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Effect of Isokinetic Sampling on Combustion Airflow and Heat Energy Produced in 600 MW Coal-Fired Boiler

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The focus of this research is to study the effect of isokinetic sampling of the secondary airflow on the energy input to the fuel-fired boiler. The relocation of the secondary airflow test ports from horizontal to vertical transverse sampling was implemented after the observation that the airflow in the duct was not constant. Additionally, the methods are used to ensure that the airflow particle inlet velocity to the sampling nozzle is the same as the duct velocity. The pressure was measured using the S-type pitot tube on four boiler levels at the full load capacity of the boiler. At 100% fuel-fired boiler capacity, the energy equation accurately projected the kinetics of pressure drop. It was established that the decrease in pressure results in increased airflow. The continuity principle supports the claim that these outcomes are due to the secondary air's increased velocity as it passes through the constricted duct area, which causes a decrease in pressure. These findings improve our understanding of how isokinetic sampling affects combustion airflow and heat energy, which can guide its future application in coal-fired boilers.

Keywords: Isokinetic; Coal-fired boiler; Pressure drop; Combustion airflow

1. Introduction

The majority of South African power stations burn bituminous coal in their coal-fired power stations. The global economy relies on energy, and demand is expected to increase by 80% in 2050 at 2.0% per year thereafter (Kuang et al., 2019). Due to the high mixing degree of pulverized coal and combustion air in tangential boilers, they are mainly used in South African power plants for coal combustion. There are several advantages to coal-fired power generation unit boilers connected to the grid, including the ability to regulate peak loads and the ability to operate in cold weather for extended periods of time with low loads. However, under low boiler loads, the combustion stability is poor (Zhang et al., 2021).

An insufficient amount of research has been carried out on the combustion stability of tangentially fired boilers using bituminous coal, especially with respect to evenly distributed combustion airflow. The airflow deflection in tangentially fired boilers has been extensively studied, and it is generally attributed to the airflows' entrainment of the surrounding flue gas, the transverse impingement force of swirling flue gas, and the burners' structure (Li et al., 2022). However, most of the studies dominating the scientific literature have reported that the sub-stoichiometric combustion of high-sulphur coals in the boiler unit here considered, indicated by a measured lack of oxygen and the consequent excess of carbon monoxide in the flue gases adjacent to the walls, is suspected to trigger and enhance the formation of various chemical species, especially H_2S, which have adverse effects on the steel surface. As a result, along with monitoring coal chemistry and possibly intervening in coal pre-processing to eliminate or reduce harmful components, the problem can also be reduced by carefully reworking burners, furnaces, and air supplies and by adjusting operating conditions.

One of the most significant factors impacting boiler performance is air distribution, regardless of the type of boiler (Liu et al., 2013). A variation in furnace dimensions can cause significant differences in combustion characteristics, even among tangential boilers based on the same technology. Compared to non-tangential boilers, there was an increase in flame deflection of 350 to 300 to 600 MW for tangential boilers.

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Jing et al. (2010) placed fuel-lean nozzles on the front and back walls of a 600 MW down-fired boiler and introduced separated over-fire air (SOFA) to reduce NOx emissions. These modifications reduced NOx emissions by 50% and increased boiler efficiency by placing SOFA in the upper furnace. In other work related to adjusting the air distribution, Jing et al. (2010) added extra secondary air in the furnace hopper and bottom regions. An analysis of aerodynamic fields demonstrated that this air distribution eliminated dead recirculation zones and avoided airflow washing the water wall while simultaneously providing two large symmetrical recirculation zones in the furnace and an increased primary air penetration depth. In addition to improving combustion efficiency and reducing pollutant emissions, the safe operation of the water wall is also an important concern.

In this study, the focus is on studying the effect of isokinetic sampling of the secondary airflow on the energy input to the tangentially fuel-fired boiler burning bituminous coal at a 600 MW load by conducting industrial-scale tests. The combustion air inlet temperature, pressure, density and viscosity of coal vary by boiler level. A sampling at such a rate that the velocity and direction of the gas entering the sampling nozzle are the same as those of the gas in the duct or stack at the same sampling point is called isokinetic sampling. On the other hand, a venturi works by measuring the difference in pressure at two different locations. Reducing pipe diameter speeds fluid flow due to the pressure difference created. The fast-moving fluid has a lower pressure than the slower fluid in the larger section of the venturi.

2. Materials and methods

2.1 Experimental set-up

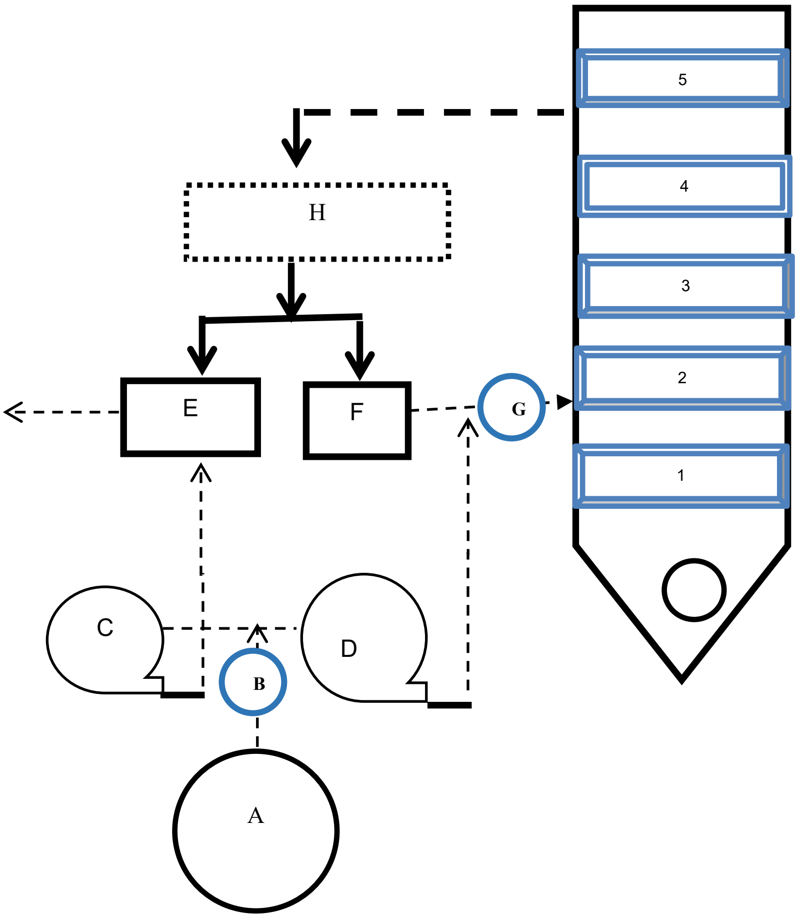

Figure 1 : Process Flow diagram A - Total Air, B - Total airflow measurement point, C - Primary Air Fan, D - Forced Air Fan, E- Primary Air Preheater, F- Secondary Air Preheater, H - Economiser, I – Boiler

A field test was conducted at a full load of 600 MW coal-fired boiler located in the Limpopo province of South Africa. The tested boiler is a tangentially fired pulverized coal boiler, and the gas cleaning devices primarily consist of an electrostatic precipitator (ESP) for removing particulate matter (PMs) from the flue gas for further reducing emissions of PMs. The tangentially fired boiler was originally designed for burning bituminous coal and has a NOx emissions limit of 750 mg/m^3 at 2.8 to 3.5% O_2 at the furnace exit. During the test, the negative pressure of the furnace was stable, and the temperature and pressure of the main and reheat steam reached the designed values. Moreover, the loads were kept stable, and the damper opening and adjustable vane angle of the swirl burner, secondary air vane angles, and damper openings remained unchanged during the test. All the air inlet ducts of the boiler are equipped with measurement devices and can be monitored online. Cold airflow experiments carried out in the full-scale boiler serve to calibrate each measurement device prior to the boiler's operation, which can guarantee precise air control. In addition, a large number of detailed industrial adjustment experiments and cold-modelling airflow experiments need to be performed to determine the optimal control strategy.

2.2 Calculating airflow

Equations 1 – 6 were used to calculate airflow and the details of the subscripts used are detailed on the nomenclature.

$$Air\ velocity = \mathrm{C_p}\sqrt{Pv/D} \tag{1}$$

$$Air\ Density = \mathrm{k}\frac{(Pb)}{\mathrm{T}} \tag{2}$$

$$\text{Airflow (kg/s)} = \mathrm{k}\sqrt{\Delta p}.\rho \tag{3}$$

$$\mathrm{K} = \frac{\Delta Pc}{1/2\rho V^2} \tag{4}$$

$$\rho = K\frac{P}{273+T} \tag{5}$$

$$\text{Alternatively mass flow (kg/s)} = \rho.D.v \tag{6}$$

3. Results and Discussions

3.1 The effect of combustion airflow temperature as a function of Boiler ID Duct

Figures 2– 6 depict both venturi measurements and isokinetic sampling of boiler duct ID for different levels. For all the boiler levels under consideration, the highest amount of high-temperature recirculating flue gas occurred under the arch, leading the coal and airflow to take more heat from it except for Figure 6. The average heating rate of the coal/air flow was lower than during the circular venturi readings. Retrofitted bottom-fired boilers should set the inner secondary-air vane angles to the minimum or maximum adjustable angle to maximize the heating rate and ignite coal or airflow in the burner region (Fan et al., 2010).

According to the comparison of the heating rate for different combustion airflow levels, the heating rate of the coal/air flow rose more quickly when the mass flow increased. In other words, compared with the high-temperature flue gas entrained by the burner itself, the high-temperature recirculating region under the arch was more beneficial to the ignition of the coal and air flow in the burner region. The average measured temperature across different boiler levels using the isokinetic sampling method is just above 300 °C, whereas the circular venturi readings are approximately 280 °C, meaning there is around a 7% difference observed. In terms of the combustion airflow rates and viscosity, the step change is observed in the decrease in density of 34%, which can be attributed to the better-controlled air particle movement where there are no movement restrictions. At the same time, the same effect is seen in the pressure drop. The average pressure from the circular venturi reading is 94 kg/m^2, while the average pressure from the isokinetic sapling at different boiler levels was 83 kg/m^2.

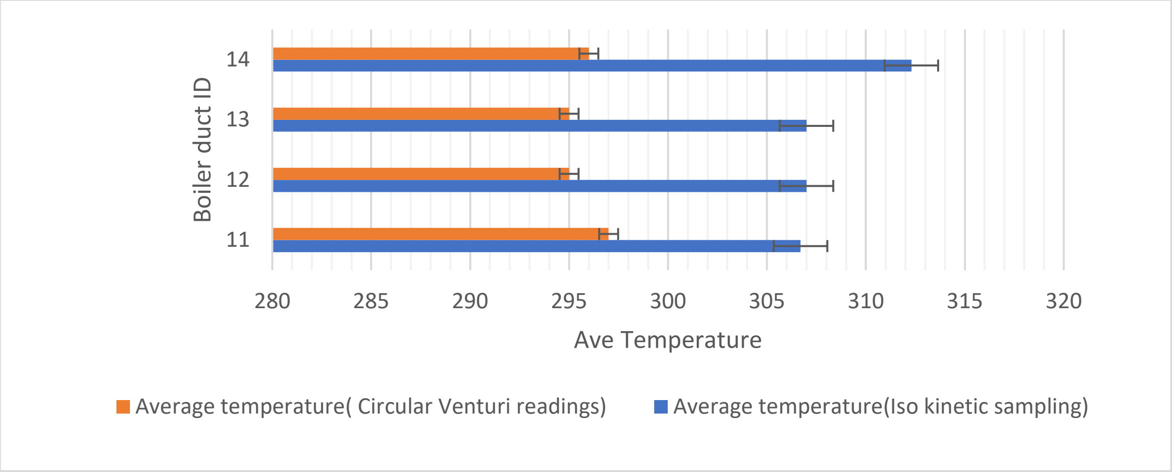

Figure 2: Combustion airflow temperature as a function of boiler duct ID for level 1

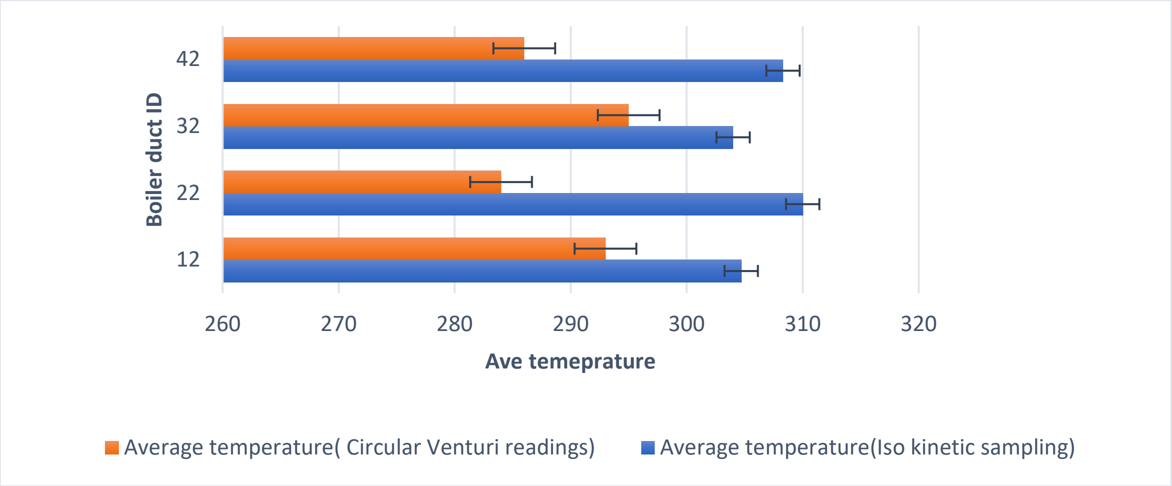

Figure 3: Combustion airflow temperature as a function of boiler duct ID for level 2

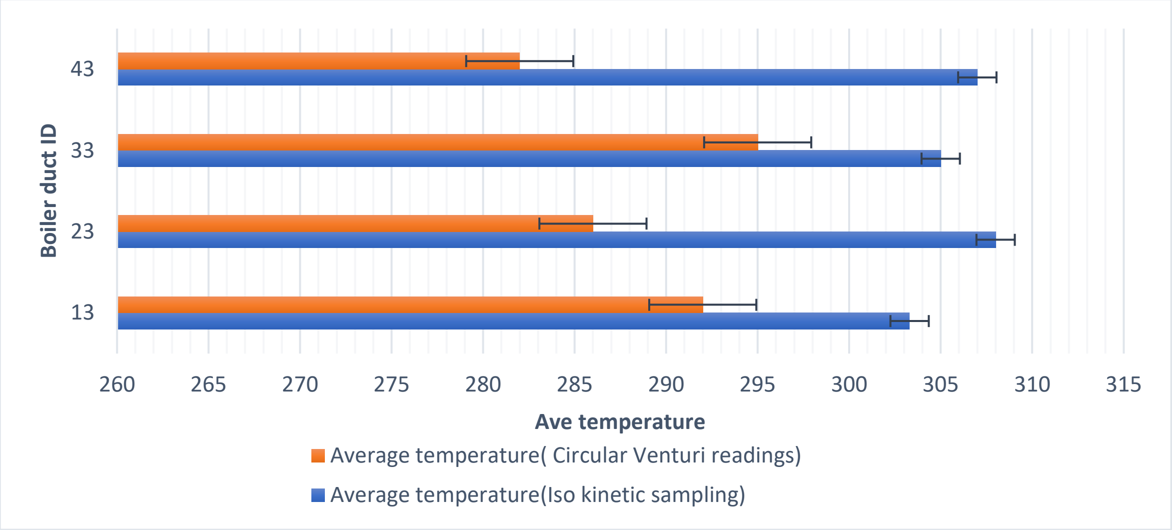

Figure 4: Combustion airflow temperature as a function of boiler duct ID for level 3

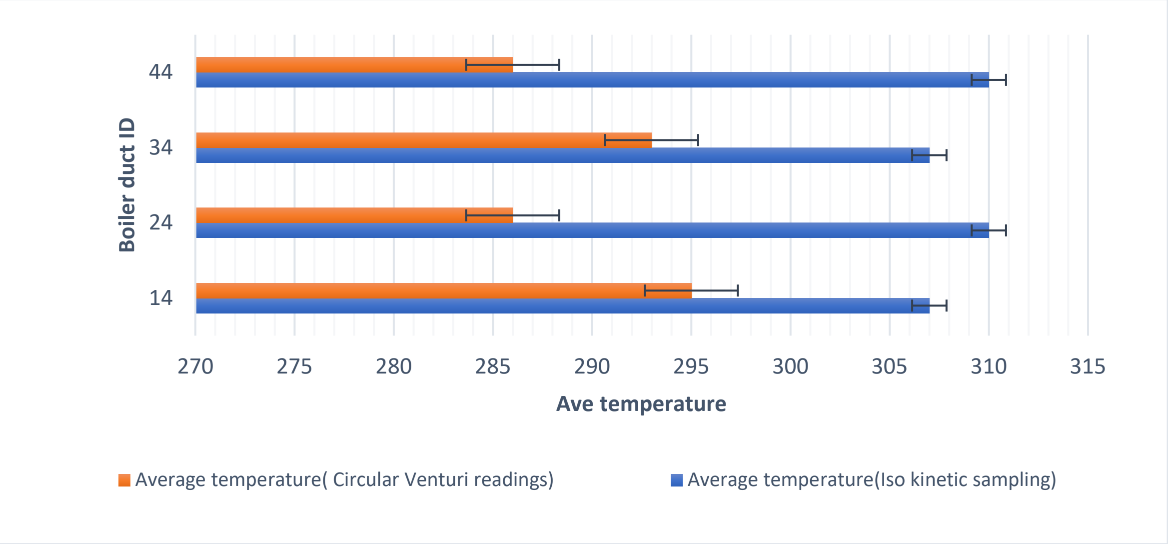

Figure 5: Combustion airflow temperature as a function of boiler duct ID for level 4

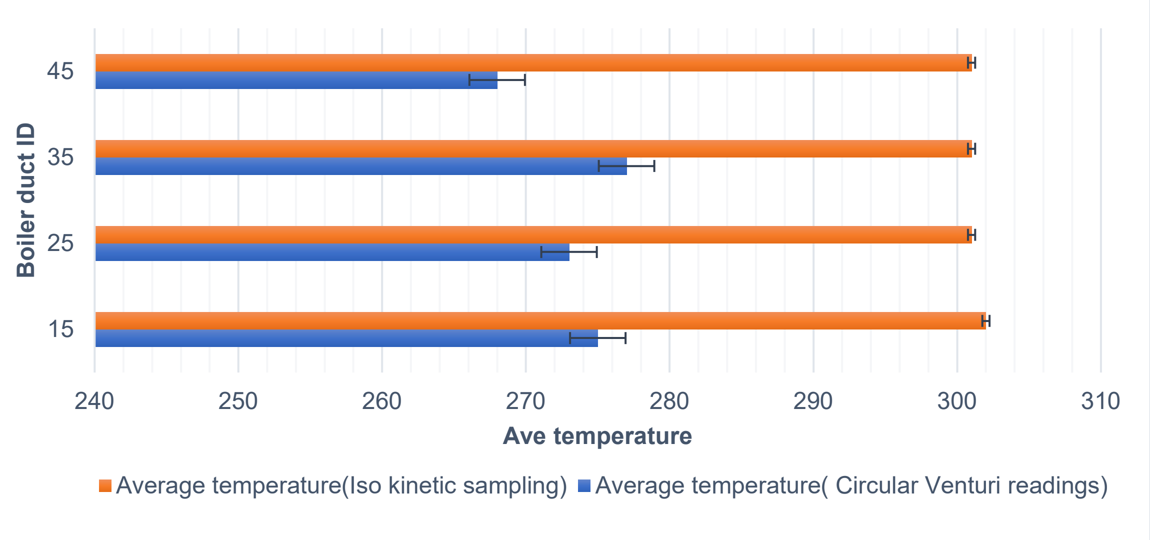

Figure 6: Combustion airflow temperature as a function of boiler duct ID for level 5

The reheat steam temperature can be effectively guaranteed to reach the designed value under the same heat absorption condition of a water-cooled wall due to the early ignition of bituminous coal, severe combustion, and high gas temperature in the lower furnace. Moreover, the slagging is slight, and there are no problems such as water-cooled walls overheating or boiler fire extinguishing. For each type of tangential boiler, the coal or airflow at the front and rear wall corners turns back. It recirculates back to the burner outlet region, creating a large recirculating region under the arch. The recirculating region under the arch is favourable for the ignition of the coal/airflow, and the recirculating region under the arch increases with an increasing penetration depth of the coal/airflow. As a result, pulverized coal combustion in the burner outlet region is influenced by both the high-temperature flue gas entrained by the burner itself and by the high-temperature recirculating region under the arch for the down-fired boiler with swirl burners. The swirling intensity is the ratio of the tangential momentum moment and the axial momentum moment of the airflow at the burner nozzle. With increasing swirling intensity, the capacity of the rotating airflow increases, as does the amount of heat. As the burner's entrained flue gas grows, airflow axial velocity attenuation increases and penetration depth decreases (Zhang et al.,2021). It indicates that the small ignition heat of burning bituminous coal can ensure the coal/air flow ignition is timely.

4. Conclusions

The objective of this study is to investigate the effect of isokinetic sampling of the secondary airflow on the energy input to the 600 MW coal-fired boiler. The kinetics of the secondary air pressure drop on combustion temperature was experimentally explored at full load using different sampling methods under stable conditions. The combustion air inlet temperature, pressure, density, and viscosity of coal varied by boiler level. Isokinetic sampling uses laminar flow to conserve energy, while circular venturi measurements focus on momentum and mass conservation. The combustion air expansion and acceleration mainly contributed to the temperature drop, resulting in thermal effects. It can be concluded that the velocity increased with the decrease in pressure during the circular venturi measurements as a result of the restricted airflow affecting the combustion air inlet temperature (reduction), assuming that the density and unit load remain constant. On the other hand, during the isokinetic sampling, the airflow remains laminar, resulting in an insignificant effect on the combustion inlet temperature. Comprehensively evaluating combustion performances (combustion stability, combustion air temperature, combustion air mass flow, coal/air flow ignition), it is concluded that the tangentially fired boilers burning bituminous coal have strong combustion stability and high combustion efficiency. As a result, a more refined secondary air design for tangential boilers will be possible with the insights gained from the study. The decreased pressure on the circular venturi measurement is attributed to the slow measurement of the combustion air and the increased pressure on the isokinetic sampling is attributed to the faster-moving combustion air particles.

Nomenclature

Pv	(C)	Sensed pressure difference
D	(kg/m^2)	Air density
Cp	(kg/m^2)	Pitot tube coefficient
PB	(m/s)	Barometric pressure
T	(m)	Absolute Temperature
P		Atmospheric + static pressure
K	(L^3)	Venturi constant
ρ	(kg/s)	air density
v		air velocity
D	(m^2)	pipe area
Δp		Differential pressure

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