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Developing of a stove powered by solid biofuel pellets

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ABSTRACT

The shortage of energy and oil fuel is one of the most important challenges facing the world today. Biomass has become an important source of renewable energy. Residues are the third source of renewable energy after wind and solar energy. Farmers have incinerated of these residues causing serious environmental damage rather using this huge energy for useful purposes. The research aims to develop and test a stove powered by solid biofuel pellets. The experiments and the data analysis were carried out in the Agricultural Engineering Research Institute. Palm fronds were used in this study because it has a high calorific value and available in the desert of Egypt, also its neglected and priceless. The total availability of pruning's from palm date production was estimated to be around 813.9 Gg/year (FAO, 2017). Solid biofuel pellets were manufactured from palm fronds. Use different fan air speeds which has low energy to take ultimate advantage of burning palm fronds pellets requires a stove with high thermal efficiency and requires sufficient oxygen for combustion. The stove was manufactured according to Winiarski's design. The fan air speed from 0.2 to 2.2 m/s and some physical and mechanical properties of palm fronds pellets were studied. The stove performance was based on determining the combustion duration and temperature from palm fronds pellets, emissions of stove (CO_2 and CO) and stove heats efficiency. The calorific value of palm fronds pellets was 17.2 MJ/kg at a moisture content of 7.4% and true density of 1250 kg/m3. The maximum combustion duration was 153 min/kg at fan air speed of 0.2 m/s. The maximum temperature was 500⁰C and minimum value of CO was 282 mg/m3 at fan air speed of 2.2 m/s. The optimum point of stove heats efficiency was 64.4% was obtained at fan air speed of 1.0 m/s.

1. Introduction

Biomass have become an important renewable alternative energy resource which considered as the third source of renewable energy after wind and solar energy. To find alternatives to support renewable electricity generation and Liquefied Petroleum Gas (LPG) replacement targets, the end-use options for energy being considered are pellets, briquettes and energy combined from direct combustion (FAO, 2017). The briquettes and pellets could be burned in stoves and boilers for household and greenhouse heating and co-firing with coal in the plants of heat and power generation (Bilgin et al., 2015). Most agricultural residues have high calorific value or high heat value, which are about 15-17 MJ/kg (Kargbo et al., 2010). In the desert of Egypt, there is a high abundance of palm residues which contain a high heat value of 17 to 19 MJ/kg at a bulk density of 1200 kg/m³ (Munawar and Subiyanto, 2014). Density and moisture content of pellets and briquettes are very important variable for combustion efficiency. When increasing the bulk density of briquettes leads to increase the combustion duration (Khairy et al., 2015). The calorific value of solid biofuel increases with decreasing moisture content (Szymajda and Łaska, 2019). The moisture content of the pellets must be below of 12 % (Lunguleasa, et al., 2020). The impact of the operating parameters on the physical properties of solid and hollow pellets as applied pressure, die temperature, and moisture

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content (Mostafa et al, 2021). Biofuel combustion leads to harmful gas emissions such as NOx, SO_2, CO and CO_2 (Tsai et al., 2007). The combustion efficiency is necessary to reduce smoke and harmful emissions that damage health. Improving heat transfer efficiency can significantly reduce fuel use. Insulate around the fire to help it burn hotter to improve combustion. The combustion chamber should be about three times taller than its diameter. Air needs to pass under or up through the fuel and into the fire. Maximize heat transfer to the pot with properly sized gaps, the hot flue gases from the fire are forced through these narrow gaps (Bryden et al., 2005). Skirt gap is the most important parameter for higher efficiency of the stove (Kshirsagar, 2009). It is depending on area of the combustion chamber.

The main objective of this research was to:

1. Developing and manufacturing a simple stove powered by solid biofuel pellets with high heat efficiency.
2. Study of some physical and mechanical properties of palm fronds pellets.
3. Evaluate the performance of the stove using palm fronds pellets.

2. Materials and methods

Palm fronds were used in this study because it is neglected, priceless and moisture removal faster (FAO, 2007). Palm fronds were chopped to fine particle size, particles were separated into seven categories to get of mean length according to ASABE S319.3 (ASAE Standard, 2003). The mean length of palm fronds chopped was 1.96 mm (CV: 5.94 %). Palm fronds pellets were manufactured in Alarabia factory for fodder, Fayoum Government, 12 g of sugar cane molasses have been added to one kg palm fronds chopped as an adhesive material (Figure 1). Some physical and mechanical properties of palm fronds pellets such as true and bulk density, moisture content, coefficient of friction and calorific value were studied.

Figure 1. Palm fronds Pellets.

Figure 2 illustrates the developed stove, the stove was fabricated in Agricultural Engineering Research Institute workshop and all experiments were carried out in Agricultural Engineering Research Institute laboratory, Giza Egypt.

The stove was designed as recommended by Winiarski's design approach which combines both clean burning and optimized heat transfer characteristics (Bryden et al., 2005) .

The stove has an overall length of 559 mm, overall width of 300 mm and overall height of 660 mm. The stove consists of five main parts:

1) Combustion chamber. 2) Feed entrance.
3) Air inlet. 4) Dust outlet. 5) Pot.

1. Combustion chamber

The combustion chamber was fabricated from steel quarter of 100×100×0. 4 mm and it was two times taller than its diameter, so that helps the fire burn hot and fierce. The height of the combustion chamber was 200 mm.

2. Feed entrance

The feed entrance was inclined to an angle of 45° to horizontal axis to overcome friction angle of palm fronds pellets. The mesh has been installed under feed entrance to receive the pellet fuel and perforated with a diameter of 5 mm to allow the air pass through by using a fan which installed on the air inlet gate. It was fabricated from steel quarter of 100×100×0. 4 mm. It has a length of 400 mm, and has a volume of 0.004 m^3, while bulk density of pellets was 750 kg/m^3; thus, the maximum feed was 3 kg.

3. Air inlet

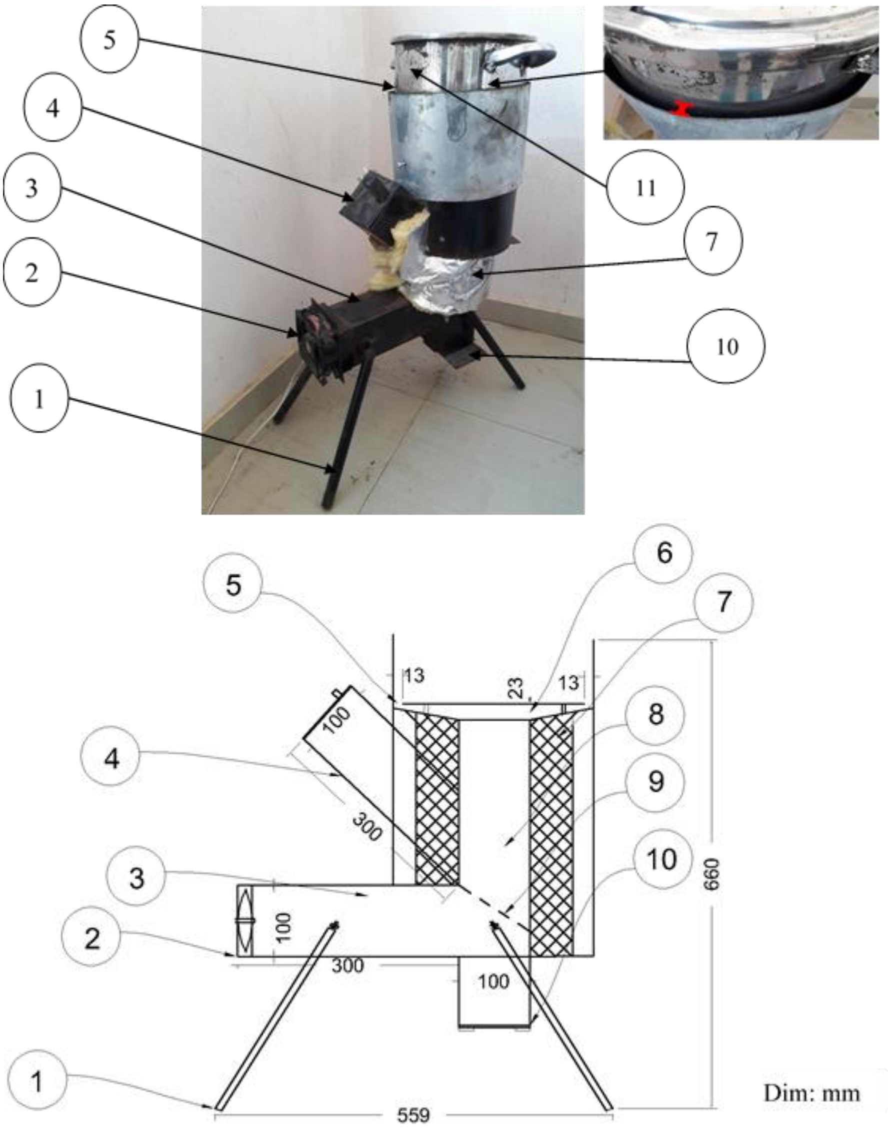
The air inlet was installed under the combustion chamber for helps the pellets to reach complete combustion. It was fabricated from steel quarter of 100×100×0. 4 mm. It has a length of 400 mm. AC electric fan was fixed by four nails on the front of the air inlet with a diameter of 100 mm to push the air to combustion chamber. The fan was made in Mexico and worked at 0.09 A and 220 V. Dimmer switch was connected to control of fan speed. Dimmer switch was divided manually to get nine different of fan air speed.

4. Dust outlet

The dust outlet was connected under combustion chamber to collect the dust in dust container; it was fabricated from steel quarter of 100×100×0. 4 mm. The dust container has a height of 100 mm and volume was 0.001 m^3. The dust was collected and exited out by dust gate.

5. Pot

The pot was made of stainless steel 304 to resist corrosion and scaling. It has a diameter of 240 mm and height of 160 mm so that the volume was 7.2 liter.



1. Trestle.
2. Fan.
3. Air inlet.
4. Feed tray.
5. Skirt gap.
6. Gap A.
7. Insulation.
8. Combustion chamber.
9. Mesh.
10. Dust outlet.
11. Pot

Figure 2. The developed stove.

2.1. Calculation of Gap A and skirt Gap

Maximize heat transfer to the pot with sizing gaps properly. It is best to do heat in pots with small channels. The hot flue gases were forced from the fire through these gaps, where they were forced to against the pot (Bryden et al., 2005).

The height of the gap under the pot must be determined correctly. This height will vary as you move from the center of the combustion chamber out the edge of the pot. To do this, calculate the needed gap at the edge of the combustion chamber (Gap A) and at the edge of the pot (Skirt Gap) as shown as (Figure 2).

The gabs were calculated according to Bryden et al., 2005 as follows:

Gap A at the edge of the combustion chamber (under the pot) was calculated as follows:

$$G_A = {}^{A}/_{C_C} \quad \text{... [1]}$$

where:

G_A= Gap A, cm;

A= the area of combustion chamber, cm^2 (100 cm^2)

C_c= the circumference of the combustion chamber, cm.

The circumference of the combustion chamber (C_c) as the follow:

$$C_c = 2\pi r_c \quad \text{... [2]}$$

where:

r_c= length from the center of the combustion chamber outlet to the farthest edge (0.5×diagonal), cm. (7cm)

C_c= 44 cm and G_A =2.27 cm.

Determine the gap at the edge of the pot (skirt gap) using the formula:

$$G_S = A/C_p \quad \dots [3]$$

where:

G_S= Skirt gap, cm;
A= the area of combustion chamber, cm^2 and
C_p= the circumference of the pot, cm. (75.3 cm)
G_S = 1.3 cm.

2.2. Maximum mass burning rate

Combustion air requirement was based on the mass composition gives a stoichiometric air/fuel ratio (A/F) of 4.6 kg air per kg solid biofuel. For an actual air supply which is 20 % in excess of stoichiometry, actual air/fuel ratio (A/F_{ac}) of 5.5 kg air per kg fuel (Ayo, 2009). The volume flow rate was related to the area of the air inlet, as the follow:

$$\bar{v}_a = A_a \times v \quad \dots [4]$$

where:

$\bar{v}_a$= The volume flow rate, m^3/s;
A_a= The area of air inlet, m^2 and
v = Air velocity, m/s.

Density of air depends on ambient temperature and pressure so that, the density of air is 1.18 kg/m^3 at 25^0c under atmospheric pressure. So that, the actual air supply rate was founded at each fan air speed. Fan air speed were 0.2, 0.5, 0.7, 1.0, 1.7, 1.9, 2.0, 2.1 and 2.2 m/s measured by using an anemometer (resolution of 0.1).

The actual air supply rate corresponding to the mass burning rate can also be expressed as,

$$\bar{m} = A/F_{ac} \times b \quad \dots [5]$$

where:

$\bar{m}$= actual air supply rate, kg/s;
b= maximum mass burning rate kg/s, and
A/F_{ac}= 5.5 kg air/ kg fuel.

Substituting in equation (5), theoretical maximum mass burning rate was 0.4 g/s at 0.2 m/s fan air speed and 4.7 g/s at 2.2 m/s fan air speed.

2.3. Performance evaluation methodology

2.3.1. Physical and mechanical properties of palm fronds pellets

- *Palm fronds pellets dimension:* The length of the pellets was measured in mm by using the vernier caliper (0.01mm resolution) at a constant diameter of 8 mm. A sample of 500 pellets were used to determine this property.
- *Moisture content:* The moisture content of palm fronds pellets was determined according to ASABE S358.3 (ASAE standard, 2003). Three replicates were used for each measurement.
- *True density:* The samples were weighed using a digital balance made in Korea which has range of 0:3000 g and a resolution of 0.1 g. A sample of 100 g from palm fronds pellets was used to determine the true density. A calibrated bottle (ml) was used to measure the volume. The bottle was filled to half with the gasoline (Mohsenin, 1998), the sample was slightly poured and the results were recorded directly. Three replicates were used for each measurement.
- *Bulk density:* An empty container (3000 cm^3) and the samples were weighed using a digital balance. The container was filled with the sample and the material was slightly compacted to ensure absence of large void spaces (Mohsenin, 1998). The container and the sample were weighed. Three replicates were used for each measurement.
- *Compressive strength:* The compressive strength is a mechanical test to measure the maximum amount of compressive load applied at the point of failure. Its indicator for durability and combustion efficiency. The maximum force was recorded by using a digital force gauge device, five replicated were used. While the cross-sectional area was constant at 78.5×10^{-6} m^2.
- *Calorific value of palm frond pellets:* Calorific value of palm fronds pellets was measured by the Egyptian Petroleum Research Institute (EPRI).
- *Coefficient of friction:* The coefficient of friction between palm fronds pellets and steel sheet was measured by using inclined plate methods to determine the angle of feed entrance. Five replicated were used.

2.3.2. Stove performance

2.3.2.1. Combustion duration and temperature of palm fronds pellets

Fire was set to palm fronds pellets using gasoline (5 ml), the combustion duration and fire temperature were recorded for tested air speed using a 100 g from palm fronds pellets. The temperature was recorded at the top of the combustion chamber using infrared thermometer (±1°c accuracy).

2.3.2.2. Emissions of stove

Emissions of the stove were measured during combustion of palm frond pellets at moisture content of 7.4 %. Carbon monoxide (CO) and carbon dioxide (CO_2) were measured by using the emission measurement devices. The specifications of the emission measurement devices were shown in Table 1.

Table 1

Specifications of the emission measurement devices.

Items	Values	
Model	AZ 7752	UT337A
Measure	CO_2	CO
Range	0 - 9999 ppm	0 -1000 ppm
Resolution	1 ppm	1 ppm

2.3.2.3. Heat efficiency of stove

Fire was set to palm fronds pellets using gasoline (5 ml), in order to allow water in the pot to boil and to get evaporated for another 30 min. Initial standard amount of water taken during each test was 1.5 kg. The heat efficiency of stove can be expressed as the following (Kshirsagar, 2009):

$$\eta = \frac{M_w \times C_p (T_b - T_i) + M_{we} \times L_v}{M_f \times CV} \quad \dots [6]$$

where:

M_W = Initial mass of water, kg;
C_p = Specific heat of water (4.18 kJ/kg.°C);
Ta_b = Boiling temperature of water, °C;
T_{ie} = Initial temperature of water, °C;
M_u = mass of water evaporated, kg;
L_v = latent heat of vaporization of water (2258 kJ/kg);
M_f = Mass of fuel used, kg and
CV = Calorific value of fuel (17198 kJ/kg).

3. Results and discussions

3.1. Studied physical and mechanical properties of palm fronds pellets

The mean value of length, diameter and moisture content of palm fronds pellets are shown in Table 2. The true density, bulk density and compressive strength were increased to reach of 1250 kg/m³, 750 kg/m³ and 12.06 MPa respectively, this increases the combustion duration and durability (khairy et al., 2015). The calorific value of palm fronds pellets was 17.2 MJ/kg this indicates a better value compared with bio-oil was made from palm fronds which has a calorific value of 10.25 MJ/kg (Solikhah et al 2017).

The coefficient of friction between pellets and steel sheet was 0.53 (friction angle of 28°). The inclination of feed entrance must be greater than 28°.

Table 2

physical and mechanical properties of palm fronds pellets.

Physical parameter	Mean	CV %
Length, mm	25.5	8.4
Diameter, mm	8	---
Moisture content, %	7.4	0.02
True density, kg. M^{-3}	1250	0.004
Bulk density, kg. M^{-3}	750	0.04
Compressive strength, MPa	12.06	0.004
Calorific value, MJ/kg	17.2	----
Coefficient of friction (steel)	0.53	0.01

3.2. Stove performance

3.2.1. Combustion duration and temperature of palm fronds pellets

Figure 3 illustrates that the combustion duration significantly decreased with increase of fan air speed. The temperature of palm fronds pellets significantly increased with the increase of fan air speed. The maximum temperature was 500 ⁰C at 2.2 m/s fan air speed while the minimum temperature was 200 ⁰C at 0.2 m/s fan air speed. The maximum combustion duration was 153 min/kg at 0.2 m/s fan air speed while the minimum combustion duration was 74 min/kg at 2.2 m/s fan air speed. This means when the fan air speed was increased, the high value of oxygen has been pressured to the fuel. The combustion duration was increased due to high of true density of palm fronds pellets (khairy et al., 2015).

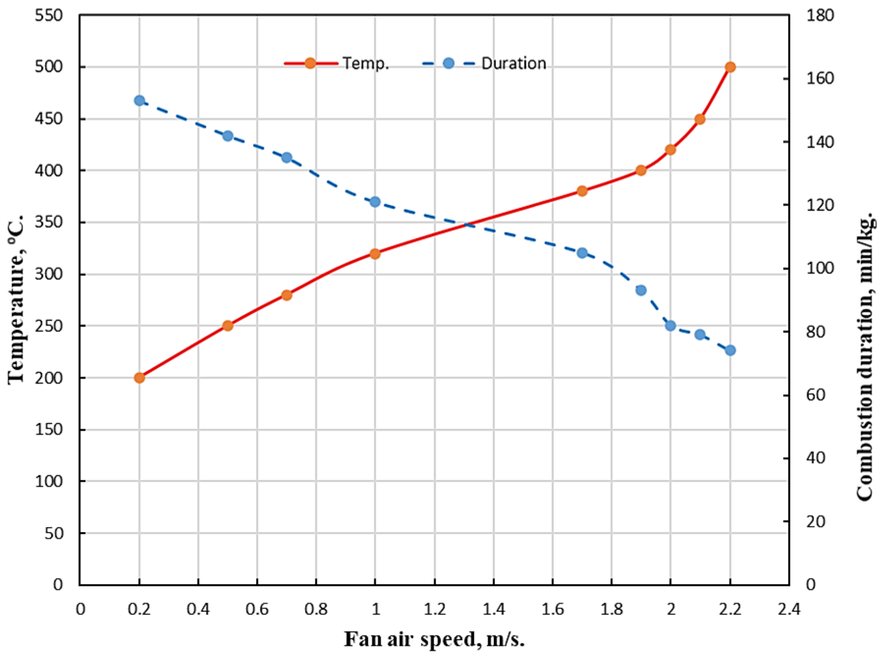


Figure 3: Effect of fan air speed on combustion duration and temperature.

3.2.2. Emissions of CO and CO_2

Figure 4 shows that the maximum value of CO_2 was 6030 mg/m³ at 2.2 m/s fan air speed while the minimum value of CO_2 was 1440 mg/m³ at 0.2 m/s fan air speed. The results indicated that the CO_2 increased gradually with the increase of fan air speed. This due to the increase of the amount of oxygen whose unites with fixed carbon to produce carbon dioxide (CO_2).

The maximum value of carbon monoxide (CO) was 948 mg/m³ at 0.2 m/s fan air speed while the minimum value of CO was 282 mg/m³ at 2.2 m/s fan air speed. The results indicated that the CO decreased gradually with the increase of fan air speed. The obtained results at studying of fan air speed variable from 0.7 to 2.2 m/s equivalent 785 to 282 mg/m³ below the maximum of carbon monoxide (CO) of 800 mg/m³ according to Egyptian standard: 6122/2008 (adjusted in 2013) C.F. Orabi et al., 2020.

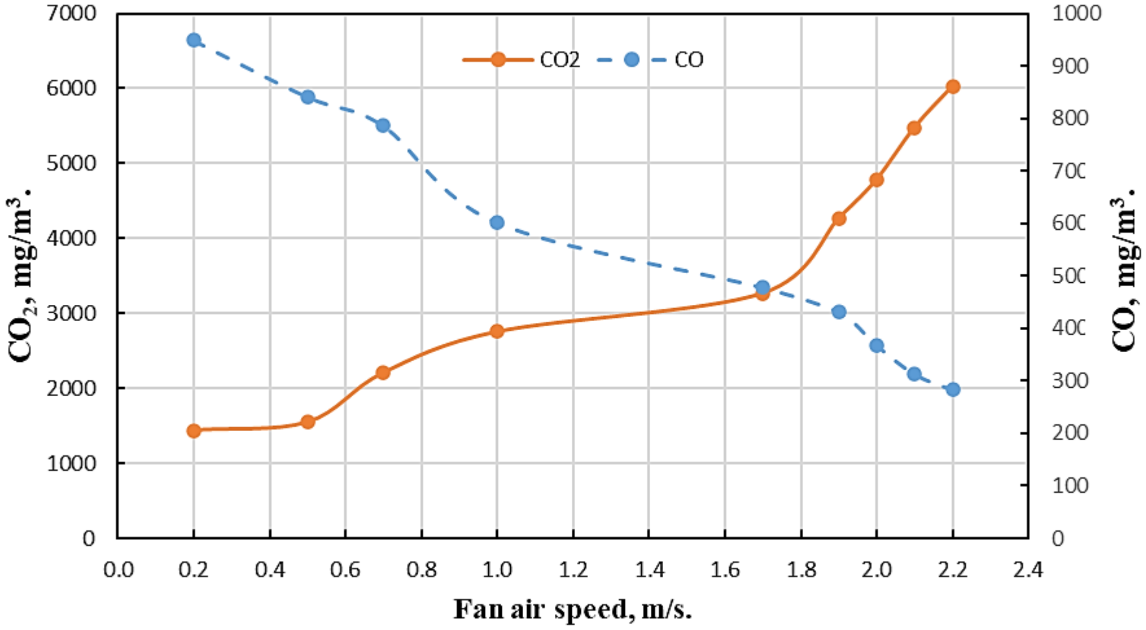


Figure 4: Effect of fan air speed on the emissions of CO and CO2.

3.2.3. Heat efficiency of stove

Figure 5 illustrates that the heat efficiency of stove increases with an increased rate by increasing fan air speed from 0.2 m/s up to 1.0 m/s. While decreases with the increase of fan air speed from 1.0 m/s up to 2.2 m/s. The maximum of heat efficiency was 64.4 % of the fan air speed of 1.0 m/s. This indicates a better performance when compared to the maximum heat efficiency of 62.3% according to Kshirsagar, 2009.

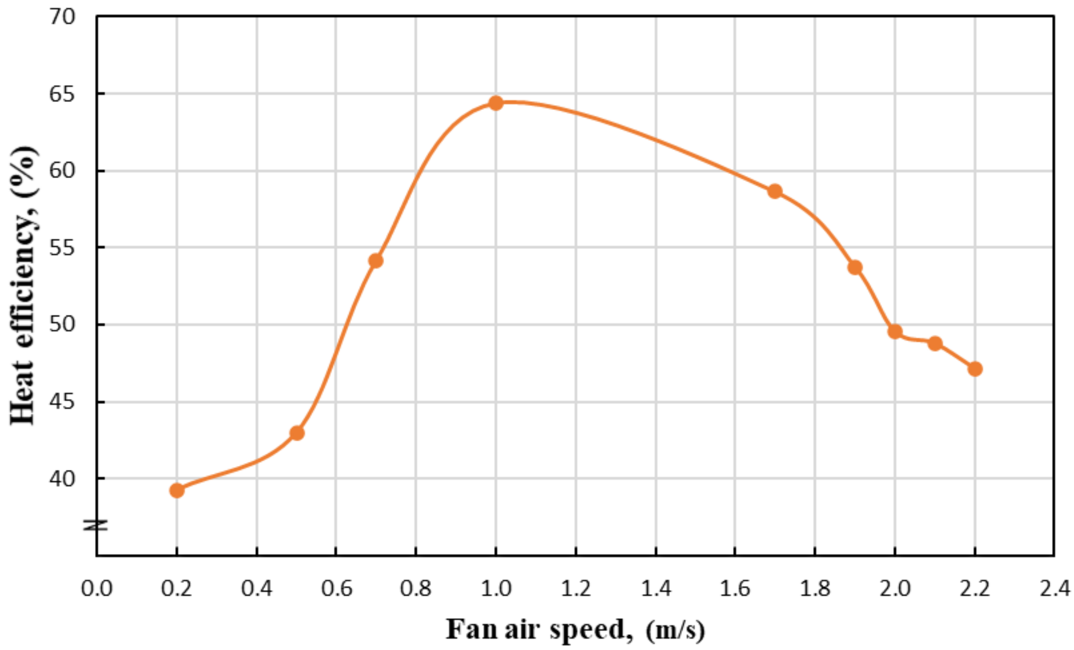


Figure 5: Effect of fan air speed on heat energy efficiency of stove.

4. Conclusions

The calorific value was 17.2 MJ/kg of palm fronds pellets at a moisture content of 7.4% and true density of 1250 kg/m^3. The optimum conditions lead to high heat efficiency of 64.4% at fan air speed of 1.0 m/s. This indicates a better performance when compared to the maximum heat efficiency of 62.3% according to Kshirsagar, 2009. The emission of CO was 400 mg/m^3, temperature was 320 ^{0}C and the combustion duration was 121 min/kg at fan air speed of 1.0 m/s. The developed stove will be used for various purposes, such as water desalination and biochar production or as an alternative to oil and natural gas.

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تطوير موقد يعمل بمصبعات الوقود الحيوي الصلب

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الملخص العربي

تعتبر مشكلة النقص في الطاقة والطلب المتزايد عليها وانخفاض الوقود النفطي من أهم التحديات التي تواجه العالم في هذا الوقت الحالي، لذلك أصبحت الكتلة الحيوية مورداً هاماً للطاقة المتجددة وتعتبر المخلفات المصدر الثالث للطاقة المتجددة بعد طاقة الرياح والطاقة الشمسية. عادةً ما يلجأ المزارعون بحرق المخلفات بغرض التخلص منها مما ينتج عنه أضرار بيئية كبيرة إلى جانب عدم استغلال هذ الطاقة الكبيرة والاستفادة منها في أغراض مفيدة. توجد كميات كبيرة من أوراق سعف النخيل مهملة وغير مستفادة خاصة في المناطق الصحراوية تقدر بحوالي ٨١٣,٩ جيجا جرام/عام (FAO, 2017). ولتعظيم الاستفادة من هذه المخلفات في هذا البحث تم تصنيع مصبعات الوقود الحيوي الصلب من مخلفات سعف النخيل حيث تم جمع أوراق سعف النخيل وفرمها بأحجام صغيرة وكبسها لعمل مصبعات وذلك لاحتوائها على محتوي حراري عالي يقدر بحوالي ١٧ ميجا جول/ كجم. للاستفادة القصوى من

حرق المصبعات يتطلب وجود موقد جيد ذو كفاءة حرارية عالية كما يتطلب نسبة أكسجين كافية لعملية الاحتراق وذلك باستخدام سرعات مختلفة لمروحة ذات طاقة منخفضة.

لذلك تم في هذا البحث:

- تطوير موقد يعمل بالوقود الحيوي الصلب سهل الاستخدام والصيانة ويعمل بكفاءة عالية ويقلل من الانبعاثات الضارة.
- دراسة بعض خصائص الوقود الحيوي الصلب المصنع من أوراق سعف النخيل.
- تقييم أداء وكفاءة الموقد باستخدام مصبعات سعف النخيل.

تم اجراء التجارب وتحليل النتائج في معمل معهد بحوث الهندسة الزراعية الدقي محافظة الجيزة. وتم تقييم أداء الموقد عن طريق استخدام ١٠٠ جم من مصبعات سعف النخيل لقياس فترة الاحتراق ودرجة الحرارة الناتجة وقيمة انبعاثات أول أكسيد الكربون وثاني أكسيد الكربون وكفاءة الموقد عند سرعات مختلفة لهواء المروحة.

وكانت أهم النتائج المتحصل عليها هي:

القيمة الحرارية من الوقود الحيوي هي ١٧,٢ ميجا جول/ كجم عند محتوى رطوبي ٧,٤٪ والكثافة الحقيقة ١٢٥٠ كجم/م٣ والكثافة الظاهرية ٧٥٠ كجم/م٣. وكانت كفاءة انتقال الحرارة هي ٦٤,٤٪ عند سرعة هواء المروحة ١,٠ م/ث. زيادة سرعة هواء المروحة يمكن أن يقلل من انبعاثات أول أكسيد الكربون إلى أقل من ٨٠٠ مليجرام/م٣ حسب المواصفات القياسية المصرية حيث كانت أقل قيمة لانبعاث أول أكسيد الكربون هي ٢٨٢ مليجرام/م٣ عند سرعة هواء المروحة ٢,٢ م/ث. درجة الحرارة القصوى هي ٥٠٠ درجة مئوية عند سرعة هواء المروحة ٢,٢ م/ث، في حين أن أقصى مدة للاحتراق هي ١٥٣ دقيقة /كجم عند سرعة هواء المروحة ٠,٢ م/ث ويمكن أن تستخدم هذه الأفران لأغراض مختلفة، مثل تحلية مياه البحر وإنتاج الفحم الحيوي، أو كبديل للنفط والغاز.