Simulation of Olive Cake Combustion in a Fluidized Bed Burner

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***Abstract*—This study presents a theoretical investigation for olive cake biomass combustion in a fluidized bed combustion unit. Proximate and ultimate analyses for olive cake were performed to estimate the percentage of C, H, O, N, and S existing in this biomass. A mathematical model was built to represent the physical model of the combustion process of the biomass. Then a simulation was carried out using ANSYS/Fluent software to solve numerically the governing equations of continuity, momentum, energy, and mass diffusion using finite volume method. The simulation results show that the adiabatic flame temperature reaches 1270 K. The concentration of pollutants was also determined.**

***Index Terms*—biomass, olive cake, combustion, fluidized bed, CFD.**

I. Introduction

Biomass is an organic material resulted from plants and animals. When it burns, the chemical energy inside releases heat that can be used to produce steam, which can further be used to generate electricity [1]. Even utilizing biomass for heat and power has a large potential as a source of renewable energy and greenhouse gases reductions, this potential is only being realized at a slow pace. Furthermore, there are significant growth barriers facing accelerated development that require a concerted effort by companies and public institutions to remove [2]. Biomass may be used to meet a wide variety of energy needs, including electricity generation as well as heat for industries and homes. Replacing the conventional fossil fuels with biomass for energy production leads to a net reduction of greenhouse gases emissions [3] in addition to cutting down waste that can help reduce landfills [1]. The most common types of biomass energy applications reduce carbon dioxide emissions by 55 to 98 percent compared to fossil fuels, even when transported for long distances. This is subjected to the condition that the biomass production does not cause any land-use change [2].

Biomass may be utilized in different techniques such as direct burning, gasification, fermentation, anaerobic digestion, and pyrolysis [1,3]. Direct burning is the oldest and most common way of converting biomass energy into heat, mechanical power or electricity. Still, direct burning has problems in terms of net conversion efficiency, which ranges from 20% to 40%, and pollutant produced [4,3]. Circulated fluidized bed (CFB) technique is one of the most competitive direct burning technologies for biomass utilization. CFB enhances the efficiency of the combustion process while reducing the emission of harm gases [3]. During its combustion, biomass fuel undergoes ignition, de-volatilization, and solid char particles combustion stages. Ignition is the process of initiating the combustion phenomenon. Ignition is very important due to its influence on flame stability and pollutant formation and emission. De--volatilization process involves the emission of the volatile gaseous matters, which are ignited and combusted homogenously after being heated up to a certain temperature. Solid char particles combustion stage is ignited by the volatiles combustion. This stage includes heterogeneous reactions that involve a direct attack of oxygen on the solid particles [5].

Olive cake biomass an organic material resulted from olive oil-mill. In addition to providing an acceptable disposal for the large volume of solid waste resulted from oil mills, the low Sulfur content in olive cake makes it an environmentally friendly fuel in terms of SO_X [3]. Topal et. al.[6], studied the combustion characteristics of olive cake produced in Turkey using, a circulating fluidized bed. The combustion was carried out with various excess air ratios. The concentrations of O_2, SO_2, CO_2, CO, NO_x, and total hydrocarbons were measured in the flue gas. It was found that the combustion efficiency for olive cake changes between 82.25% and 98.66% for various excess air ratios

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used in the study. Abu-Quadis [7] has studied the combustion of olive cake in a fluidized bubbling bed combustor. The fluidizing medium was sand. A fairly uniform bed temperature has been obtained. The temperature ranged between 800 and 930 0C.

The main problem of utilizing olive cake is the continuation of the supply since it is a season product. This problem could be solved by co-firing olive cake with other fuels such as coal, oil shale, and other biomass like date seed in industrial and utility boilers. Suksankraisorn *et al*. [8] have investigated the co-firing of olive oil waste with coal in a fluidized bed combustor of 0.15 m in diameter and 2.3 m in height. The results show a reduction of SO_2 emissions because of fuel-S dilution. A slight increase in emissions of NO and N_2O has been observed. Atimaty and Topal [9], studied the co-combustion of Turkish olive cake with coal in a circulating fluidized bed of 125 mm diameter and 1800 mm height. Various runs were conducted with different mixture of olive cake and coal, namely 25, 50, and 75 wt. percentage olive cakes. These mixtures were burned with various excess air ratios. The results suggest that olive cake is good fuel that can be mixed with coal for cleaner energy production in small-scale industries by using CFB.

Co-combustion of coal and olive oil waste has been investigated by Armesto *et al.* [10]. Two different Spanish coals were used for this study. The tests were carried out in a bubbling fluidized bed combustor having a 0.2 m in diameter and 3 m in height and two high efficiency cyclones in series. The results of the tests have shown that the combustion of olive cake/coal mixtures decreases the emissions of SO_2 and NO_x. Al-Widyan *et al.* [11] studied direct burning of Jordanian olive cake in pulverized form in a vertical tube furnace with equivalence ratios varies from 0.8 to 1.4. The furnace design proved acceptable, and the pulverized olive cake burned efficiently. The maximum thermal and combustion efficiencies were 69% and 82%, respectively. The maximum flame temperature reached 980° C, and the cooling water temperature gradient was about 20 ° C. Exhaust gas analyses showed that the concentration of CO was below 1.6%, while the NO_x emission was within 550 ppm and the SO_x maximum concentration was 30 ppm.

In this study, proximate and ultimate analysis for olive cake will be performed to estimate the percentage of C, H, O, N, and S existing in this biomass. A mathematical model will be built to represent the physical model of the combustion process. After that, the simulation will be implemented using ANSYS/Fluent software in order to estimate maximum temperature, heating values, and pollutants concentrations.

II. Composition and Thermophysical Properties

The elemental composition of olive cake in terms of the molar percentages of C, H, O, N, S components was determined experimentally. The proximate composition in terms of moisture, volatile, fixed carbon, and ash fractions were determined [12]. Thermal conductivity test equipment and Bomb Calorimeter were used to determine the thermal conductivity and heating value. Table 1 shows the results of proximate and ultimate analyses in addition to experimentally estimated thermo-physical properties [13].

TABLE I. Ultimate (dry, Ash Free Basis) and Proximate (as Received) Analyses

Analysis	Olive Cake	
Ultimate:	Weight	DAF (mole %)
C	53.9	0.3432
H	6.1	0.4660
O	38.5	0.1832
N	1.4	0.0074
S	0.1	0.0002
Proximate:		
Volatile matter	71.5	76.8 dry, 80.7 DAF
Fixed Carbon	17.1	18.4 dry, 19.3 DAF
Moisture	6.9	-
Ash	4.5	-
Density(kg/m3)	600	
LHV(kJ/kg)	19500	
HHV(kJ/kg)	21200	
(A/F)stoic	6.50	

Olive cake density is 1260 kg/m^3. The density of the fuel affects the minimum fluidization velocity required. It could be seen that the amount of volatile material for biomass is considered high while the amount of ash is low. In addition, it could be noticed that the Sulfur contents in the olive cake is low. These properties are much better those for conventional fuels like coal or non-conventional fuels like oil shale [13], [14]

III. Physical and Mathmatical Model

The physical model consists of an experimental combustion unit, Fig. 1, composed of the following main components, combustion chamber, cyclones, feeder, distribution plate, Temperature measurement system, and Gas Analyzer. The combustion chamber is made of Stainless steel SX 310 S with 3 mm thickness. The high chromium and nickel contents in the material give the steel excellent oxidation resistance as well as high strength at high temperatures. Low carbon content makes it suitable for applications where subsequent corrosion by high temperature gases may pose a problem. It is 3 m in height and 0.5 m in diameter. The design of this combustion chamber was based on a fluidization velocity of 0.3 (m/s).

Two cyclones system was used; the first cyclone is 0.3 m in diameter and 1 m in height. The main purpose of this cyclone is to recycle the unburned particles back to the burner. The second cyclone is 0.5 m in height and 0.3 m in diameter. It is used to separate the ash from the exhaust gases. For this reason, the second cyclone is connected to the ash box.

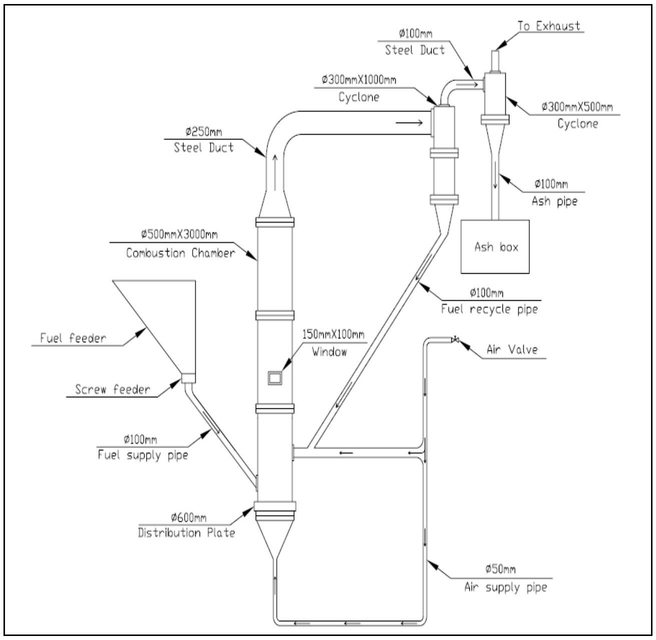

Figure 1. Sketch for a fluidized bed combustion chamber for olive cake

The air distribution plate was designed to assure good distribution of the air among the burner cross section. The diameter of the plate was 0.6 m with 3000, 2 mm in diameter 2 mm-apart holes. More details about the design were presented in [15].

The mathematical model represents the governing equations of continuity, momentum, energy, mass diffusion and chemical combustion reactions kinetics. Those equations were solved numerically using a high resolution mesh accounting for the solid and gaseous phases, k-ε turbulence, non-premixed combustion model and reacting CFD model with the same dimension and material of the experimental combustion burner of this study [16].

The burner mesh was created with two velocity inlet surfaces; one for the air at 2 m/s and the other for the fuel with a flow rate of 0.01 kg/s, one pressure outlet surface at the exhaust and three walls surface with a temperature of 500 K for the combustion chamber walls. Non-premixed combustion model was selected since the fuel and the oxidizer enter the chamber in distinct streams. Since non-adiabatic system is assumed, the solution is required for the modeled transport equation for time average enthalpy:

$$\frac{\partial}{\partial t}(\rho h)+\nabla.(\vec{\upsilon}\rho h)=\nabla.(\frac{k_t}{c_p}\nabla h)+S_h \qquad (1)$$

Where S_h accounts for source terms due to radiation, heat transfer to wall boundary, and heat exchange with the second phase, and the total enthalpy is defined as:

$$h=\sum_j Y_j h_j \qquad (2)$$

Where Yj is the mass fraction of species j, and

$$h_j=\int_{T_{ref,j}}^{T} c_{p,j}\,dt+h_j^o(T_{ref,j}) \qquad (3)$$

$h_j^o(T_{ref,j})$ is the formation enthalpy of species j at the reference temperature Tref,j. The turbulent viscosity is solved using the $k-\varepsilon$ model that considers:

$$\mu_t=\rho C_\mu \frac{k^2}{\varepsilon} \qquad (4)$$

Where k and ε are obtained from the transport equations and C_μ is constant.

The mole fraction of biomass species during the combustion process were estimated using probability density function module integrated in ANSYS/Fluent software. Then, a discrete particle model (DPM) in 3-D steady state space is used to solve numerically the governing equations of continuity, momentum, energy, and mass diffusion to estimate species fraction before and throughout combustion, temperature, radiation, convection heat transfer, pressure, and density. The chemical reversible reactions involving those species during combustion were considered [16]. Table II summarizes the mathematical model and the input data.

TABLE II. SUMMARY OF THE MATHEMATICAL MODEL

Space	3-D
Time	Steady
Viscous	Standard k-ε turbulence model
Heat transfer	Enabled
Species	C, H, N, O, S, C(s), S(s), CH_4, H_2, CO, CO_2, N_2, O_2, OH, H_2O, C_2N, C_3, C_2, H_2S, SO, SO2, CS, NO, NO_2, and C_2H_2
Fuel	olive cake
Fuel flow rate	0.01 kg/s
Air velocity	2 m/s
Wall temperature	500 K
NOx model	Thermal, prompt, fuel
SOx model	Thermal

The simulation model was validated by comparing the results obtained the literature and the experimental results as shown in [15]. The mathematical model shows good agreement with experimental results and the results are considered valid.

IV. Results and Discussion

The following set of figures present obtained simulation results of direct burning of olive cake. The de-volatilization and burnout rate contours for olive cake are presented in Figs. 2 and 3 respectively. The figures show that volatiles are released with a maximum rate of 1.8 g/s occurs slightly downstream of solid fuel feeding position After that the burnout started with maximum rate of 0.0746.

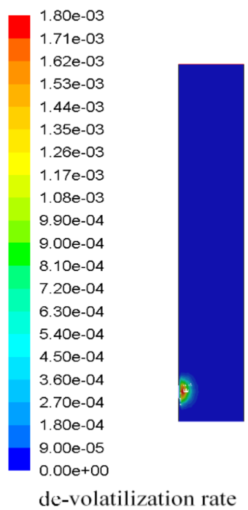

Figure 2. The DPM de-volatilization for fluidized bed combustion chamber.

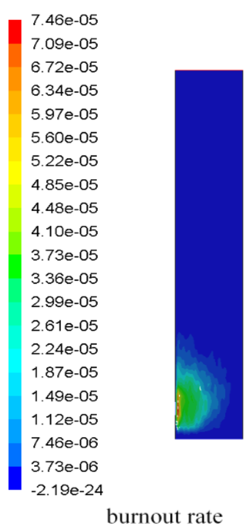

Figure 3. The burnout rates for fluidized bed combustion chamber.

Fig. 4 shows the temperature distribution in the fluidized bed burner. Even the maximum temperature achieved in case of olive cake was 1380 K. The average bed temperature is about 950 K, which gives a good agreement with experimental results and the literature [6].

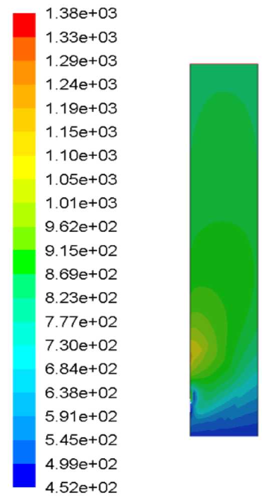

Figure 4. Temperature contours for fluidized bed olive cake combustion chamber

The maximum carbon dioxide CO_2 resulted from the combustion is presented in Fig. 5. It is noted that the highest concentration of CO_2 is 5.9% just above the burnout region. However, it is noted that this amount is diluted in the air to reach less than 4% at the exit of the combustion chamber. In addition, one can notice that the mass fraction of CO_2 is almost constant after the middle of the burner. This suggests that increasing the length to more than 1.5 m will have no effects on the emissions of CO_2.

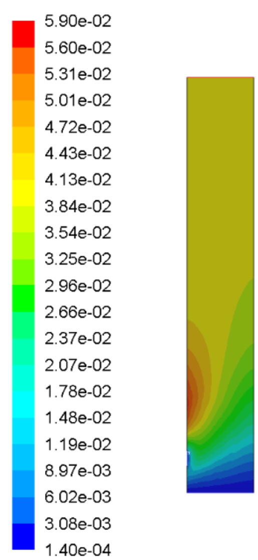

Figure 5. Mass fraction of CO_2 for fluidized bed olive cake combustion chamber

Figs. 6, 7, and 8 show the amount of NO, SO_2, and SO_3 resulted from the olive cake combustion respectively. The maximum NO, SO_2, and SO_3 mass fraction were 0.00066%, 0.0075%, and 0.000036% in the burnout region respectively, and then it decreases as temperature decreases to the half at the exit. Again, it is noticed that the pollutants' concentrations do not change after the half-length of the burner, which again indicates that the length of the burner has no effect on the pollutants after 1.5m. This means that decreasing the length of the burner from 3m to 1.5m will decrease the heat lose without increasing the emission of the pollutants, which will result a more efficient combustion.

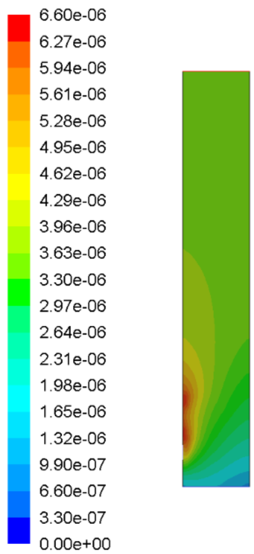

Figure 6. Mass fraction of NO for fluidized bed olive cake combustion chamber

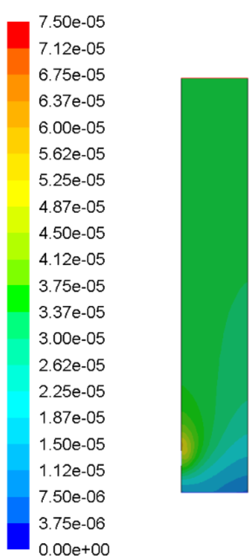

Figure 7. Mass fraction of SO_2 for fluidized bed olive cake combustion chamber

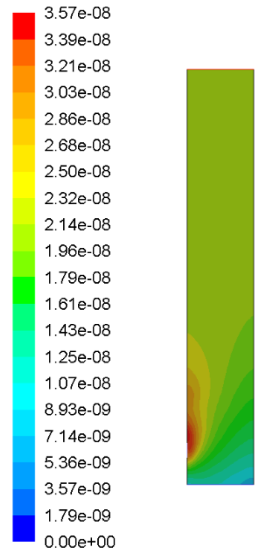

Figure 8. Mass fraction of SO_3 for fluidized bed olive cake combustion chamber

V. Conclusion Remarks

In this study, proximate and ultimate analyses for olive cake were performed to estimate the percentage of C, H, O, N, and S existing in this biomass. It was found that the lower heating value was 19500 kJ/kg for olive cake. A mathematical model was built to represent the physical model of the combustion process of the biomass. The simulation was implemented using ANSYS/Fluent software in order to estimate maximum temperature and pollutants concentrations. It was found that the temperature contours of the combustion process showed that the adiabatic flame temperature was 1380 K for olive cake respectively. The mass fraction of CO_2 was 5.9% at the burnout region and decreased at the exit to less than 4%. The concentration of NO, SO_2, and SO_3 is very low, which indicates that olive cake is environmentally friendly fuel. It also noted that the length of the combustion chamber could be decreased to 1.5m with affecting the amount of pollutants emitted. These results show that olive cake has a good potential to be used in electricity generation. Further studies shall be carried out on the feasibility of utilizing olive cake in electricity generation.

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