Simulation of concentrated slop combustion in cyclone furnace using Computational Fluid Dynamics (CFD)

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Abstract. This study examined the combustion behavior of concentrated slop in a cyclone furnace, primarily aiming to determine the appropriate amount of air supplied for concentrated slop combustion under the adiabatic process using computational fluid dynamics (CFD) in four different air settings: 100\%, 120\%, 140\% and 160\% theoretical air. The results show that 100\%-120\% theoretical air were suitable for concentrated slop combustion because they created a high average temperature and formed cyclone motion in the combustion chamber. Moreover, ash particles swirled against the furnace wall and could be melted into liquid slag, resulting in a decrease of fly ash.

1. Introduction

In Thailand, the noticeable growth of industries has resulted in an increase of waste generated from the industrial sector, especially alcoholic industry in which molasses are primarily used as raw material and the waste water generated in the production process, concentrated slop, has been utilized to produce biogas or to be used as fuel in a boiler.

To leverage the utilization of the industrial waste under the 3Rs principle, Reduce, Reuse and Recycle, the concentrated slop by-product from industrial plants is used as an alternative fuel to replace or reduce the amount of primary fuel currently used in factories. When the concentrated slop is burned in a conventional furnace, the plentiful fly ash generated is a burden to management costs. To overcome this problem, the concentrated slop is fired in a cyclone furnace, in which the air enters the furnace tangentially to generate a swirl motion in the combustion chamber. This also prolongs the residence time of the fuel and air in the furnace \cite{1}, and gives a very high temperature compared to other types of combustion. Thus, 30-50\% of ashes can be melted into liquid slag and then released at the bottom of the furnace \cite{2-5}. Theoretically increasing the air in the combustion lowers the combustion temperature inside the furnace, resulting in excessive heat loss. However, in practice, air is usually supplied at 130-140\% theoretical air \cite{6-10}. The proper air fuel ratio and adequate residence time cause a more complete combustion with decreased carbon monoxide, carbon in ash and fly ash \cite{11}.

This paper proposes ways to use the concentrated slop as fuel through combustion in a boiler. The simulation was performed to examine the combustion behavior of concentrated slop fuel in a cyclone furnace. Average combustion temperature and flow characteristics in the cyclone furnace were predicted under the adiabatic process condition using computational fluid dynamics (CFD).
2. Method

2.1. Effect of amount of air for concentrated slop combustion
A cyclone furnace as shown in Figure 1 was developed for combustion of 3 g/s concentrated slop and 1 g/s diesel in the combustion chamber at four different air settings: 100%, 120%, 140% and 160% theoretical air. The concentrated slop and the secondary air were preheated to 90°C and 250°C respectively, before entering the furnace. The furnace was tilted at an angle of 23.8° to the horizontal.

![Figure 1. Dimensions of cyclone furnace simulation](image)

2.2. Analysis of concentrated slop in cyclone furnace

2.2.1. Ultimate analysis of concentrated slop and diesel. The results of the ultimate analysis of concentrated slop and diesel were determined under the standard as shown in Table 1.

Table 1. Concentrated slop and diesel ultimate analysis

|          | C    | H$_2$ | O$_2$ | N$_2$ | S    | H$_2$O | Ash   |
|----------|------|-------|-------|-------|------|--------|-------|
| Concentrated slop % wt | 15.874 | 3.925 | 19.380 | 0.7927 | 1.566 | 35.550 | 22.912 |
| Diesel % wt | 86   | 13.1  | 0     | 0     | 0.9  | 0      | -     |

At 100% theoretical air, the combustion equation for 3 g/s concentrated slop and 1 g/s diesel can be expressed in equation (1)

\[
(0.11135C+0.12438H_2+0.01817O_2+0.00085N_2+0.00175S+0.05925H_2O+Ash)+0.1571(O_2+3.76N_2) \\
\rightarrow 0.11135CO_2+0.18363H_2O+0.9674N_2+0.00175SO_2+Ash
\]

According to the above equation, the stoichiometric air fuel ratio is 5.4 and the adiabatic flame temperature is calculated to be 2,214°C.

2.2.2. Calculation of primary air and secondary air flow rate. The air supplied into the furnace is primary air and secondary air. They were determined to supply for concentrated slop (3 g/s) and diesel (1 g/s) combustion corresponding to each case as shown in Table 2.

Table 2. Primary air and secondary air flow rates

| % Theoretical air | Total air flow rate (g/s) | Primary air flow rate (g/s) | Secondary air flow rate (g/s) | Velocity of secondary air (m/s) |
|------------------|---------------------------|-----------------------------|-----------------------------|-------------------------------|
| 100%             | 21.6                      | 2.32                        | 19.28                       | 8.2                           |
| 120%             | 25.9                      | 2.32                        | 23.6                        | 10.1                          |
| 140%             | 30.2                      | 2.32                        | 27.9                        | 11.9                          |
| 160%             | 34.6                      | 2.32                        | 32.2                        | 13.8                          |
2.2.3. Testing for ash particle size. The actual ash from the furnace was analyzed using a Laser Diffraction Particle Size Analyzer. It was found that the smallest ash particle was 2.269 µm and the largest was 116.210 µm, with an average size of 29.742 µm.

2.2.4. Computational Fluid Dynamics (CFD) Analysis. Computational Fluid Dynamics (CFD) analysis was performed using the ANSYS Fluent v.15.0. Combustion of 3 g/s concentrated slop and 1 g/s diesel in the adiabatic process was predicted. The prediction of combustion requires an energy equation, k-ε model and a non-premixed combustion model [12]. A swirl number greater than 0.5 is generally used to indicate a cyclone motion [13]. The higher the swirl number, the higher the cyclone motion intensity. The swirl number can be determined by equation (2) and equation (3) as follows.

$$s = \frac{\int r w \vec{v} \, d\vec{A}}{\int \vec{u} \, d\vec{A}} \quad (2)$$

$$\vec{R} = \frac{A}{P} \quad (3)$$

where $s =$ swirl number, $r =$ the radial coordinate, $w =$ the tangential velocity, $u =$ the axial velocity, $\vec{v} =$ the velocity vector, $\vec{A} =$ cross section area vector, $\vec{R} =$ hydraulic radius (m), $A =$ cross section area of flow (m$^2$), $P =$ wetted perimeter (m).

In this study, 2.0 million meshes were used for all cases. A computer with Xeon CPU and 56 GB of RAM was used to perform these computations.

3. Results and discussion

With a constant mixed fuel and varying quantities of air supplied to the combustion chamber, cases were called M1.0, M1.2, M1.4 and M1.6 referring to 100%, 120%, 140% and 160% theoretical air, respectively.

3.1. Average Temperature in the furnace

The average temperature over the combustion chamber was calculated from the overall temperature across the combustion chamber volume and used to compare with the adiabatic flame temperature.

| % Theoretical air | The average temperature over the combustion chamber (°C) | Adiabatic Flame Temperature(°C) |
|------------------|--------------------------------------------------------|--------------------------------|
| 100% (M1.0)      | 2,198                                                  | 2,214                          |
| 120% (M1.2)      | 2,119                                                  | 2,142                          |
| 140% (M1.4)      | 2,016                                                  | 2,039                          |
| 160% (M1.6)      | 1,871                                                  | 1,894                          |

As illustrated in Table 3 and Figure 2(a), the temperature profile was high at the far end of the combustion chamber. For M1.0 and M1.2, the average temperatures over the combustion chamber volume were 2,198 and 2,119°C, respectively, and the temperature profiles were higher than M1.4 and M1.6. Decreases in temperature profile were because of the amount of air exceeding theoretical air. Since the air was just 250°C when added to the combustion chamber, it affected the temperature in the combustion chamber. The average temperature across the combustion chamber decreases consistently with combustion theory.

The comparative analysis of the average temperature across the combustion chamber and the adiabatic flame temperature was found to be very similar; the difference was approximately 1% and there was the same thermal tendency. Thus, this simulation is reliable compared to the theory and so the combustion simulation for concentrated slop in a cyclone furnace can be predictive for further study.
3.2. Flow characteristics inside cyclone furnace and swirl number
Swirl number was calculated for each section as shown in Figure 3. The average swirl number was then computed based on the 10 sections.

Generally, the swirl number of the cyclone separator is approximately 3-7 [14-17]. In this study, the average swirl number of 10.0, 11.3, 12.4 and 13.1 for the four cases indicated that cyclone motions were generated in the combustion chamber. Cyclone motion occurred in the first half volume and expanded to the rear end when air flow was increased as shown in Figure 2(b).

![Figure 2](image)

**Figure 2.** (a) Temperature profile in the furnace (b) Flow characteristics inside furnace and swirl number

3.3. Ash particles motion analysis
The quantities of fly ash particles and ash particles held on the furnace wall are listed in Table 4. Theoretically, when increasing air flow, cyclone motion will be higher resulting in a better separation or more particles held inside the combustion chamber. However, in this study, the opposite phenomena was found, because the ash particles of the concentrated slop were tiny (only 20-100 µm) and the combustion chamber was not big enough to generate a good separation. On the other hand, with a too small combustion chamber, turbulent flow occurred and carried the ash particles out of the combustion chamber.
Table 4. Results of ash particle motion analysis

| Model       | M1.0   | M1.2   | M1.4   | M1.6   |
|-------------|--------|--------|--------|--------|
| % Fly ash   | 57.8%  | 65.5%  | 66.4%  | 69.6%  |
| % Ash held in combustion chamber | 42.2%  | 34.5%  | 33.6%  | 30.4%  |

4. Conclusions
A comparative temperature analysis showed the similarity in the average temperature inside the combustion chamber and the adiabatic flame temperature. Thus, this simulation was reliable compared to the theory and will be further properly applied to cyclone furnace design. Simulations of fluid flow motion and ash particle motion inside the combustion chamber revealed that supplying 100-120% theoretical air for concentrated slop combustion in a cyclone furnace was most suitable, because this gave high average temperature inside the combustion chamber, and ash particles were held at an average of 35-42% and fly ash discharged from the furnace at an average of 58-65%.

In conclusion, the results suggested that separation of fine ash particles would be successfully obtained if the furnace diameter was bigger. This will be investigated in future work.

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