MITIGATION OF IN-DOOR AIR POLLUTION AND GREEN HOUSE GASES BY USE OF RETROFITTED PRESSURE LAMP UTILIZING STRAIGHT VEGETABLE OIL

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Abstract
The potential of traditional fossil fuels to be exhausted has increased of late. This has affected the many sectors of the economy which rely on petroleum products. Apart from depletion of fossil fuel and escalating oil prices, there is also need to conserve the environment to reduce global warming, ozone layer depletion, and climate change. This will reduce health issues associated with pollutant emissions from fossil fuel use. Among the efforts being made is the search for alternative renewable fuels. The objectives of the study were to study the performance characteristics of pressure lamps while using pure kerosene, kerosene-straight vegetable oil (SVO) blends and finally to modify the pressure lamp to utilize higher SVO/ kerosene blends. The performance of unmodified lamp was investigated and compared to that of a retrofitted pressure lamp utilizing straight vegetable oil/kerosene blends at 1.5 bar, 2.0 bar and 2.5 bar lamp pressure. Light output, carbon monoxide (CO) emission, carbon dioxide (CO_2) emission, particulate matter (PM) emission, fuel consumption and heat generated were compared. Using a portable air compressor, air regulators and hoses, the lamps were maintained at constant pressures. Carbon dioxide data logger was used to monitor and record CO_2 in real time. Easy Log carbon monoxide data logger was used to record carbon monoxide concentrations. University of Caronia, Barkley (UCB) particle monitor was used to monitor and record particulate matter in the room. Light output was measured using lux meters. Heat generated was measured using thermocouple. The unmodified lamp handled a maximum of 30% blend. Retrofitted lamp had an average of 17% CO reduction, 18% particulate matter reduction, 5.5% fuel consumption reduction, 10% temperature reduction, 5% CO_2 increase while light output increased between 11% and 23% compared to the unmodified pressure lamp. In conclusion, the retrofitted pressure lamp utilizing SVO was designed and fabricated. This lamp emitted comparatively more light and CO_2 but less PM and CO than the unmodified lamp at all pressures and fuel blends. The fuel consumed increased with increase in lamp pressure for both lamps. It is recommended that the lamps be tested in households to compare the outcome with the lab results. Further work should also be done to improve atomization of the fuel in lamps. Other emissions like NOx, and SOx should also be measured.

Key words: Straight vegetable oil blends, pressure lamp, light, pollutant, emissions

1.0 Introduction

The potential of traditional fossil fuels to be exhausted is increasing of late (Sharma, *et al*, 2008). Moreover, fossil fuel combustion is believed to contribute to global degradation. This has led to a lot of effort being directed towards curbing this anthropogenic contribution to global degradation which claims six million children every year globally (Smith *et al*, 2001). To reduce dependency on fossil fuels use, great research and campaign has been on the use of alternative renewable energy sources to reduce or replace the use of non-renewable fossil fuels. Among the potential sources, straight vegetable oils (SVO) represent a promising alternative since they are renewable and environmentally friendly. The carbon dioxide which is produced by the combustion of the biofuel is the same amount that had been consumed by the plant during photosynthesis. Therefore, there is no net increase of carbon dioxide by the biofuel into the atmosphere (McCormick, 2006).

Since one-third of the world population or about 1.6 billion people live without electricity (World Bank 2000), these people, in approximately 300 million households use kerosene for lighting, spending around 10-30 billion dollars /year, or an average of about 1dollar/week (Apple *et al*, 2010). These people utilize a variety of lamps operating on kerosene as the main fuel (Mills; 2002). These lamps include the simple wick lamp, small and big lanterns and pressure lamps.

Research has been done to measure emissions from these kerosene lamps. Tami *et al*, 2012 conducted laboratory and field research measurements on simple kerosene tin lamps. It was found out that 7-9% of kerosene consumed by widely used simple wick lamps was converted to carbonaceous particulate matter that is nearly pure black carbon (BC) Figure 1.

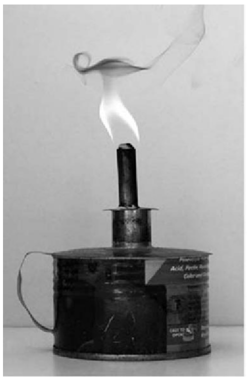

Figure 1: Simple wick tin lamp emitting black carbon

PM for a simple wick lamp operated at baseline settings in laboratory tests was 81 ± 15 g/kg kerosene. The research performed did not measure the relationship between the lamp emissions and the light output from the lamp. Schare and Smith, 1995, measured total suspended particulate matter (TSP) concentrations in a simulated village house with a volume of 16.9 m^3. The indoor steady state TSP concentrations were measured as 3400 ± 900 $\mu g/m^3$ for a single simple wick lamp. No relationship between light output and emissions was given.

Apple *et al*., 2010) did a comprehensive study on the emissions that market and kiosk vendors are exposed to as they use simple wick lamps. Average fuel consumption for the simple wick was 14.9 g/h with a maximum and minimum consumption being 25.0 g/h and 4.5 g/h respectively. The vendors using simple wick lamp for illumination were exposed to an average $PM_{2.5}$ of approximately 500 $\mu g/m^3$. This exposure is higher than the WHO 24-hour limit of 10 $\mu g/m^3$. The researcher did not give any relationship between light outputs from the lamps to the emissions.

Figure 2: Kerosene hurricane lamp

Fan and Zhang, (2001), examined the performance of a kerosene hurricane lamp Figure 2 in a 0.15 m^3 chamber (Zhang and Smith, 2007). The peak number concentrations for a hurricane lamp were 1.4 10 μ/m^3 for particles with 0.304 µm diameters. They also estimated peak PM_{10} concentrations of 640 $\mu g/m^3$ for a 40 m^3 room with an air exchange rate of 2/h. They did not examine particulate matter concentrations resulting from the use of pressure lamps (Figure 3).

The objectives of this paper were to investigate the relationship between unmodified pressure lamp performance and emissions and also the relationship between a retrofitted pressure lamp and performance.

Figure 3: Unmodified pressure lamp

2.0 Materials and Methods

2.1 Design of Retrofitted Pressure Lamp

The main objective of any lamp is to burn a fuel and give out as much light as possible. This is not always possible as some lamps compromise air pollution to light emitted. Mostly, there is a positive correlation between the amount of fuel used to light produced. Also there exists a positive correlation between the amount of fuel used and the amount of harmful emissions emitted.

Designing a 100% efficient lamp is not possible. Hence, an equilibrium has to be sought which balances the amount of light produced to the permissible harmful emissions emitted. The challenges associated with simple tin lamps, big and small lantern lamps and pressure lamps were considered in the design of a retrofitted pressure lamp to handle vegetable oils. The design parameters optimized were: safety, fuel preheating, air and flue gas circulation, fuel evaporation and plunging system. The lamp had four major modifications: the lamp chimney, fuel evaporator, spirit holding cups, and the pumping mechanism. To ensure proper alignment of different components during the assembly, all openings, tabs, folds and shapes were well cut with a tolerance of 0.5 millimetres. The construction of each individual component is presented:

(i) Lamp Hood

Shown in Figure 4a and 1.4b are the unmodified and retrofitted pressure lamp hood. The vents of the retrofitted lamp hood were increased as compared to that of unmodified pressure lamp to increase air flow for optimum combustion and exhaust of flue gas delivery from the lamp. The hood was circular in cross-section. The base circumference of the modified hood was made to the same dimension as the unmodified lamp so that the flexibility of the hoods is improved.

A stainless steel sheet, 0.5 mm thick, was used to make the hood. The hood has two air inlet openings, cut at the lower part of the hood. The openings had an arc length of 50mm and a height of 30mm.

Figure 4 (a) and (b): The lamp hoods

(ii) Lamp Fuel Vaporizer

The lamp vaporizer shown in Figure 5 has the following parts: the nipple, nozzle, ring, column and socket nut. The unmodified pressure lamp has one ring made from brass. The ring is made from a 5mm brass pipe having an internal diameter of 4.8mm. The modification made on the vaporizer was introduction of two rings instead of one and the material was changed from brass to copper. Copper was chosen because of its desirable quality of being a better conductor of heat and it is relatively durable as compared to other material.

Figure 5: Unmodified lamp vaporizer

Figure 6: Modified Lamp Vapourizer

(iii) Pre-heaters

Pre-heaters are used to heat the vapourizer, nozzle, mantle and burner before fuel is allowed to flow into the burner. Preheating is done by heating methylated spirit which is contained in a spirit holding cup situated at the base of the vapourizer. The spirit holding cup was offset so that it burnt the vaporizing tube and ring more than any other part in the assembly. The capacity of the preheater was increased by having two spirit burning cups of same dimensions. The volume of methylated spirit held in the cup was 120 mm^3.

Figure 7: Unmodified spirit cup

Figure 8: Modified spirit cup

2.2 Performance of the Retrofitted Lamp

The retrofitted pressure lamp was tested in a simulated room measuring 4m by 4.2m by 3.5m on June 2013 in Nairobi. The atmospheric conditions were of pressure 1.01 bar and temperature of an average 24^{o} C. The weather was calm with minimal wind. The relative humidity was 56% on average throughout the entire measurement period. The door and windows were closed with black thick cotton curtains to prevent light from coming to the room. The windows and doors were also closed to limit atmospheric air affecting the lamp performance measurements. Two Lux meters were placed 1metre away from the lamp perpendicular to the lamp mantle. The lamp was placed 2m above the ground to represent the actual positioning of lamps in ordinary working night. The UCB particle monitor, CO_2 and CO data loggers for measuring particulate matter, CO_2 and CO devices were also positioned at a distance of 1 metre horizontal and 1 metre high from the lamp to simultaneously make real time readings. The data was downloaded at the end of the day through a provided software. The lamp was placed on a weighing balance throughout the entire testing period. The mass of the lamp was recorded at intervals of two minutes and entered on a data sheet.

The exhaust flue gas temperature was recorded by placing a thermocouple thermometer at the exhaust chimney. The metal probe of the thermocouple was placed at the same position for all the lamps. The temperature readings were made at the same intervals as the weight of the lamp. After the twenty minute experimental time, the sum of the temperature is done and an average of temperature found. This is the value which is used in calculations.

2.3 Performance Test Procedure

The following procedure was adopted while measuring the performance of the lamp.

2.3.1 Pressure Lamp Operation

Before lighting the lamp, basic visual checks were done on the lamp to ensure that it will work and be safe. The nipple, nozzle and all connections were checked to ensure that they were tight enough and that no leakage was noticed. Any loose connection noticed was tightened using a special spanner provided by the unmodified lamp manufacturers. The filling screw gauge was unscrewed and a measured volume of fuel poured into the fuel reservoir using a funnel. A funnel was used because it had a screen which could filter out some large solid particles. For all tests done, 500ml of fuel was used. The screw gauge was then tightened back ensuring that it was tight enough not to allow any air to escape from the lamp. The lamp was pressurized using a hand pump provided on the lamp. Methylated spirit was poured into the two spirit holding cups. The spirit burning cups were filled to the brim. Using a lit match, the spirit was ignited.

The spirit was allowed to burn till it was over. The hand wheel was then turned clockwise slowly. This opened the flow of fuel from the fuel reservoir. Since the fuel vaporizer assembly, nozzle and mantle had been heated, vapourized fuel is injected into the nozzle which in turn burns to light the mantle. If the lamp was not preheat properly, liquid fuel will flow through the needle and the lamp will not light. The experiments were conducted for twenty minutes per sample. Time taken was taken as the difference between final and initial clock readings. Each sample was run in three lamps and repeated twice. Average values of light, fuel consumption and pollutant gas emissions were then averaged from the collected data.

2.3.2 Specific Fuel Consumption Measurement

Specific fuel consumption of the lamp is the amount of fuel used to produce one lumen of light. This was obtained as an average of the amount of lumen divided by the average fuel used during the same period as shown in Equation 1.

$$sfc = \frac{Light\ output}{Fuel\ consumed} \quad \ldots\ldots \quad (1)$$

2.4 Pressure Lamp Light Measurement

The amount of light produced by the lamp was measured using one hobo device shown in Figure 9 together with two luxmeters shown in Figure 10 which measured light, relative humidity and temperature of the room. The hobo had an internal memory which stored data till the end of the tests when the data was downloaded via a software installed in a computer. The luxmeter is a digital device which displayed the amount of light emitted by the lamp. The data displayed was then manually recorded down on a data collection sheet.

The Hobo Figure 10 is a device which was used to measure the light output from the lamps. It also measured the relative humidity of the environment together with temperature.

2.5 Pressure Lamp Emission Test

The emissions measured were particulate matter (PM), carbon mono oxide (CO) and carbon dioxide (CO_2). These are the most important emissions considered to adversely affect human beings. The available devices used to measure the emissions were the Telaire 7001 monitor, Easy Log USB data logger and a University of California- Berkley (UCB) Particle Monitor. These devices measured CO_2, CO and PM measurement respectively. A computer-aided data acquisition software was employed to download the data at the end of the exercise. The emission monitoring devices are discussed hereafter in details.

Figure 9: The Hobo

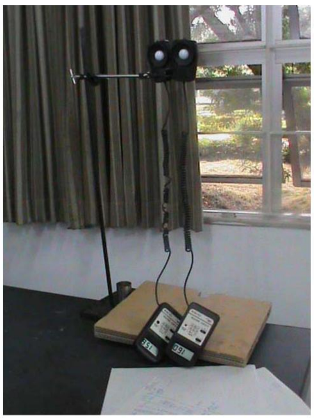

Figure 10: The Luxmeter fastened onto a stand

2.5.1 Easy Log Carbon Monoxide Data Logger

The Easy Log USB CO data logger Figure 11 was placed 1metre above the lamp 1m away. The device recorded the real time carbon monoxide concentration in the room at one minute intervals. All the readings made within the twenty minutes test time are averaged to give an average CO concentration for that period.
The CO data logger used had a range of 0 to 1000 ppm and an accuracy of ±6% of reading. The data is stored in a in-built non-volatile memory which is later downloaded into a computer.

Figure 11: Easylog CO data logger

2.5.2 University of California at Berkeley (UCB) Particle Monitor

The University of California at Berkeley (UCB) particle monitor Figure 12 is a programmable continuous particle monitor which also logs in temperature and relative humidity. When airborne particles enter the chamber, the ionized air molecules attach to them and current is distributed proportionately to the product of the particle number and particle diameter of the airborne particles in the active chamber.

Figure 12: University of California at Berkeley (UCB) particle monitor

The UCB was used to measure PM less than 2.5 µm in aerodynamic diameter ($PM_{2.5}$) which have been said by many health institutions including WHO, to pose great health risks. The data recorded in the UCB particle monitor was downloaded at the end of the testing period by connecting the device into a personal computer installed with a software to download the readings.

3.0 Results

3.1 Carbon Monoxide Emission

The unmodified pressure lamp was only able to light with up to 30% SVO/Kerosene fuel blend. Comparison between the CO emitted by the two lamps between 0% blend (0% straight vegetable oil and100% kerosene) to 30% blend (30% straight vegetable oil/70% kerosene) showed the retrofitted lamp had a mean CO emission of 3.9 ppm with a standard deviation from the mean of 2.2 while the unmodified lamp had a mean CO emission of 5.1 with a standard deviation of 2.1.

On average, for the 0% to 30% blends, the retrofitted pressure lamp reduced CO emission by between 3.9% and 6.8% with a mean CO reduction of 4.9% as compared to the unmodified lamp. The modified pressure lamp lit with up to 90% fuel blend. Higher lamp pressure led to reduced CO emission. On average, a 0.5 bar lamp pressure increase between the range of 1.5 bar and 2.5 bar lamp pressure, there was a between 10- 30% CO reduction on the 0- 90% fuel blends.

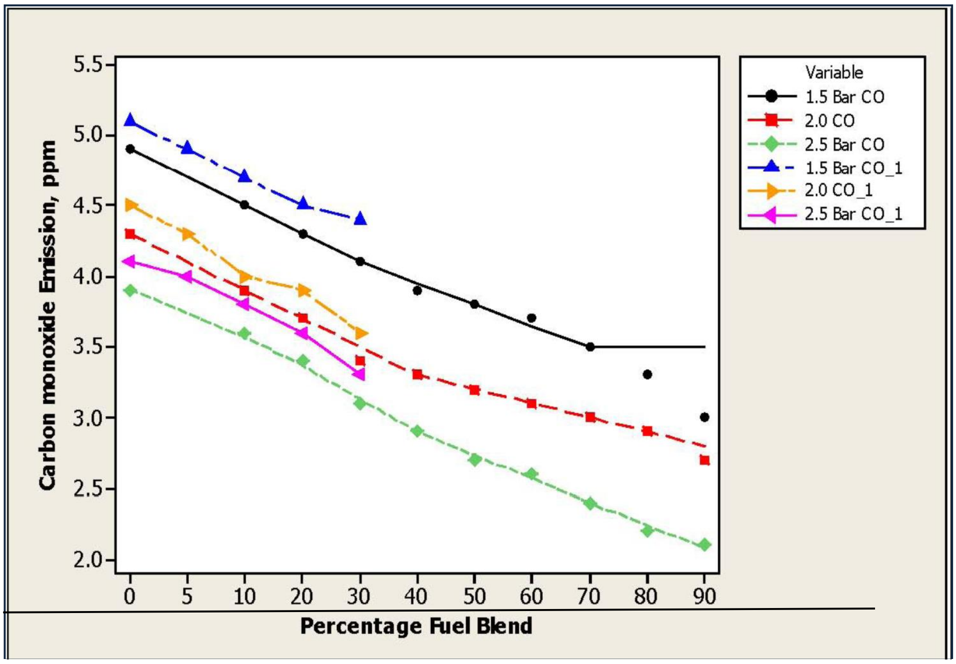

Figure 13: Carbon monoxide emissions vs Fuel blend at various pressures

3.2 Particulate Matter Emission

Figure 13 shows the particulate matter emission from the retrofitted and the unmodified lamps at 1.5 bar, 2.0 bar and 2.5 bar at 0% to 90% straight vegetable oil/ kerosene fuel blend. The values designated with 1.5 bar pm1, 2.0 bar pm1, and 2.5 bar pm1 represent particulate emissions from the unmodified lamp at the given fuel blends. Particulate emissions from unmodified lamp are higher than the PM from the retrofitted lamp at the same pressures and fuel blends. There was an average reduction in particulate matter emission of 18% over that of unmodified lamp.

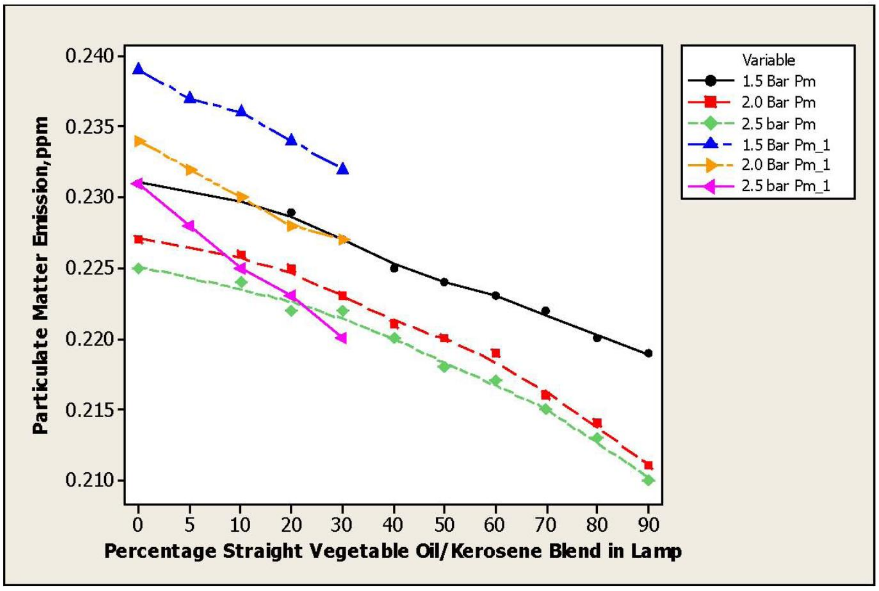

Figure 14: Particulate matter emission from retrofitted and unmodified lamps

3.3 Carbon dioxide Emissions

Figure 15 shows the carbon dioxide emission from the retrofitted and the unmodified lamps. The carbon dioxide emission from lamps at 2.5 bar lamp pressure were higher than the emission from lamps at 1.5 bar. The CO_2 emission from the unmodified lamp was comparatively lower than those of the retrofitted lamp. The CO_2 emissions at higher fuel blends increases though at a low rate of an average rate of 5 ppm per 10% increase in fuel blend. This is experienced by at all lamp pressures of 1.5 bar, 2.0 bar and at 2.5 bar.

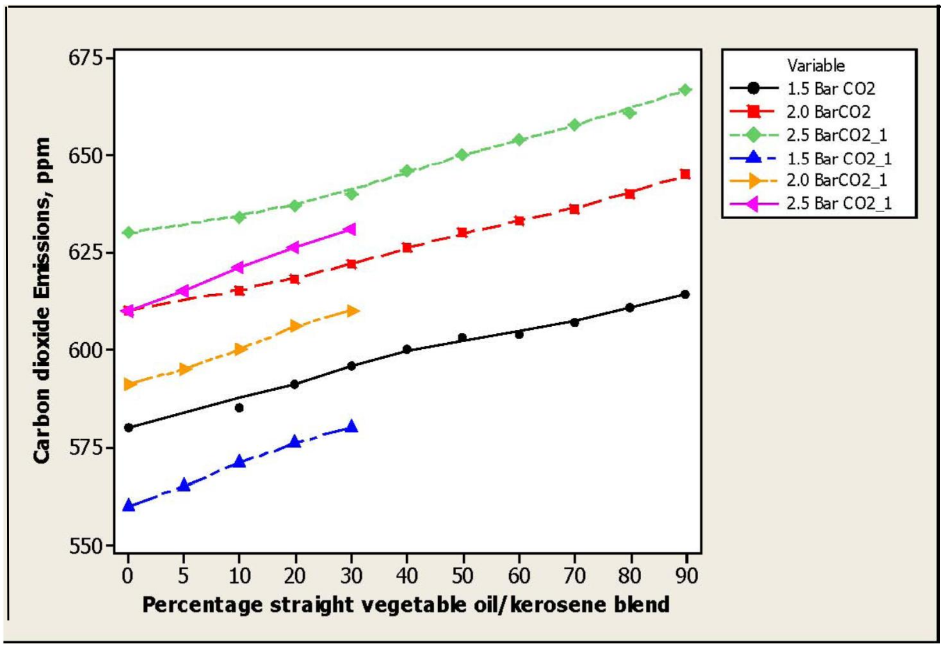

Figure 15: Carbon dioxide emission from retrofitted and unmodified lamps

3.4 Fuel Consumption

Figure 16 shows the relationship between the fuel consumption by the retrofitted pressure lamp and the unmodified pressure lamp at different fuel blends and lamp pressure. The unmodified pressure lamp was only able to light using fuel blends of up to 30% after which it did not light. The unmodified lamp had a mean fuel consumption of 50.7 grams, standard deviation from the mean of 0.447 and a range of 3 grams at 1.5 bar. At 2.0 bar, the unmodified lamp had a mean fuel consumption of 52.4 grams for a twenty minutes duration with a standard deviation from the mean of 0.894 and a 23 range of 2 grams. At 2.5 bar, the unmodified lamp had a mean fuel consumption of 53.3 grams for a twenty minutes duration with a standard deviation from the mean of 1.03 and a range of 4grams.

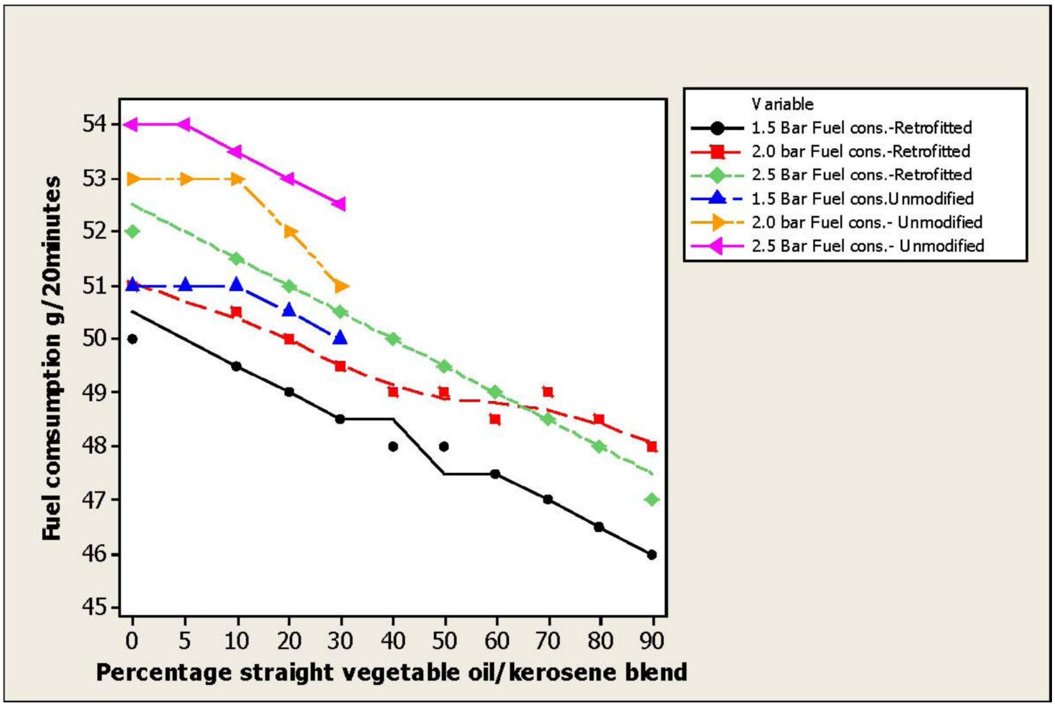

Figure 16: Graph of fuel consumption for retrofitted and unmodified lamps

3.5 Light Output

Figure 17, shows light output from the retrofitted lamp at 1.5 bar, 2.0 bar and 2.5 bar at varying fuel blend for the unmodified and the retrofitted lamp. The figure shows that light output for both the modified and unmodified lamps are higher at higher lamp pressures. The light output decreases at higher blends due to difficulties associated with high viscosity of the blends. Higher straight vegetable oil/kerosene blends requires longer and higher heat energy to reduce their viscosity.

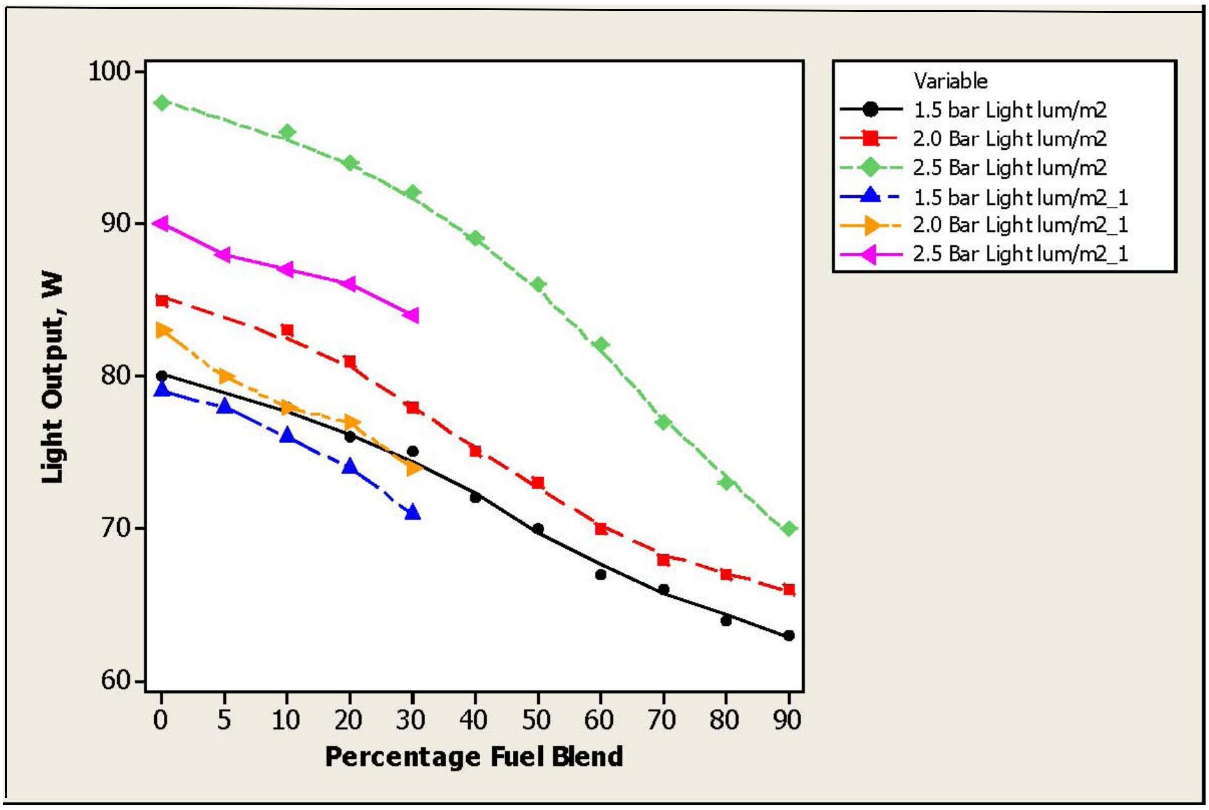

Figure 17: Light output for retrofitted and unmodified lamps

4.0 Discussions

The reduction of CO emission was attributed to the improved air circulation. More air was made available for complete combustion as well as the chimney was wide open to reduce flue gas exhaust restriction. This can be attributed to better combustion associated with better air circulation. Reduction in PM emissions was attributed to better combustion associated with better air circulation. Particulate emission for the retrofitted lamp showed a reduction in PM emissions as the lamp pressures were increased. This was because at high lamp pressures, there was a better fuel combustion than at lower fuel pressures. This ensured that all the volatile matter were burned and hence low particulate emissions.

High CO_2 emissions at higher pressures was due to favourable combustion conditions of high pressure, temperature and better atomization of the fuel blends. The increased emissions was due to conversion of CO to CO_2 in the modified lamp. For the complete combustion of hydrocarbons, the desired products of combustion are CO_2 and H_2O, therefore and increased CO_2 emissions in the modified lamp is an expected and desirable outcome. The emissions emitted are within the OSHA allowable limits.

There was an average fuel consumption reduction of 6% between 0% and 90%. This reduced fuel consumption was due to reduced fuel flow due to increased viscosity of the fuel at high fuel blends. In overall, the retrofitted lamp had an average 5.5% fuel consumption reduction as compared to the unmodified lamp. This reduction can be attributed to better fuel combustion and reduced fuel wastage due to correct fuel vaporization.

The retrofitted lamp had a higher light output due to improved fuel combustion. Increased lamp pressure also increased light output at all fuel blend. Higher lamp pressures increases atomization of the fuel blends and hence better combustion. Higher lamp pressures also increases fuel mass flow which, when combined with sufficient air circulation increases combustion and light output in turn.

5.0 Conclusions and Recommendations

5.1 Conclusions

The following conclusions were made:

(i) The retrofitted pressure lamp utilizing straight vegetable oil which was designed and fabricated is able to mitigate in-door air pollution and greenhouse gases.
(ii) The retrofitted lamp emitted comparatively more light than the unmodified lamp at all pressures and fuel blends. Light emitted increased with increase in lamp pressure for both lamps.
(iii) The retrofitted pressure lamp utilizing straight vegetable oil produced comparatively less particulate matter emissions than the unmodified lamp at the same condition of pressure and fuel blend.
(iv) The retrofitted pressure lamp utilizing straight vegetable oil produced less carbon monoxide as compared to the unmodified pressure lamp at the same pressure and fuel blend.
(v) The retrofitted lamp comparatively emitted more CO_2 than the unmodified pressure lamp at the same conditions of lamp pressure and fuel blends.
(vi) The fuel consumed increased with increase in lamp pressure for both the retrofitted pressure lamp utilizing straight vegetable oil and the unmodified pressure lamp.

5.2 Recommendations

The following are suggestions for further study following this study on retrofitting of a pressure lamp to utilize straight vegetable oil and optimize performance.

(i) Further research should be carried out to identify readily available feed stocks to be used to produce the straight vegetable oils to reduce dependence on first generation feed stocks.
(ii) Further work is recommended to come up with ways of improving fuel atomization at high fuel blends.
(iii) The retrofitted lamp was able to light using fuel blend of a maximum of 90%. Further work is required to ensure that the lamp works with 100% straight vegetable oil.
(iv) The retrofitted lamp was tested in a simulated room. There is need to have a computerized simulation of the lamps so that the variables can be easily controlled and the results obtained compared with that obtained from practical experiments.

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References

Apple, J., Vicente, R., Yarberry, A., Lohse, N., Mills, E., Jacobson, A. and Poppendieck, D. (2010). ‘Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps. *Indoor Air,* **5**, pp 399–411.

Mills, E. (2002). ‘Global lighting energy savings potential’, *Light and Engineering* **10**(4), pp 5–10.

MCormick, R. L. (2006). National Renewable Energy Laboratory (NREL) Biodiesel handling and use guidelines, second edition, Technical report, US. Department of Energy.

Smith, S. J., Pitcher, H. and Wigley, T. M. (2001). ‘Global and regional anthropogenic sulfur dioxide emissions’, *Global Planet Change,* **29**, pp 99–119.

Schare, S. and Smith, K. R. (1995). ‘Particulate emission rates of simple kerosene lamps’, *Energy Sustainable Development*. **2**, 32–35.

Sharma, B. Singh and S. N. Upadhyay (2008). ‘Advancements in development and characterization of biodiesel: a review’. *Fuel, 87*, pp 2355–2375.

World Bank (2000). World energy assessment, Technical report, World Bank.

Zhang, J. and Smith, K. R. (2007). ‘Household air pollution from coal and biomass fuels in china: measurements, health impacts, and interventions.’ *Environmental Health Perspective,* **115**, pp 848–855.

Nicholas, L., Yanju, C., Cheryl, W., Chandra, V., Pankaj, S., Michael, J., Kirk, R., Benjamin, B., Joseph, A., Justin, E. and Tami, B. (2012). “Household light makes global heat: High black carbon emissions from kerosene wick lamps.” *Environmental Science and Technology*, vol. **26**, pp 11703–11708.