flow mixing promoted by the swirl burner, therefore the $O_2$ is the only one parameter that varies monotonically with combustion advance. The char concentration visualized in the particle trajectories can show an estimation of flame front because it is expected that char is produced when volatiles are released from bagasse burning. Fig. 10 illustrates the temperature profile in the interface surface between the two subdomains of Volume II and in the bagasse particles.

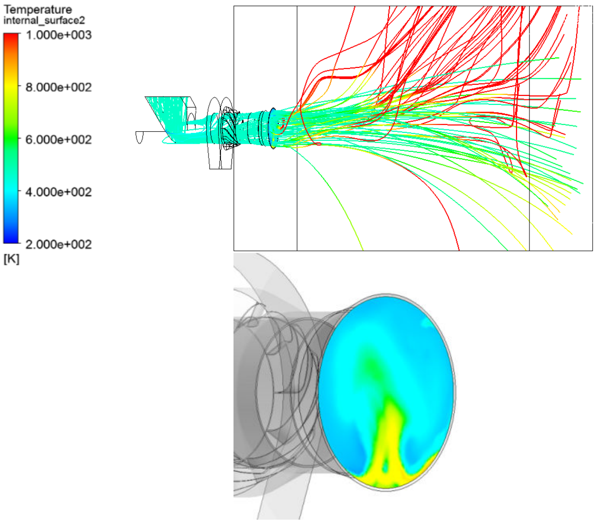



Fig. 10 Temperature profile in the interface surface between the two subdomains of Volume II and in the bagasse particles

It can be observed that the temperature profile for gas phase must be exported but the temperatures for particle trajectories look be uniform around 600 K. So, as the particles are dragged by air flow under consideration of zero reference velocity, there is no need to export information about particle trajectories.

### *C. Volume III*

Fig. 11 show volume rendering to velocity and temperature obtained in the furnace.

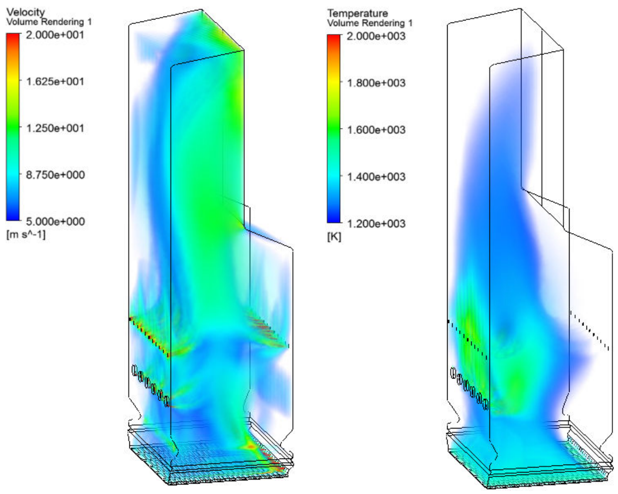



Fig. 11 Volume rendering to velocity and temperature profiles of simulations of Volume III

According to volume rendering obtained to velocity and temperature, it can be observed that interlaced upper secondary air supply keeps high mixing and high temperatures below its level. Above the same level the flue gas flow presents a uniform behavior but there is a central core of high temperature values near front walls. To evaluate the dependence of temperature profile with combustion advance, the volume rendering of CO mass fraction is presented in Fig. 12. The $O_2$ and $CH_4$ mass fraction profiles presented predominant vertical variations due to high lateral mixing promoted by lower secondary air supply level, observed in the volume rendering velocity profile of Fig. 11. As CO is the only compound present in both chemical reactions of homogeneous combustion mechanism, it can be used to analyze the combustion advance in the boiler furnace.

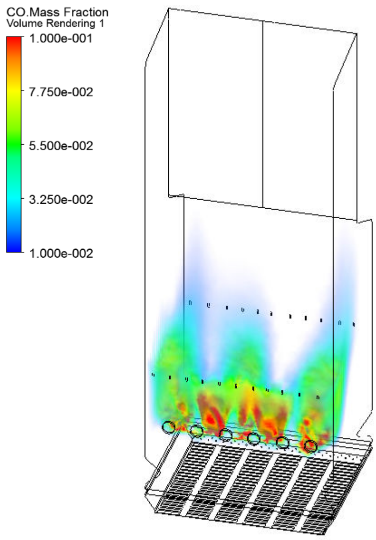



Fig. 12 Volume rendering to CO mass fraction profile of simulations of Volume III

The volume rendering of CO mass fraction evidences the interaction between neighbor burners supplying combustion air and fuel particles in different rotation directions. It also can be observed that temperature profile of Fig. 11 is partially influenced by flue gas flow and by chemical consumption of released volatiles. The regions with high temperatures are localized next to front and lateral walls, but there is a ascendant preferential channel of temperature and velocity in the middle of boiler above upper secondary air level.

### *D. Volume IV*

The horizontal velocity profiles and vertical profiles at the outlet surface of the two sides of the superheaters domain are presented in Fig. 13.

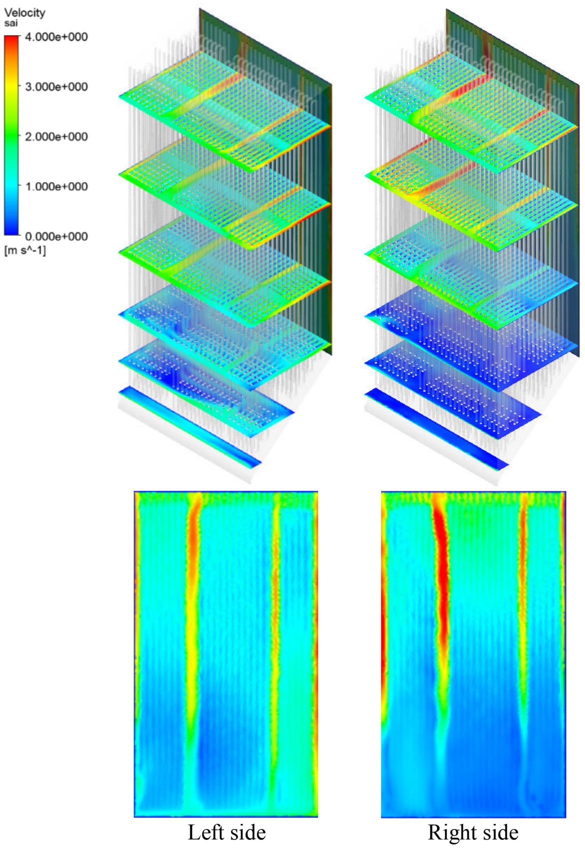



Fig. 13 Horizontal velocity profiles passing through superheaters and vertical velocity profiles at outlet surface of Volume IV

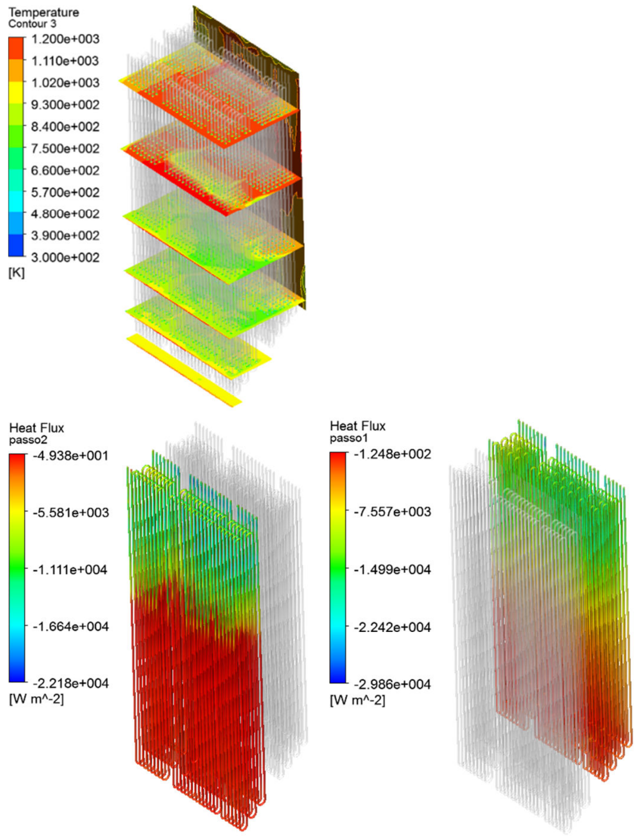



Fig. 14 Horizontal temperature contours and heat flux in external surfaces of superheaters pipes of simulation of Volume IV

It can be seen that the presence of pipes promotes a significant pressure drop and increases the uniformity of the flue gas at the Volume IV outlet and the resulting velocity profiles at the outlet can be considered similar to both superheaters region. As this region is called of convection heat transfer zone, the next analysis about the thermal behavior of flue gas flow could be done for only one side. Fig. 14 presents temperature profile in contours and heat flux profiles at external surfaces of superheaters pipes.

It can be observed that the heat transfer in lower part of pipes is more efficient than upper part. It can be an evidence of possible preferential high temperature flow channeling and source of corrosion due thermal gradient in the same metallic structure.

### *E. Volume V*

As the simulations of the boiler banks consider isothermal conditions, Fig. 15 shows horizontal velocity profiles of flue gas flow to the subdomains Volume VA and Volume VB.

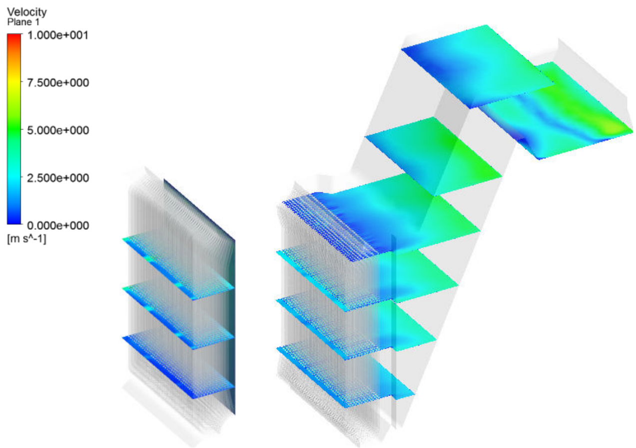



Fig. 15 Horizontal velocity profiles passing through boiler banks of Volume VA and Volume VB

It was found that flow at outlet surface does not present lateral variation and the straightforward variation of velocity would be promoted by the sharp curve next to computational domain of Volume VB.

## IV. Conclusions

The simulation of the global circuit of a Brazilian sugar-cane bagasse grate boiler was done with several simplifications in the geometry, physical models and boundary conditions.

The results presented velocity, temperature and chemical species profiles in good agreement with equipment design and the expected behavior of flow inside the system. The use of comprehensive CFD modeling can be very useful in the evaluation, analysis and optimization of bagasse grate boilers.

## Acknowledgment

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