www.serd.ait.ac.th/reric

Flow Field and Thermal Behaviour of Bagasse in a Furnace with Tangential Over Fire Air System

K. S. Shanmukharadhya*

Abstract *– Furnaces with tangential over fire air system are vortex-combustion units and are widely used in modern steam generation units of industrial plants. In these furnaces, the fuel particles are accelerated by the distributor air jets to enter the furnace chamber. As soon as they enter the furnace, they are further subjected to undergrate air and tangential over fire air, which helps in rapid mixing of the fuel with air. The present study provides computational and experimental investigations made on an industrial biomass-fired furnace with spreader stoker suspension burning. The influence of tangential over fire air system on temperature distribution and the flow model of the turbulent reacting flows across the tangential plane are well predicted. Also, the thermal behaviour of the fuel which influences the combustion is investigated. The predicted temperature distribution along the tangential plane is in good agreement with the temperature measured at tangential plane level. The model prediction gives higher heat flux and gas concentration on walls than at the center.*

Keywords – Bagasse, combustion, tangential plane, temperature, turbulence.

1. INTRODUCTION

Bagasse is a by-product of sugar milling and an important fuel for that industry. It is a fibrous, low-density material with a very wide range of particle sizes and high moisture content. Bagasse consists of three components namely pith, fiber and rind mixed in different proportions [1].

The primary source of combustion instability in bagasse-fired furnaces is believed to be the higher moisture content of the fuel. The delay to ignition due to the drying of the bagasse lead to a cyclic pattern of material depositing, drying and then burning on the grate. While the majority of the bagasse burns in suspension, the presence or absence of material burning on the grate has a significant effect on the stability of the furnace [2], [3].

Tangentially fired furnaces are units with four, six, eight or more sides, with fuel and air supplied tangentially from the furnace corners or near the corners [4]. Furnaces with tangential over fire air system to aid the suspension burning are vortex-combustion units and are widely used in modern days in steam generators of thermal power plants. The flow pattern, thermal and combustion fields inside the furnace depend on many parameters such as air flow rate, fuel and the inclination of the tangential air ducts. In this furnace, the jets of air coming from the ducts are directed tangentially to an imaginary circle in the middle of the furnace in such a way that a vortex is created, which would be moved upwards. The limits of the ignition are found to depend on the size of the vortex and the inclination angle [5]. Vortex motion with proper design may, to a large extent, prevent or minimize slogging of the furnace walls and erosion due to impingement and local over heating. Efficient mixing due to this vortex motion ensures reliable combustion with uniform temperature distribution and uniform heat flux distribution to the furnace walls. Available experimental measurements were used for validating the calculation procedure. Regions of very high temperature appear close to the furnace walls due to the effect of tangential over fire air system. In order to gain insight into the location of flow fields and thermal distribution at the tangential plane, temperature measurements were made at tangential plane level in an industrial size bagasse-fired furnace. The furnace was modeled by using three dimensional computational fluid dynamics package FLUENT 6.2 with 99% confidence level by incorporating various sub models. The experimental data set provides a valuable base for the validation of the computational side of this present work.

Some investigations have been carried on predicting the unstable regimes in the furnace due to various operating conditions and stated that that the steady state and time dependant calculations suggest a higher level of instability than indicated by measurements of the test furnace[6].

In the present work, the furnace has tangential over fire air system. Only air comes from the tangential ducts. The fuel is sugar cane bagasse, a residual fuel from sugar mill. It enters the furnace separately from the bagasse spreaders on the front wall. The flow of bagasse into the combustion chamber is aided by the jets of distributor air situated at the bottom of the bagasse spreader. The main source of air for combustion is the undergrate air coming from the bottom through the grate. Nearly 65% of the total air is coming from the undergrate, 30% from the tangential ducts and remaining 5% from the distributor ducts.

The sugarcane residues can be divided into bagasse and trash [7], [8].The furnace used for the test is a spreader stoker furnace with traveling grate. The test boiler operates at a nominal power of 20 MW.

2. TEST PROCEDURE

The boiler operating parameters were noted regularly during the test period. The percentage of moisture of the fuel was tested during the test period by using a moisture analyzer. A specially-built k-type chromel-alumel thermocouple in flexible stainless steel tube was used to measure the temperature. A digital temperature indicator

---

* Professor, Department of Mechanical Engineering, Bannari Anman Institute of Technology, Sathyamangalam, India 638401.
E-mail: kss_bit05@yahoo.co.in

was used to record the temperature. The measurements were made at several points at the level of tangential over fire windows level at a height of 3.8 meter above the grate. Also temperatures were recorded at various points on the furnace. Figure 1 shows the locations of the tangential over fire air locations. The measurements were made several times and the average values were recorded. In the present work, temperature measurements were made at tangential air ducts level and at the points of key interest to know the influence of the tangential air on the distribution of temperature. Also, thermal analysis of the bagasse was carried out by using sophisticated instruments and found that the particles behave differently with respect to their sizes and moisture contents.

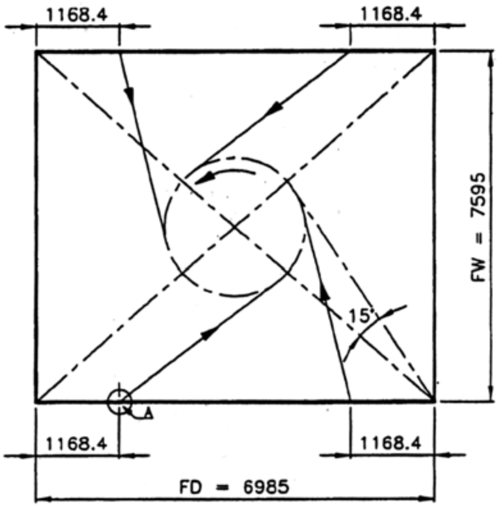

Fig. 1. Tangential over fire air system

3. COMPUTATIONAL MODELING

The furnace was modeled by using three dimensional Computational Fluid Dynamics package FLUENT. The segregated implicit solver was used for solving the transport equations. The turbulence was modeled by standard $k-\varepsilon$ model. Radiation was modeled using P-1 model. Single-mixture fraction approach was used for combustion and combustible particles were assumed for bagasse particles. The turbulence kinetic energy k and its rate of dissipation ε were obtained from the following transport equations.

$$\rho\frac{Dk}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\mu_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k+G_b-\rho\varepsilon-Y_M \tag{1}$$

and

$$\rho\frac{D\varepsilon}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\mu_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{2}$$

In these equations, G_k represents the generation of turbulent kinetic energy due to the mean velocity gradients. G_b is the generation of turbulent kinetic energy due to buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. $C_{1\varepsilon}, C_{2\varepsilon}$, and $C_{3\varepsilon}$ are constants. σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively.

Flow Model

The entrained particle phase was modeled using Lagrangean method to include the effect of mass, momentum and energy that characterize the change in particle properties along particle trajectory as it moves through the gas continuum [9].

$$\frac{dm_p}{dt}=-R_p \tag{3}$$

$$m_p=\frac{du_p}{dt}=\sum F_p \tag{4}$$

The variable m_p is the mass of the particle and R_p is rate of change of mass due to phenomena such as droplet vaporization, particle devolatilization, or char oxidation; u_p is the velocity of the particle and F_p is the sum of the various forces acting on the particle such as drag and gravity.

Radiation Model

The radiative heat transfer model P-1 chosen was based on the expansion of the radiation intensity I into an orthogonal series of spherical harmonics. The radiation flux q_r was obtained by:

$$q_r=-\frac{1}{3(\alpha+\sigma_s)-C\sigma_s}\nabla G \tag{5}$$

where α is the absorption coefficient, σ_s is the scattering coefficient, C is the linear anisotropic phase coefficient, and G is the incident radiation.

The transport equation for G is

$$\nabla\frac{\nabla G}{3(\alpha+\sigma_s)-C\sigma_s}-\alpha G+4\alpha\sigma T^4=S_G \tag{6}$$

where σ is the Stefan-Boltzman constant and S_G is a user-defined source.

Particle Devolatilization

The rate of devolatilization of the particle may be represented approximately as a first order reaction with an Arrhenius rate constant [10].

$$\frac{dm_v}{dt}=-m_v k_{pyr} \tag{7}$$

where

$$k_{pyr}=-k_{0,pyr}\exp\left(-E_{pyr}\Big/\hat{R}T_p\right) \tag{8}$$

and

$$m_v=m_p-m_c-m_a \tag{9}$$

where m_v is the mass of the volatile, m_p is the mass of the particle, m_c is the mass of the char, m_a is the mass of the ash, $\hat{R}$ is the universal gas constant, K_{pyr} and E_{pyr} are the rate constants and T_p is the temperature of the particle.

Char Combustion

For a global reaction rate of order n with respect to oxygen, the char burning rate was given by:

$$\frac{dm_c}{dt} = -i\left(\frac{M_c}{M_{O2}}\right) A_p k_c (\rho_{O2}(s))^n \tag{10}$$

Where i is the stoichiometric ratio of moles of carbon per mole of oxygen, A_p is the external particle surface area, k_c is the kinetic rate constant, $\rho_{O2}(s)$ is the oxygen partial density at the surface of the particle, and n is the order of the reaction.

The grate was modeled as a packed bed using porous zone and the SIMPLE algorithm was used to solve the equations.

The parameters used for the measurement are velocity, temperature, moisture. Undergrate air velocity, distributor air velocity, Tangential over fire air velocity, bagasse input, temperature of the wall (353° C) were considered as input boundary conditions for the model.

4. RESULTS

The simulation results obtained were similar to the experimental data collected. The thermal analysis conducted revealed that the endothermic reaction rate depends on the size of the particles and on the moisture content of the particles. The raw bagasse used for the test attained -50 *mW* during endothermic reaction while it is only -6 *mW* with 250 micron particles. Both TG and DSC analysis were conducted for the bagasse samples. But there was no significant changes observed in thermogravimetric analysis. The DSC analyses were made by using Mettler Toledo DSC 822e with an accuracy of Temperature: ± 0.2°C, Temperature reproducibility: ± 0.1°C, Measurement resolution: 0.04 mW at RT, Temperature Range: -150 °C to max. 700°C.

DSC measures the temperatures and heat flow associated with transitions in materials as a function of time and temperature. The technique provides qualitative and quantitative information about physical and chemical changes that give out or take in heat as well as changes in heat capacity using minimal amounts of sample. DSC allows accurate determination of temperatures associated with thermal events. The machine temperature measurement can be calibrated with respect to reference materials which allows highly accurate, precise and reproducible values. The thermal behavior of the bagasse was studied by conducting DSC analysis. The result of DSC experiment obtained is as shown in Figure 2. The Differential scanning calorimetry experiment was conducted for small particles with size around 250 microns. In DSC, the heat flows associated with transitions in materials were measured as a function of temperature in a controlled atmosphere. The experiment was conducted with high heating rate of 86°C/min and the maximum temperature upto 550 °C. The endothermic reaction starts at 27.90 °C and reaches a peak value at 91.67 °C. The endset point for the endothermic reaction ends at around 141.67 °C. This endothermic reaction is due to the absorption of radiation from the surrounding atmosphere. The particle's temperature remained stable from 150°C to 275°C. The exothermic reaction started at 270°C and continued up to an intense exotherm at 550°C.

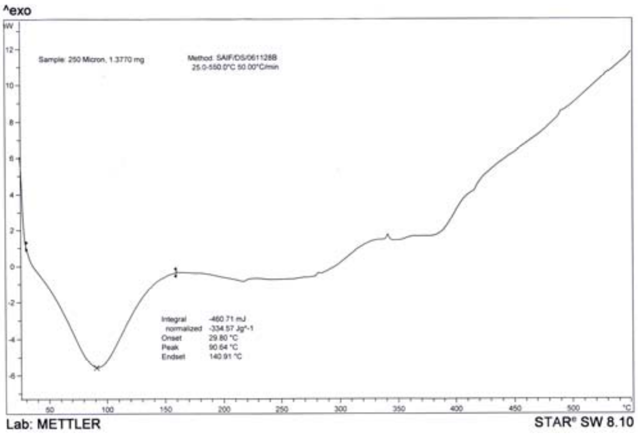

Fig. 2. Differential scanning calorimetry result of bagasse

The simulation results obtained for the test furnace are summarized below. In Figure 3, the particle traces colored by the residence times are indicated. The bagasse particles coming out of the spreader were influenced by the under grate air as well as the jets of tangential over fire air. The fine particles of fuel are rapidly burned in suspension and follow the gas stream and move upwards. The medium-sized particles and heavier particles were spread evenly on the forward moving grates, forming a thin, fast burning fuel bed. If the moisture is more, it leads to the formation of mounds of bagasse on the grate, which is to be handled manually otherwise it falls out as a waste. Bagasse particles coming out from the end spreaders were influenced by the tangential jets resulting in swirl burning. With the same vortex formed, the flame rises up the neck of the furnace.

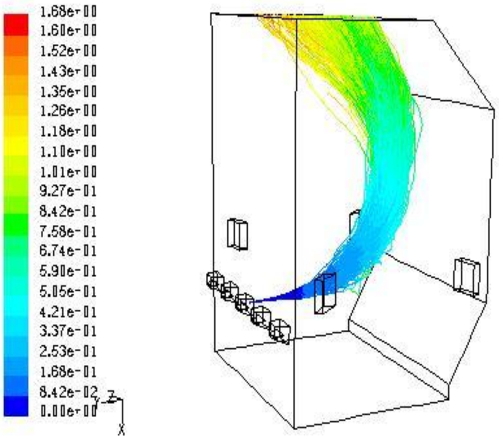

Fig. 3. Particle traces colored by particle residence time(s)

Figure 4 indicates the distribution of temperature at the tangential over fire air plane. Due to vortex formed, the temperature is more towards the walls. At the rear side of the furnace, the temperature is higher due to combustion of particles at the sloping wall. The jet of air coming from the left side of the furnace pushes back the bagasse particles coming from the spreaders. As a result, temperature is higher on the front wall. Temperatures measured at various point at the tangential plane. Maximum temperature of about 1100°C was measured at the rear end of the furnace. The measurements made at side walls were approximately

1017°C. During the test period, it was observed that the bagasse particles entering the combustion chamber are mixed and burned rapidly in the vortex caused by the tangential air jets. The effect of this vortex will be carried up to the neck of the furnace where the temperature reaches the maximum value. The simulation prediction of carbon dioxide at the tangential plane is as shown in Figure 5.

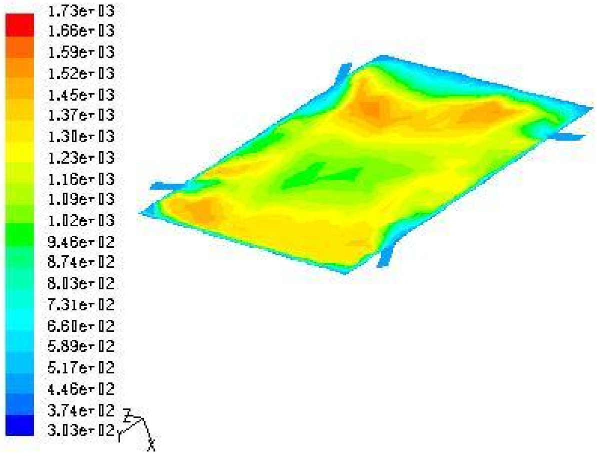

Fig. 4. Temperature distributions at tangential plane

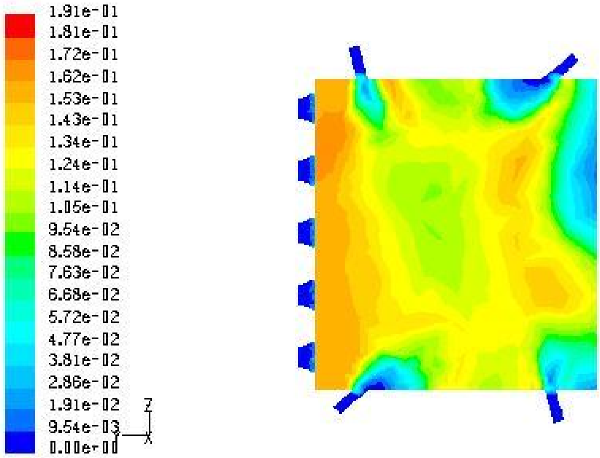

Fig. 5. Distribution of carbon dioxide at tangential plane

Figure 6 shows the velocity magnitude in m/s at the tangential plane and spreader plane level. Bagasse particles enter the combustion chamber driven by the distributor air at a velocity of 38 m/s, the same velocity of the distributor air jets. The velocities of both distributor air and bagasse particles are assumed to be the same in the beginning. Once the particles leave the spreader, their velocity is influenced by under grate air and tangential over fire air jets. Due to this, the velocity of the bagasse particles reduces towards the rear end. The velocity contour at the spreader plane shows that the velocity of the particles reduced to minimum. This is due to the influence of undergrate air on the bagasse particles. The intense combustion zones near front and rear ends are marked blue, because the particles velocity is less in these regions. This slow velocity is induced by the tangential jets. The velocity of the particles remains around 19 m/s at the tangential plane level. This is due to the entrained particles due to updraft.

Figure 7 shows the predictions of the mass fraction of H_2O at the tangential plane. Since bagasse is coming with high moisture (47% - 53%), the intensity of moisture is high at the entry to the furnace. Here, as soon as it enters the furnace, demoisturization of the fuel particles starts. The mass fraction has been reduced from 4.90 x 10^{-1} at the entry to around 3.00 x 10^{-1}at the centre of the furnace. At the rear end of the furnace, the mass fraction reduces to 1.96 x 10^{-1}. This is due to the combustion of the fuel particles at the rear end of the furnace. Also, the mass fraction of H_2O reduces at the water walls. This is due to the effect of tangential over fire air systems.

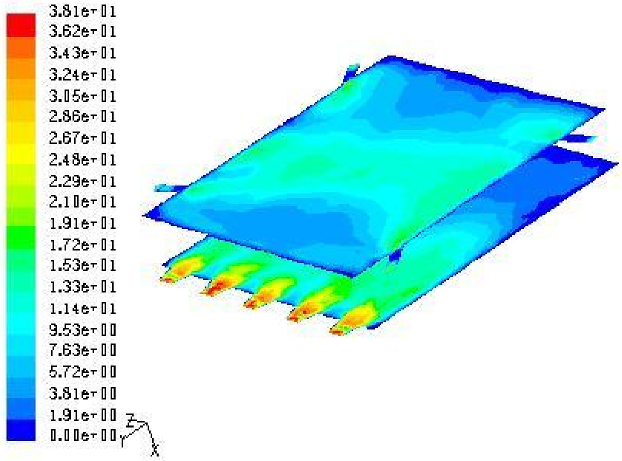

Fig. 6. Contours of velocity magnitude (m/s)

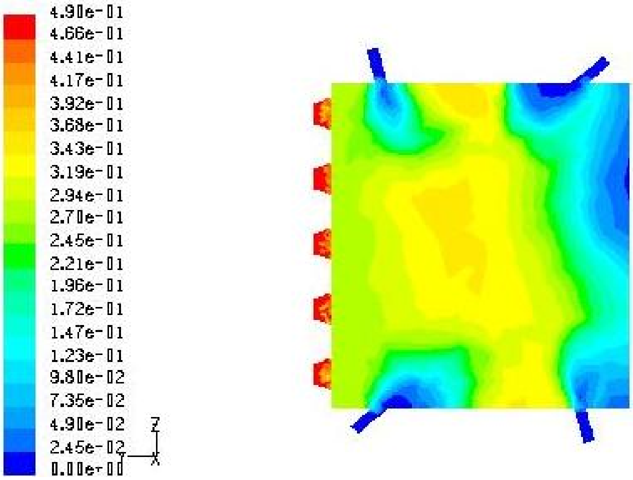

Fig. 7. Contours of mass fraction of H_2O

Figure 8 shows the prediction and the advantage of the tangential over fire air system in reducing the nitric oxide concentration. The mass fraction of N_2 has been reduced from 7.90 x 10^{-1} at the entry to 1.98 x 10^{-1}. This flow will be extended up to the neck of the furnace where it reaches the maximum temperature. The combustion of the particles will be intensified by the imaginary vortex and results in complete combustion of the particles. The concentration of N_2 is high at the entry of the tangential ports and at the rear side of the furnace, where the influence of the tangential air system is not much. During test period, it was observed that the sloping back at the rear end of the furnace was viewed clearly. There was no combustion on the sloping back. This zone at the rear end of the furnace is predicted with higher N_2 concentration.

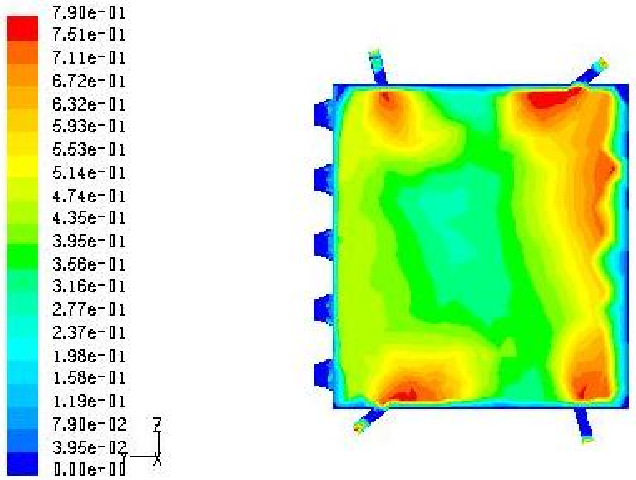

Fig. 8. Contours of mass fraction of N_2

Particle Behaviour on the Grate

The bagasse particles collected during the experiment is shown in Figure 9. Theses particles are available in various sizes from 100 microns to few centimeters. The scanning electron microscope image of the bagasse particles is shown in Figure 10. The surface of the particles is broken into pieces due to the crushing of the cane. The image reveals minute holes on the surface of the particle which would help devolatilizaton during combustion.

Fig. 9. Image of the bagasse particles used for the analysis

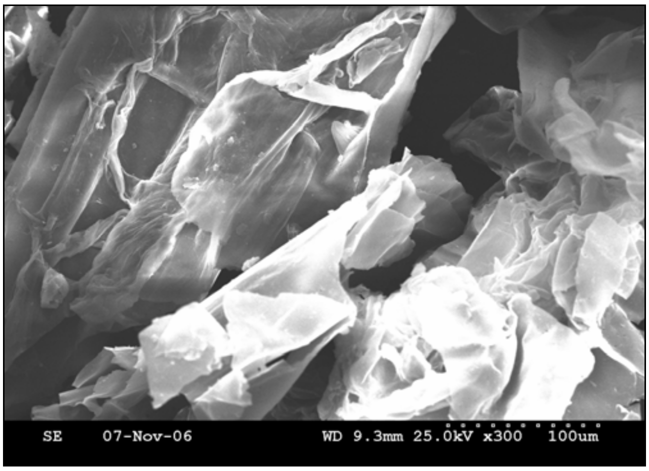

Fig. 10. Scanning electron microscope image of bagasse particles

Figure 11 shows the temperature of the particles along the grate. The bagasse particles reach the maximum temperature around 0.5 to 0.6 seconds. Then the thermal degradation of the particles starts and ends around 1 second. Later the particles are continuously influenced by the undergrate air as well as tangential air jets. The behavior of the particles flow along the grate length varies from spreader to spreader due to the effect of tangential over fire air system. The random behaviour in the temperature of the particles depends on the size, density of the particles.

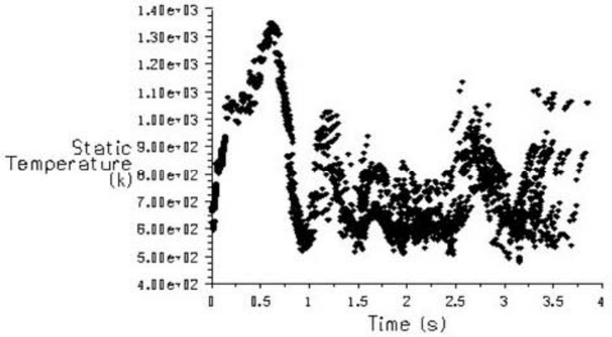

Fig. 11 Temperature profile for the particles along the grate

Figure 12 shows the particle velocity magnitude along the grate length. Here, all the particles are coming with the same velocity from the spreader. At the spreader the velocity is gained by the distributor air jets situated at the bottom of the spreader. Combustion of the bagasse particles depends to a greater extent on the efficiency spreader jets. In the result, it was observed that the velocity of the particles attain the same value after the complete thermal degradation. Figure13 shows the change in specific heat during the combustion of bagasse particles.

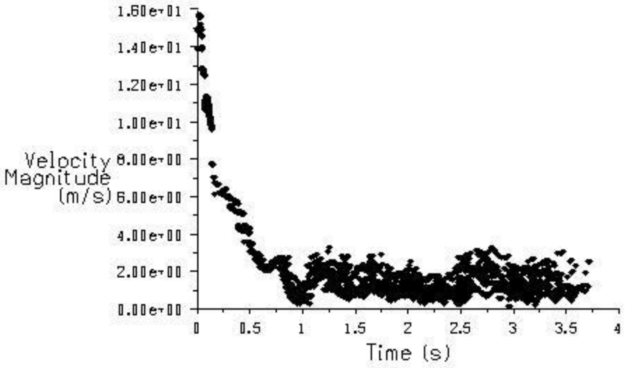

Fig. 12. Velocity magnitude attained by the particles along the grate

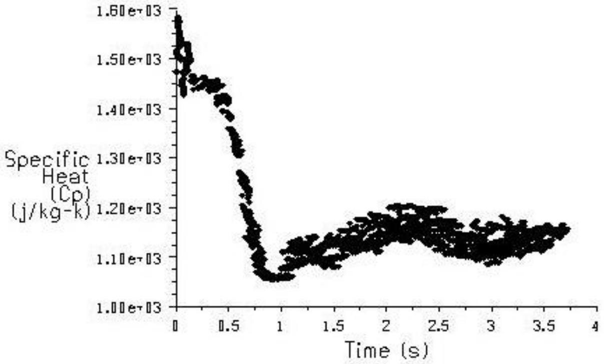

Fig. 13. Velocity magnitude attained by the particles along the grate

The bagasse particles entered the combustion chamber with different density. The density varied according to their size.

Figure 14 shows the changes in density as the thermal decomposition progresses.

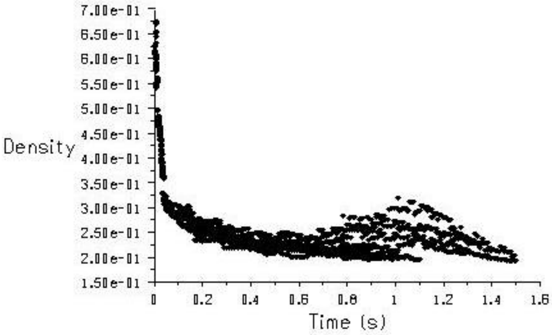

Fig. 14. Density of the particles on the grate

The profile of the individual particle velocity for a larger particle before reaching the grate is shown in Figure 15. The traveling time for the particles over the grate varies with their sizes. The larger particles took shorter duration than the smaller particles.

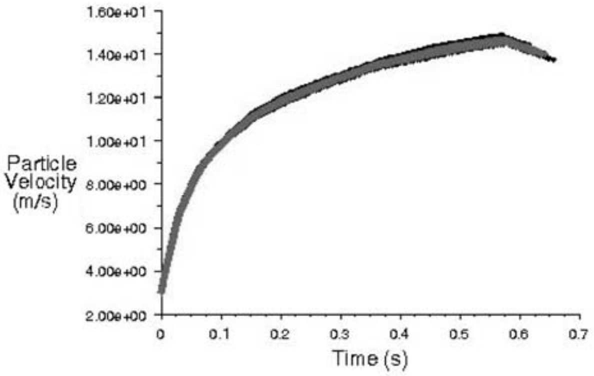

Fig. 15 Velocity of the bagasse particle on the grate

Figure 16 shows the pathlines of the particles at the tangential plane level. The angle of inclination of the two front ducts has a significant effect on the distribution of bagasse particles inside the furnace. The air coming from these two ducts pushes the particles coming from the side spreaders to the centre. This created a distinct zone in the combustion chamber in front of the centre spreader and lead up to centre of the furnace from the front wall. The intensity of combustion is less in this zone. This flow pattern will create accumulation of the bagasse particles at the centre of the furnace, which is often broken manually for proper combustion. Figure 17 shows the image taken at the centre spreader line, at the grate level during the observation. Here the temperature is higher on both sides of the fuel path.

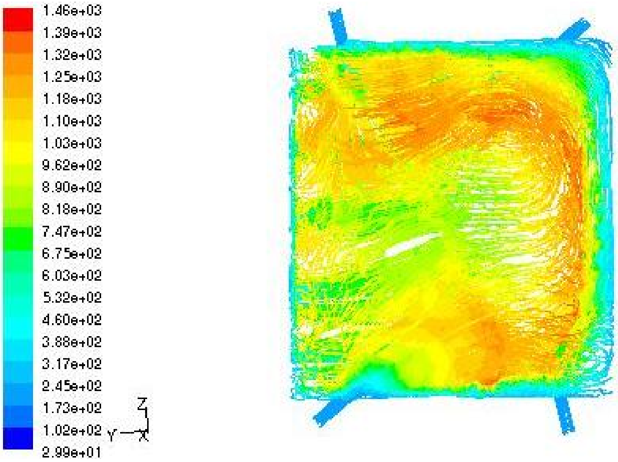

Fig. 16. Pathlines of the particles at the tangential plane influenced by the tangential air flows

Fig. 17. Image showing the flow of particles at the centre of the furnace (taken from the front wall side) influenced by the tangential air jets

5. CONCLUSIONS

The calculations, experiment, and observation show the temperature is on the higher side near the wall at the tangential plane than at the centre. Also, much of the combustion activity occurs over the rear half of the test furnace. Since bagasse comes in with higher level of moisture, there will be a delay to its combustion. However, due to tangential over fire air jets, there will be a rapid mixing of the fuel and the combustion air at the tangential plane. The angle of inclination of the front tangential ducts has a significant effect on the flow of particles. The air jets coming from the front ducts influences the fuel path towards the centre of the spreader. The tangential air flow rates have effects on the size of recirculation zone by forming an imaginary circle of flame inside the furnace to increase heat transfer to the water walls. At the tangential plane the heat transfer to the front wall is lesser than the other three sides. This is due to the angle of inclination of the two front ducts. But later, as the vortex moves upwards, the distribution of temperature became uniform along the height of the furnace. It was observed that the flow of undergrate air was not uniform over the entire grate due to the accumulation of the fuel. Also, the bagasse and air flow rates through spreaders and the location on the furnace grate where the large particles come to rest were found to have some influence on the ignition delay. The tangential over-fire air system provided cooling for the furnace walls and aided in the combustion. It provided turbulence which thoroughly mixes volatile gases thus assuring a complete combustion.

ACKNOWLEDGEMENT

The author wish to thank the Management and workers of Bannari Amman Sugars, Unit-I, Sathyamangalam for the support extended for the present work.

REFERENCES

[1] Rasul M.G.; Rudolph,V.; and Carsky, M.. 1999. Physical properties of bagasse, *Fuel* 78, 905-910

[2] Dixon, T.F. 1983. Combustion characteristics of bagasse suspension boilers. *Proc. Aust.soc. Sugarcane Technol.* 265-271.

[3] Woodfield, P.L.; Kent, J.H.; and Dixon, T.F. 1998, Computational modeling of a bagasse-fired furnace-effects of fuel moisture. *Proc. Aust.Soc.Sugarcane Technol.* 458-464.

[4] Romadin, V. P. 1973. Furnaces with corner firing tangential burners. *Therm Eng* 20 (7): 79-89.

[5]. Habib, M. A.; El-Mahallaway, F. M.; Abdel-Hafe, A.; and Nasseef, N. 1992. Stability limits and temperature measurements in a tangentially-fired model furnace, *Energy Inst. J* 17(3): 283-294.

[6] Woodfield, P.; Kent, J.; Novozhilov, V.; and Terry Dixon. 1999. Prediction of unstable regimes in the operation of bagasse fired furnaces. In *Second International Conference on CFD in the Minerals and Process Industries*, CSIRO, Melbourne, Australia: 299-304.

[7] Zanzi, R. 2001. Pyrolysis of biomass. PhD thesis, Royal Institute of Technology, KTH, Stockholm, Sweden.

[8] Waldheim, L.; Morris, M.; and Regis Lima Verde Leal M. 2000. Biomass power generation; sugarcane bagasse and trash. In *Progress in Thermo Mechanical Biomass Conversion*, Tyrol, Austria, Sept 17-22.

[9] Baukal, C.E.; Gershtein, V.Y.; and Li, X. 2000. Computational Fluid Dynamics in Industrial Combustion, CRC Press.

[10] Borman, G.L and Ragland, K. W. 1998. Combustion Engineering. McGraw Hill International Editions.