

# Numerical and Experimental Investigations for the Temperature Profiles of a Biomass Furnace

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**ABSTRACT:** Now-a-days, bagasse has been used as a fuel in spreader-stoker boilers with tangential overfire air registers in industrial plants. These furnaces have proven to be very effective ones for the production of steam to generate electricity and the effective disposal of waste bagasse. It is not easy to reach a satisfactory model for tangential firing system due to its peculiar aerodynamics. The location of the combustion zone is not easy due to the complicated air flow system. In these boilers the fuel particles are accelerated by the distributor air jets to enter the furnace chamber. As the particles enter the combustion chamber, they are further subjected to under grate air and tangential over fire air, which helps in rapid mixing of the fuel with air. The present study provides numerical and experimental investigations of an industrial biomass fired furnace with tangential overfire air system. The profiles of the flue gas path along the height and depth of the furnace have been investigated. The effect of air flow system on combustion of bagasse inside the combustion chamber is well predicted and compared with good agreement with the measurements.

**KEYWORDS:** Temperature, Profile, Bagasse, Combustion, Tangential plane

## I. INTRODUCTION

Bagasse, the crushed remnants of sugarcane, is a biomass resource and offers the advantage of being a cheap, plentiful and low polluting fuel. Bagasse has benefited the environment by reducing the GHGs in the atmosphere in terms of its usage as a fuel. It is a renewable energy source and can play a major role in substituting fossil fuel for future power generation. The present studies are connected with the temperature profiles inside the combustion chamber with spreader-stoker travelling grate and tangential over fire air systems. In the test furnace, the fuel is continuously fed from the fuel receiving chutes and deposited across the distributor plate. The forced air supply system lifts the fuel from the distributor plate and propels into the furnace. The air-swept system provides steady feeding with a spraying effect that distributes the fuel uniformly over the entire effective grate area. Tangential overfire air jets provide turbulence and thorough mixing of the fuel and air to assure complete combustion. Fine particles of fuel rapidly burn in suspension. The coarser and heavier particles of fuel are spread evenly on the forward moving grate, forming a thin and fast-burning fuel bed. The flue gas travels upward in the furnace and downward through the rear pass to the air heater. The influences of tangential air flow and under grate air on temperature profiles have been studied. The furnace gas temperature, which is the critical parameter for any furnace is selected as the main parameter for measurement. In the present investigation, attempts are made to measure the temperature distribution at various locations of the furnace and to identify the zones of intense combustion. In the present work, CFD simulation has been carried out to predict the distribution of temperature inside the furnace and the temperature profiles of combustion

## II. RELATED WORK

Bagasse, a biomass resource and has been used in sugar industries for the production of steam and process heat [1]. Bagasse offers the advantage of being a cheap, plentiful and low polluting fuel [2]. Bagasse has benefited the

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environment by reducing the GHGs in the atmosphere in terms of its usage as a fuel. It is a renewable energy source and can play a major role in substituting fossil fuel for future power generation.

There have been a number of computational fluid dynamics studies concerned with flow predictions in bagasse-fired furnaces. It has been reported that a good agreement between the predictions of temperature with the measurements taken at steady-state conditions in a furnace [3]. Flue gas composition and flame intensities on two different suspension-fired bagasse boilers have been investigated at various operating conditions [4]. A major work in the field of computational modelling of bagasse-fired furnaces has been done and they have reported a good agreement between steady-state calculations and experiments on temperature and concentration of oxygen [5].

Several numerical computations and field tests that applied to the tangentially-fired boiler have been carried out [6, 7]. Flow pattern, mixing, temperature distribution are the main targets in their studies. A numerical investigation on the performance of a large-scale tangentially-fired boiler using pulverised-coal has been performed with respect to flow field and heat transfer [8].

Numerical studies and measurements that applied to the tangentially-fired boiler have been carried out. Profiles of temperature distribution have been studied. The performance of a large-scale tangentially-fired boiler using pulverised-coal has been performed with respect to flow field and heat transfers have been studied.

Experimental investigation of a 250 MW coal based thermal power plant to predict the performance of tangential fired (TF) boiler and to determine the flow patterns of the gas and coal particles, with an emphasis on increasing the flame stability in combustion zone at low load conditions have been studied. The experimental results show considerable increase in flame stability at low load conditions. The work has been validated with the help of CFD code Fluent [9].

A three-dimensional numerical simulation was carried out to study the pulverized-coal combustion process in a tangentially fired ultra-supercritical boiler. The characteristics of the flow field, particle motion, temperature distribution were numerically investigated and had good agreement of measurements and predictions imply that the applied simulation models were appropriate for modelling commercial-scale coal boilers. [10]

The characteristics of the flow, combustion and temperature in a 300 MW tangentially fired pulverized-coal furnace were numerically studied using computational fluid dynamics. The complex flow patterns and combustion processes in tangentially fired pulverized-coal furnaces have been analysed. The results demonstrate also that the numerical method is useful and promising for practical application [11].

Numerical investigations on the boiler temperature stability on a tangentially –fired 700MW coal power plant have been studied. Computational fluid dynamics simulation techniques was undertaken to simulate the combustion process, the combustion gas flow pattern and temperature distributions inside the boiler. The results show that the uneven temperature distribution at upper furnace elevation exists regardless of the types of fuels used. [12]

Tangentially-fired furnaces have been used successfully and extensively throughout the world with many types of oils, gas and coal as fuels and are widely used in steam generators of thermal power plants. The temperature distributions in the combustion chamber at various operating conditions of excess air factor with varying the air mass flow rate, combustion air temperature have been studied. [13]

### III. EXPERIMENT AND MODELLING

Practically, experiments on an industrial furnace are not easy. It involves high risk coupled with expenses of measurements. The research on industrial furnaces has traditionally been based on a combination of experience and experiment supplemented by a very limited amount of analysis. This approach has already been unsuccessful, since it is limited by the fact that experiments on full scale furnaces are either extremely difficult or costly, or both, and by the complexity of the many interacting physical and chemical processes occurring in furnaces, which encumber the analysis of the experimental data. In this situation, simulation results of the furnaces conveniently provide complete knowledge on the process taking place inside the furnace. The experimental part of the present study includes the measurement of gas temperatures.

The numerical modelling of combustion of bagasse is carried out by non-premixed combustion model. The non-premixed combustion model is also used in the present work due to its proven success for modelling furnaces. The non-premixed model is best suited for modelling turbulent diffusion flames. For modelling radiation, both P-1 and DO models are used in the present work to get the better predictions closer to the experimental values. The DO radiation model, which has advantage in solving radiation in combustion problems, is incorporated with non-premixed

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combustion model. Computational costs and memory requirements are moderate in the DO model. DO accounts for the scattering and particulate effects.

Particle trajectories are calculated by the Lagrangian method. Particle size distribution is defined by the Rosin-Rammler method. Bagasse particle devolatilisation is modelled by the single kinetic rate model. For char combustion, the kinetic/diffusion surface reaction rate model is used.

## Gas Phase Equations

The gas flow is described by the steady state conservation equations of global mass, momentum, energy and species fractions. Turbulent effects are handled by well-known standard  $k - \varepsilon$  model without including the generation of turbulent kinetic energy due to buoyancy. All equations are coupled with the gas density which is a function of the combustion heat release and radiation losses. The gas phase conservation equation in three dimensions is given by equation:

$$\frac{\partial}{\partial x}(\rho u \phi) + \frac{\partial}{\partial y}(\rho v \phi) + \frac{\partial}{\partial z}(\rho w \phi) = \frac{\partial}{\partial x}\left(\Gamma_{\phi} \frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_{\phi} \frac{\partial \phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\Gamma_{\phi} \frac{\partial \phi}{\partial z}\right) + S_{\phi} + S_{\phi p} \quad (1)$$

Here,  $\phi$  is solved for 1 (conservation of mass),  $V$  (conservation of momentum),  $h$  (conservation of energy),  $k$  (conservation of kinetic energy),  $\varepsilon$  (conservation of dissipation of kinetic energy),  $S_{\phi}$  is the source or sink term in the gas phase and  $S_{\phi p}$  is the source term due to particle phase. The turbulent kinetic energy due to the mean velocity gradients,  $G_k$  which appears in the source terms for  $k$  and  $\varepsilon$  is given by the following equation 2.

$$G_k = \frac{1}{2} \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (2)$$

For the non-premixed model, equilibrium chemistry is modelled by considering the non-adiabatic combustion system. The single mixture fraction approach is used to find mixture fractions and their variances under prePDF. Empirical fuel stream is used for the prePDF table with lower calorific value and specific heat of bagasse. In non-premixed modelling, the mixture fraction  $f$  can be written in terms of the atomic mass fraction as

$$f = \frac{Z_i - Z_{i,ox}}{Z_{i,fuel} - Z_{i,ox}} \quad (3)$$

The sub-script  $ox$  and  $fuel$  denote the value at the oxidiser stream inlet and the fuel stream inlet, respectively.

Under the assumption of equal diffusivities, the species equations can be reduced to a single equation for the mixture fraction. The mean mixture fraction equation is

$$\nabla \cdot (\rho \vec{V} \bar{f}) = \nabla \cdot \left( \frac{\mu_t}{\sigma_t} \nabla \bar{f} \right) + S_m \quad (4)$$

In addition to solving for  $f$ , a conservation equation for the mean mixture fraction variance is solved:

$$\nabla \cdot (\rho \vec{V} \overline{f'^2}) = \nabla \cdot \left( \frac{\mu_t}{\sigma_t} \nabla \overline{f'^2} \right) + C_g \mu_t (\nabla^2 \bar{f}) - C_d \rho \frac{\varepsilon}{k} \overline{f'^2} \quad (5)$$

The constant  $\sigma_t$ ,  $C_g$  and  $C_d$  take the values 0.85, 2.86 and 2.0 respectively.

**IV. RESULTS AND DISCUSSION**

**Measurement of Gas Temperature in a Vertical Plane at the Centre of the Furnace**

The various locations considered for the measurement of gas temperature on the furnace are shown in Fig. 1 at the centre of the furnace. During the test period, bagasse and forced draft air inputs are collected regularly at the plant's control room. The boiler operating parameters are also noted regularly during the test period. Throughout the test period, the boiler is observed to run continuously at normal conditions.

Fig. 1 shows the gas temperature measurements at various locations of the furnace. These measurements are taken at various positions in a vertical central plane of the furnace located at a distance of 3790 mm from the north wall. In the Fig. 1, Front side is on west and rear side on east. The vertical plane of the furnace extends from front to rear walls of the furnace. The cross (+) marks indicate the positions where gas temperatures are measured. The measurements are taken at the rear side of the furnace at a height of 3860 mm above the grate, which coincides with the level of tangential air registers and 8200 mm above the grate, located near the neck of the furnace. In the front side, the same are taken at a height of 10700 mm above the grate level. Also the same are taken at the front and rear sides of the furnace above the grate through grate level windows.

The time averaged temperature of 1152°C is observed at a height of 3860 mm above the grate. This high temperature is due to the rapid devolatilisation of the bagasse particles projected towards the sloping back of the rear end by the distributor air jets. During the measurements, highly turbulent flame is observed at this level due to the tangential air flow. The time averaged temperature of 1197°C is measured at the rear end of the furnace at a height of 8200 mm above the grate. This is the zone where the temperature is measured high in the furnace. This indicates the intense zone of combustion due to the ignition of smaller particles by suspension burning, which are swept upward by the vertical gas stream.

The time averaged temperature of 1073°C is measured at a height of 10700 mm above the grate from the front side. The measured temperature is slightly lesser than the same measured at the rear side of the furnace. The lack of combustion activity above the grate causes a column of low temperature over the entire height of the furnace. However the recirculation of flue gas enhances the temperature at this region.

Temperature measured above the grate level indicates the cold zone in front of the spreader region. A temperature of 443°C is measured in front of the front wall at a distance of 1000 mm. The low temperature indicates the lesser combustion activity on the front side. A temperature of 1099°C recorded above the grate at the rear end of the furnace is due to higher combustion. This is the zone where particles fall down after sliding down from the sloping back of the rear wall.

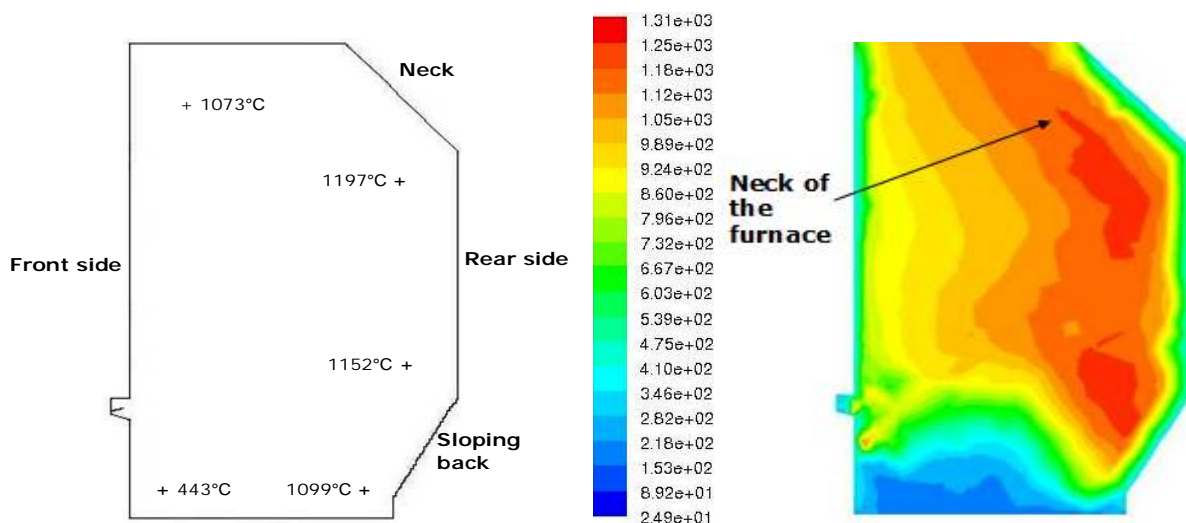


Fig. 1 Gas temperature in a vertical plane at the centre of the furnace in °C. The cross (+) marks indicate the measurement positions. The numerical result has been compared with the measurements.

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The non-premixed model predicts the moderate temperature at the vicinity of the spreaders. The low temperature is predicted in this model is due to delay in ignition. At the rear side, there is a significant difference between predicted and measured temperatures above the grate. The model predict high temperature zone in the rear side of the furnace. Measurements support this result. The temperature of this zone is around 1200°C. The high temperature is due to the combustion of bagasse particles at the rear side. The distributor air coming out at high velocity carries the particles to the rear side. The particles at the rear side will undergo rapid devolatilisation resulting in high temperature. The non-premixed model predicts another intense combustion zone at the rear end top corner. Temperature is 1000°C at the centre of the exit of the furnace. The temperature distribution predicted by non-premixed model is closer to experimental results.

The temperature gradient is observed along the depth of the furnace in the top region of the furnace, whereas the same is observed along the height of the furnace at the bottom region. The bagasse particles take considerable time for drying and heating up, which result in lower combustion activity on the front part of the grate.

A column of high temperature starts at rear side above the grate and extends up to the neck of the furnace. This column of high temperature flame is attached to the rear wall of the furnace. The temperature of the column of flame remains more than 1000°C along its height, in front of the rear wall of the furnace. This high temperature is due to the continuous updraft air passing along this column, which is not affected by the tangential air flow. The combustion of smaller particles of bagasse in suspension contributes to high temperature near the region of neck.

## Measurement of Gas Temperature along the Depth of the Grate

The variation of the gas temperature along the depth of the grate at a distance of 3790 mm from the north wall is shown in Fig. 2 for various air flow rates. The temperature increases by increasing the grate depth for all cases. The high temperature at the rear end (higher grate depth) of the furnace is due to combustion of bagasse particles which are projected to the sloping back of the furnace by the spreaders. The lower temperature near the front wall (lower grate depth) is due to the lack of combustion as this region possesses mainly ash and the deposition of larger bagasse particles with moisture. The temperature increases by decreasing the air flow rates.

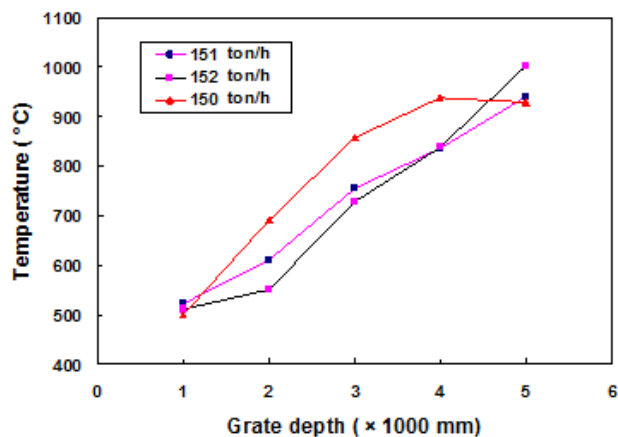


Fig. 2 Effect of air flow rates on gas temperature along the grate depth.

In Fig.2, the maximum difference in temperatures is around 150°C between these three different air flow rates. This is due to a small difference in air flow rates. These variations are influenced by the uneven distribution of bagasse particles on the grate surface. At 150 ton/h, the temperature, measured high at the centre of the furnace, is due to the minimum thickness of the fuel bed. When the fuel bed thickness increases, the gas temperature decreases due to reduced under-grate air flow.

## Gas Temperature at the Spreader Plane Level

In non-premixed combustion model, cold zone is observed at the centre of the furnace. Fig. 3 show the numerical result of temperature distribution at the spreader plane. The spreader plane lies at a height of 2630 mm above the grate. High

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temperature at the rear side of the furnace is due to the combustion of bagasse fuels. Bagasse accumulates just below the cold zone, on the grate.

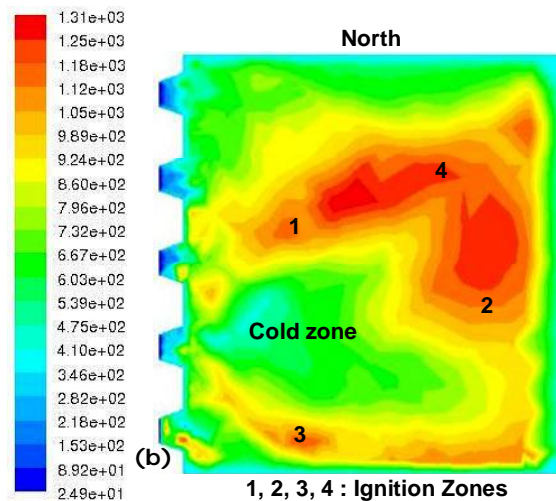


Fig. 3 Temperature distribution at the spreader plane in °C.

The cold zone in Fig. 3 is due to the lack of combustion activity on the grate surface. The intense combustion zones appearing above the grate are indicated by 1, 2, 3 and 4 in the result. A maximum temperature of about 1200°C is predicted at zone 4, which covers the north-east zone of the furnace. It is observed that the temperature distribution predicted by the non-premixed model is closer to experimental observations.

## Temperature Distribution at Tangential Plane

Fig. 4 shows the predicted temperature distribution at the level of tangential plane at 69% maximum capacity rating. T1, T2, T3 and T4 are the location of the tangential air registers on the furnace wall. The predicted results show clearly the effect of air flow from T1 on temperature distribution at the tangential plane. The region up to the middle of the furnace is seemed to be affected by the tangential air flow. The reason for the low temperature in front of the front wall is due to the lack of combustion activity on the front part of the grate. The temperature distribution is high in half of the furnace connected to the rear end.

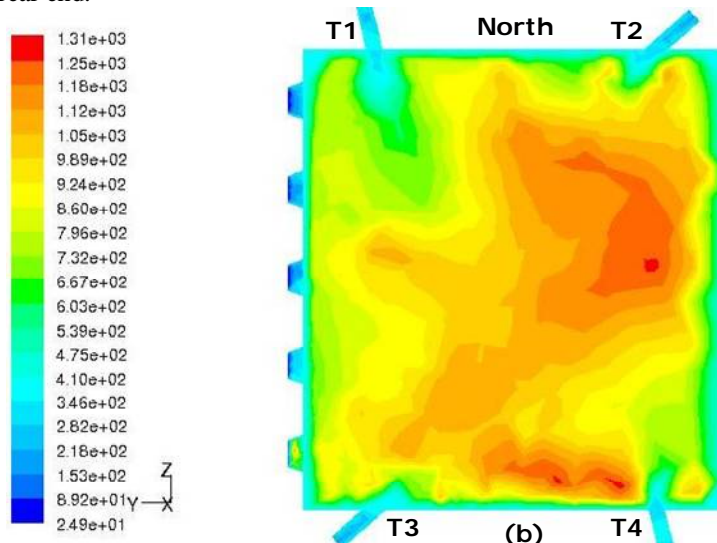


Fig. 4 Temperature distribution in °C at the tangential plane.

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In Fig.4, higher temperature is seen near the north-east zone of the furnace. Temperature at the rear end of the furnace is significantly high, where bagasse particles find sufficient time for combustion, aided by updraft air. The effect of air coming from T3 has considerable impact on temperature distribution as shown in the result. The predicted result shows the less intense temperature zone connected to the front part of the furnace.

## V. CONCLUSION

The measurements made and the simulation results of the present work have good agreement. The profiles of the flame inside the furnace have been influenced by tangential over fire air registers, under grate air as well as spreader stoker air jets. Both numerical and experimental result shows higher temperature on the rear side of the furnace. This is due to the combustion of bagasse particles on the rear side of the furnace. The bagasse after entering the combustion chamber, takes sufficient time for getting dry and by the time it travel on the moving grate towards the end it will be completely dried and rapid combustion takes place. This will be the reason for higher temperature on the rear side of the furnace. The flame extends the entire length of the furnace. This is due to the under grate air, which flows in the upward direction. The temperature decreases slightly towards the front side of the furnace. Temperature profile at the spreader level shows cold zone. This is due to the accumulation of raw bagasse, which enters the furnace as crushed. The profiles of temperature at this level are also influenced by the tangential air jets. At tangential plane, high temperature is observed at the rear end of the furnace. The results obtained at tangential plane matches with the results at spreader plane. Higher temperature profiles have been observed at the rear side of the furnace

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