Analyzing the Use of Sachet Water Film (SWF) as a Substitute for Low Pour Fuel Oil (LPFO)

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Abstract: Sachet water is an item that is highly consumed in Nigeria as it is the most affordable and easily available water consumed by common man. Its consumption comes with the problem of disposal of the sachet water film (SWF) since it is made of low density polyethylene (LDPE) and almost non-biodegradable. There is therefore the need to analyze the energy content of the film and the possibility of using it as a substitute for low pour fuel oil (LPFO) used in boilers. Analysis shows that sachet water film has higher energy content estimated at 10,601.74 cal/g compared to that of low pour fuel oil which is 10,203.36 cal/g and generate less smoke compared to low pour fuel oil. The problem with sachet water film is that it doesn't burn completely thereby leaving a solid substance which has to be removed in order to continue using the equipment. This can be done by dissolving it in benzene at a temperature of 70 ^{o}C but there is still a problem of disposal of the solution. Comparing the burning rate, sachet water film burns at a rate of 0.57 g/min lower than that of low density polyethylene which is 0.76 g/min. This value shows that even if the two fuels have the same energy values, less sachet water film will be needed to provide the same amount of energy compared to low pour fuel oil. It was therefore concluded that sachet water film can possibly be used as a substitute for low pour fuel oil but efficient cleaning and disposal of the remnant is required.

Keywords: Sachet water film, Calorific value, LPFO, LDPE

I. INTRODUCTION

Sachet Water Film (SWF) films are made from Low Density Polyethylene (LDPE) which is a thermoplastic material made from the monomer ethylene [1]. The Environmental Protection Agency (EPA) estimates that only 5.7 % of the LDPE produced is recycled in the world while the remaining is littered around, having impact on the environment [2]. The last few decades have seen a tremendous increase in the use of polyethylene films (commonly called pure water sachets in Nigeria) by sachet water producers. This has resulted to uncontrolled disposal of these sachets in our environment. Due to inadequate waste management system used in Nigeria, polyethylene films are the major waste found at dumpsites.

It has been estimated that polyethylene would degrade by less than 0.5 % in 100 years, and 1 % if exposed to sunlight for two years [3]. It is a common practice by sachet water producers to burn the films in a pit behind their industries wasting the heat energy generated during burning of these films

[4]. There is the need for effective pure water sachets management to convert this waste to economically useful and environmental friendly by-products. Heat energy can therefore be obtained from the combustion of pure water sachets to help in meeting the energy demand in the world. High demand for fossil fuel which is a major source of energy in boilers has adverse effect on the availability of Low Pour Fuel Oil (LPFO) to industries. There is also high demand for LPFO by Nigerian industries which is estimated at about 59,699,000 litres in 2015 [5]. Industries in Nigeria are therefore seeking an alternative source of energy which can be used as a substitute for the fuel.

i. Sachet Water History in Nigeria and its Environmental Effect

The exact date when sachet water was introduced in Nigeria is not known, but it was introduced to the Nigerian market around 1990 and started attracting nationwide attention in 2000 when the National Agency for Food and Drugs Administration and Control (NAFDAC) registered 134 different sachet water producers [6]. The relatively cheap and inexpensive nature of the sachet water when compared to bottled water makes it a cherished and preferred commodity in the hands of many [20]. About 70% of average Nigerian adult drinks at-least a sachet of pure water per day resulting in about 50 to 60 million used sachets disposed daily across the country [7]. This led to sachet water films being littered everywhere in most major cities of the country.

ii. Properties of Pure Water Sachet (PWS)

The packaging of the sachet water is done using a non-biodegradable Low-Density Polyethylene (LDPE) film which does not decay, decompose or corrode [8]. Low Density Polyethylene is a thermoplastic material made from the monomer ethylene. The first polyethylene was produced in 1933 by Imperial Chemical Industries (ICI) using high pressure process via free radical polymerization [1].

Low density polyethylene is soft to touch and has a density of the range 0.910-0.940 g/cm^3. It is not reactive at room temperatures, except when treated with strong oxidizing agent and some solvent which cause it to swell. It can withstand temperatures of 80-95 ^{o}C for a short period of time. It is made in translucent or opaque variations and quite flexible and tough but breakable [1].

Low Density Polyethylene has more branching than High Density Polyethylene (HDPE), so its molecular forces are weaker. It has excellent chemical resistance making it resistant to attack by strong acid or strong base and also to small oxidants and reducing agents. It burns slowly with a blue flame having a yellow tip and gives off an odour of paraffin [10]. The percentage composition of LDPE as summarized by [9] is shown in Table 1.

Table 1: Percentage Composition of LDPE

Constituent	Percentage %
Carbon	84.4
Hydrogen	14.1
Nitrogen	0.07
Sulfur	0.03
Moisture	0.2
Ash	1.2

iii. Combustion of Low Density Polyethylene Film

The combustion of LDPE film followed a pattern; the films are first being pre-heated when the flame source is applied. During the pre-heating, the films decompose and release gaseous hydrocarbons into the atmosphere around the flame source. These hydrocarbons will then become ignited at appropriate temperature and consequently combust in oxygen to release heat [11]. The heat released during this combustion is mostly lost to the environment while a fraction of this heat finds its way back to the remaining films which are then pre-heated, decomposed and ignited. Hence the cycle continues until the films are all burned or oxygen supply for combustion has stopped [12].

iv. Low Pour Fuel Oil (LPFO) Properties

Low pour fuel oil (also known as black oil) is one of the products obtained from the fractional distillation of crude oil either as a distillate or residue. It is burned in furnace, boilers and in cement kilns in many industries to produce heat. It can also be used in an engine to generate power. LPFO is a viscous liquid with varying colours such as dark brown or greenish appearance as produced in Kaduna refinery. The different grades of fuel oil depend on their volatility and degree of which they burn.

The percentage composition of Low Pour Fuel Oil (LPFO) as summarized by [13] is shown in Table 2.

Table 2: Percentage Composition of Low Pour Fuel Oil (LPFO)

Constituent	*Percentage %*
Carbon	87.49
Hydrogen	9.92
Nitrogen	0.00
Sulfur	1.40
Moisture	0.00
Ash	0.00

v. Combustion of Low Pour Fuel Oil in Boiler

Boilers are pressure vessels design to heat water or produce steam, which can then be used in various processes or heating applications. In most industries, the fuel used in a boiler is LPFO.

Oil fired boilers use controlled combustion of fuel to generate steam. The key boiler components involved in this process are the burner, combustion chamber (or furnace), heat exchanger and controls. In the burner, the fuel mixes with oxygen from the air and with the assistance of an ignition device, provides a platform for combustion. The combustion takes place in the combustion chamber, and the heat that is generated is transferred to the water by the heat exchanger.

The nitrogen from the air can combine with oxygen at high flame temperature to produce oxides of nitrogen (NO_x), which are toxic pollutants. Carbon, hydrogen and sulphur in the fuel can also combine with oxygen in the air to form carbon dioxide, water vapour and sulphur oxide, releasing heat energy according to the equations shown here. Under certain conditions, carbon may also combine with oxygen to form carbon monoxide. Carbon burned to CO_2 will produce more heat per kilogram of fuel than when CO or smoke is produced.

$C + O_2 \rightarrow CO_2$ + 8,084 kcal/kg of Carbon -- (1)

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$2C + O_2 \rightarrow CO$ + 2,430 kcal/kg of Carbon -- (2)

$2H_2 + O_2 \rightarrow 2HO$ + 28,922 kcal/kg of Hydrogen -- (3)

$S + O_2 \rightarrow SO_2$ + 2,224 kcal/kg of Sulphur -- (4)

vi. Energy Value of Fuel (Higher Heating Value and Lower Heating Value)

The energy value (heating value or calorific value) of fuel is the amount of heat released during the combustion of a specified amount of the fuel. Energy value of fuel is of great significance for the production/utilization of solid or liquid fuel.

Higher heating value (HHV) is the amount of heat released by complete combustion of a mass unit of sample at constant volume in an oxygenated atmosphere and at standard conditions 101.3 kPa and 25 ^oC [14]. Lower heating value (LHV) on the other hand does not consider the condensation heat but rather assumes that water component of a combustion process is in vapour state.

The difference between the two heating values depends on the chemical composition of the fuel. In the case of pure carbon or carbon monoxide, the two heating values are almost identical. It can be related as:

$HHV = LHV + h_v \times (\frac{nH2O,out}{nfuel,in})$ -- (5) [15]

Where hv =heat of vaporization of water.

$n_{H20,out}$ =no of moles of water vaporized

$n_{fuel,in}$ = number of moles of fuel combusted

Heating value of a substance (solid or liquid fuel) can be determined using any of Bomb Calorimeter, Calorimetry Experiment or Elementary Component analysis

a. Bomb Calorimeter:

A sample whose calorific value is to be measured is weighed and added in crucible, the stirrer is then started and the initial water temperature is measured before the circuit is switched On to start combustion. The fuel sample burn in the presence of oxygen and the heat released during combustion of the fuel is transferred to the water. The calorific value of the fuel can then be measured.

b. Calorimetry Experiment:

A known amount of water measured and weighed is added into a container and hung from a retort stand and a weighed fuel sample whose calorific value is to be measured is ignited and put below the water sample heating container. The water is then stirred using stirrer and the change in the water temperature is measured by a thermometer. For a constant pressure measurement, the heat-temperature relationship can be written mathematically for any substance and solved for the calorific value.

c. Elementary Component Analysis:

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The higher heating value of fuel can be calculated from the percentage component of that fuel. According to the statistical relationship derived by [16], the higher heating value of fuels depends positively on their hydro- carbon content. It was found that the heating value of fuel can be obtained when the percentage fraction constituent of the fuel is known.

$$HHV_{fuel} = 0.3491Z_C + 1.178\,Z_H - 0.1034\,Z_O - 0.0151\,Z_N - 0.1005Z_S - 0.0211\,ZA \text{ ------ } (6)$$

Where,

HHV_{fuel} is the higher heating value of fuel in MJ/kg

$Z_{C,}$ $Z_{H,}$ $Z_{O,}$ $Z_{N,}$ $Z_{S,}$ and Z_A are the weight fraction of carbon, hydrogen, oxygen, sulphur, and ashes.

Therefore, polymers with no oxygen content and less nitrogen and ash content will have higher heating values and ease of combustion [12]

vi. Burning Rate

This is the rate at which the combustion products are generated. This is an important factor when dealing with comparison between different fuel types. The burning material may be gaseous, liquid, or solid, but the oxygen (normally free oxygen from the air) is usually in the gaseous state. For the necessary chemical reactions to occur, the fuel and oxygen must be brought into contact at a molecular level, and this in turn means that burning is generally a vapour phase phenomenon. Since gases mix with one another readily, the burning of a gaseous fuel, hydrogen or methane, for instance, is a rapid process. However, the burning of a liquid or solid fuel requires first that the fuel be converted to the gaseous state (volatilization). This process requires the input of an appreciable amount of heat energy, often from the fire itself, and is almost always slow by comparison to the rate of burning (oxidation). As a practical matter therefore, the rate of volatilization of a material strongly affects its rate of burning. The rate of burning is a function of how fast the chemical reaction of oxidation occurs, as well as the speed at which the vaporized fuel and oxygen are delivered to the combustion zone. Burning rate can be measured using the formula;

$$\text{Burning rate} = \frac{\text{mass of fuel consumed (g)}}{\text{total time taken (min)}} \text{ -- } (7)$$

II. EQUIPMENT AND EXPERIMENTAL PROCEDURE

A simple laboratory set-up is used to measure the burning rate and specific fuel consumption of pure water sachets and LPFO. The equipment used for the experiment are; Aluminium beverage can (13×5cm; 330ml), Heat insulated container (25.5×18.5cm), Measuring Cylinder (250ml), Beaker (250ml), Electric Weighing Balance, Stirring rod, Thermometer, Sample can and Electric hot plate. The reagents used are Distilled water, pure water sachets sample, LPFO sample, Acetone and benzene.

i. Construction of Heat Insulated Container

A 25.5×18.5 cm heat insulated container was constructed in this experiment. The container was made by using a can, opened at the bottom and top, and inserted inside a bigger can with 1.5 cm distance from the wall of the bigger can. The space between the cans was then filled with insulating fibre to prevent heat lost by conduction. The cans were held together at the centre by iron wires. A hole of 5 cm diameter was punched at the top for inserting a 13×5 cm aluminium can. Eight tiny holes were also punched at the top of the container for smoke discharge. Two iron wire were then inserted 5 cm from the bottom of the can crossing each other. The two iron wires were used as support for the aluminium can. Tiny holes were punched at the middle round the can to allow inflow of air for combustion. The diagram and the pictorial representation of the container are shown in Figure 1 and 2 respectively.

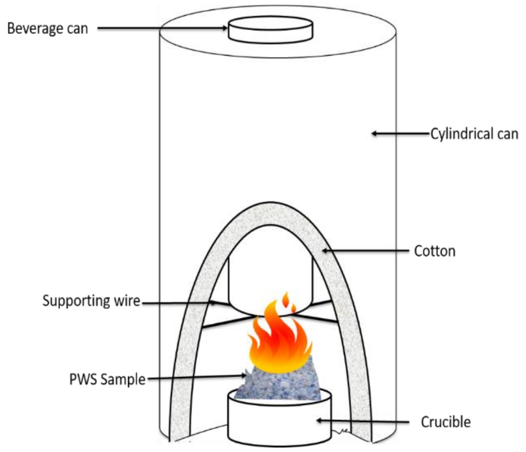

Figure 1: Cross sectional View of Heat Insulating Container

Figure 2: Pictorial View of the Heat Insulating Container

ii. Sample Collection

Sachet water films from different manufacturers in Jimeta metropolis were picked around the city. The sample collected was then washed to remove dirt and other impurities. The washed films were sun dried to remove the moisture in the films. The films were cut into small pieces for the experiment as shown in Figure 3 and 4.

Figure 3: Sun Drying of the Film

Figure: 4 Pieces of the PWS

The LPFO was obtained from Savannah Sugar Company Limited and is shown in Figure 5;

Figure 5: LPFO Sample

iii. Water Boiling Test (WBT)

Water boiling tests are short, simple simulation of standard heating procedure. It was carried out to compare the thermal efficiency of the pure water sachets film and LPFO. During the water boiling test, the burning rate and specific fuel consumption which are properties of fuel were also determined using the procedure described by [17], [18].

250 ml of water was boiled using a small aluminium beverage can which was inserted inside the heat insulating container using equal mass of the two fuel samples under similar conditions.

Temperature was measured at a time interval of two minutes to determine the heating rates of the two fuels.

The thermal efficiency (percentage of heat utilized) of the pure water sachets and LPFO were calculated using Equation 7.

Specific fuel consumption was also calculated using the formula

$$\text{Specific fuel consumption} = \frac{\text{mass of fuel consumed (g)}}{\text{Total mass of boiling water(g)}} \text{ --------------------------------------- } (8)$$

iv. Determination of Efficiency of the Calorimeter

In most practical calorimetric measurements, not all of the heat released by the combustion is used for heating the water. Some of the heat is absorbed by other materials that are present (for example, the thermometer, the walls of the container, etc.) and in a semi-open burner such as the one used, some of the heat is lost to the surrounding. One approach to account for the loss of heat is to determine an efficiency of the burner, defined as the fraction of the heat that is actually captured by the water:

$$\text{Efficiency} = \frac{\text{calorific value obtained by set-up}}{\textit{standard calorific value of the substance}} \text{ -- } (9)$$

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Efficiency in this experiment was determined by using LPFO sample which has a known calorific value as obtained from literature.

The LPFO is first heated to its flash point and then put in an empty can and weighed.

The sample is ignited and the burning sample was put under the aluminium can containing water inside the insulated container whose mass is already known and the water was continuously stirred during heating using a thermometer.

After a reasonable rise in temperature, the burning sample was extinguished and the final water temperature was measured.

The sample was re-weighed to measure the amount of fuel used and the heating value was then calculated.

The heating value obtained for LPFO using the experimental set-up was then divided by the standard calorific value of LPFO to obtain the efficiency of the set-up.

Once the efficiency was determined in this manner, it was then used to determine the calorific value when analysing pure water sachets combustion using the same device. However, it is important to note that any condition which might affect the efficiency of the burner is kept constant throughout the experiment.

Standard method was used to determine the calorific value of the two fuel samples using the equipment constructed.

v. Cleaning Unburned Sachet Water Films

During the combustion of SWF, the film pieces melt and continue burning until it reaches a point when it can no longer burn, forming a drip which then solidifies and get stuck to the container which gets very difficult to remove. Acetone and benzene were used in cleaning the melted films left after combustion. The benzene used is added to the melted film and is heated gradually to dissolve the sample at dissolution temperature of 70 ^{o}C below the boiling point of benzene (80 ^{o}C). The mixture of benzene and the sample is heated because most Low Density Polyethylene (LDPE) is very resistant to attack by solvents, however around 70 ^{o}C they will dissolve in solvents [21]. The dissolved SWF mixture was then disposed by burning the mixture in a fume hood.

III. RESULTS AND DISCUSSION

For the experiment on pure water sachet in comparison with LPFO, some results were obtained as displayed here. Result for boiling water test is shown in Table 3.

Table 3: Water Boiling Test

Fuel	*Sachet Water Film*	*Low Pour Fuel Oil (LPFO)*
Initial Mass of fuel (g)	45.00	45.00
Final Mass of fuel (g)	36.50	33.60
Mass of fuel used (g)	8.50	11.40
Time taken (min)	15.00	15.00
Burning Rate (g/min)	0.57	0.76

Rate of water boiling for pure water sachet films and that of LPFO is plotted as shown in Figure 6:

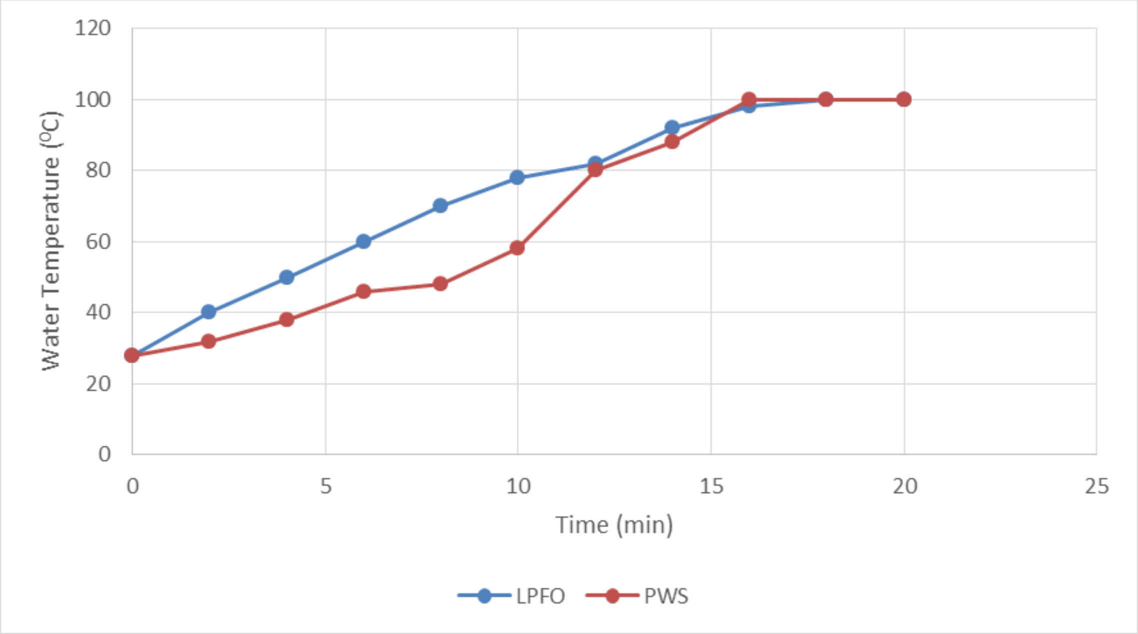

Figure 6: Variation of Water Temperature with Time for PWS and LPFO

The calorific values of LPFO and pure water sachets were determined and the results are shown is Table 4.

Table 4: Calorific Value of LPFO and SWF.

Fuel	*SWF*	*LPFO*
Initial Mass of fuel (g)	27.50	27.50
Final Mass of fuel (g)	25.20	25.30
Mass of fuel burned (g)	2.30	2.20
Mass of water (g)	254.00	254.00
Rise in water temperature (^{0}C)	48	44
Heat absorbed (cal/g)	5,300.87	5,074.00
Calorific Value (cal/g)	10,601.74	10,203.36

During the combustion experiment of LPFO and SWF, it was observed that LPFO burns giving a pungent smell with a dark smoke that burns completely without any remnant. For SWF, it burns with a white smoke that smells like paraffin leaving behind some solid non melted films. This is an indication that LPFO release higher gaseous pollutants such as CO, CO_2, SO_x than pure water sachets as suggested by [9], while the pure water sachets is having more mineral (non-combustible) matter than LPFO [13]. The solid remnant after burning SWF was removed by dissolving it in benzene at a temperature of 70 °C.

Table 3 shows that LPFO burns faster when compared to SWF as it can be observed that starting with mass of 45 g for both LPFO and PWS, the mass of LPFO left after 15 minutes of burning is 33.60 g compared to 35.60 g of PWS left for the same period of burning. From the result, it should be expected that LPFO will have higher calorific value but on the contrary, PWS has higher calorific value as can be seen in Table 4. This therefore calls for the need to examine the rate of heat absorption by boiling water. This result which is shown in Figure 6 shows that initially, the

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temperature rise using LPFO is higher compared to that using SWF. This continues until after 15 minutes which shows temperature rise of water using PWS overtook that of water using LPFO under the same condition. This explains that SWF is only at disadvantage at the initial stage of burning but when equilibrium is achieved, SWF burns at a much higher rate.

The specific fuel consumption which measures the quantity of the fuel required to boil equal volume of water showed that the mass per litre of water boiled for LPFO is 49.6g while that of PWS is 34g. This shows that less mass of SWF is consumed than when using LPFO for boiling equal volume of water.

IV. CONCLUSION

From the results obtained for the experiment which was aimed at comparing the performance of SWF to that of LPFO, the following conclusions were drawn.

SWF generates less smoke during combustion when compared to LPFO but has a solid remnant after complete burning which gives a problem of cleaning unlike LPFO which burns completely.

In their liquid state, PWS generate more heat compared to LPFO thereby having higher calorific value.

Since SWF is readily available considering the level of consumption of pure water, and can also provide sufficient heat required in boilers, it can be used as a substitute for LPFO in industries but efficient cleaning and disposal method should be devised since it will always live a solid remnant after burning.

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical statement: The authors declare that they have followed ethical responsibilities

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