INVESTIGATION ON IMPROVING THE THERMAL EFFICIENCY OF A MINI BOILER FIRED WITH STRAIGHT VEGETABLE OILS

by

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In the present work, straight sunflower oil and rice bran oil blended with diesel have been used as fuel diesel in a mini boiler. The thermal efficiency of the boiler and emission levels in the exhaust gases have been investigated by burning the oil blends of varying proportions ranging from 0-50%. An additional air supply system and compressed air atomization of fuel with a new burner have been used to improve the thermal efficiency of the mini boiler. Results revealed that the additional air supply improved the thermal efficiency up-to 7% and reduced the CO and HC emission up-to 40%. The use of compressed air atomization further increased the thermal efficiency up-to 4% and reduced the CO and HC emission up-to 70%.

Key words: *straight vegetable oil, additional air, compressed air, thermal efficiency, emission*

Introduction

The characteristics of vegetable oil have been investigated by several studies for the last few decades. The results have revealed that the characteristics of biodiesel are close to that of the petrodiesel and proved to be an alternate fuel for compression ignition (CI) engine. The research on the straight vegetable oil is being carried out in furnaces, boilers and gas turbine units. Even though, the combustion of straight vegetable oil is successful, the difficulty in complete combustion of fuel and more unburned carbon emission requires more research on the use of straight vegetable oil. Modification in the burner, heating of oil to reduce viscosity and better atomization of fuel to form fine spray would be some of the methods by which the combustion and emission characteristics may be improved. In the present work, the blends of straight sunflower oil and rice bran oil with diesel have been burnt using a commercial burner and a new burner with compressed air atomization.

The biodiesel prepared from different vegetable oils was studied by many researchers including Demirbas *et al.* [1], Bhasa *et al.* [2], Hosseini *et al.* [3] and Phan *et al.* [4]. Sukkasi *et al.* [5] reported that the emission from biodiesel is lower than that of diesel. Oprea *et al.* [6] investigated the typical properties of few crude vegetable oils. They concluded that crude sunflower oil can be used as the substitute with fossil diesel fuel and suggested oil preheating and advanced technology in fuel injection/atomization overcome the problem of high viscosity. Daho *et al.* [7] tested cotton seed oil in a commercial boiler and obtained thermal efficiency of

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22-27%. Daho *et al.* [8] studied the cottonseed oil in a modified burner to achieve suitable spray conditions with suitable particle size. Arumugam *et al.* [9] investigated the straight vegetable oil and its blends of diesel in a hot water generator and concluded that the efficiency was enhanced and emissions were lowered by an additional air supply system. Holt and Hooker [10] tested the prime bleachable summer yellow cotton seed oil (PBSY) at 28 °C and 60 °C. The overall emissions of all trails were lower including CO emissions. Alonso *et al.* [11] obtained the results from the combustion of certain samples of vegetable oils in a commercial burner and revealed the fact that the combustion of vegetable oil is totally feasible and had similar results of the diesel fuel combustion.

Ghorbani and Bazooyar [12] analysed the combustion of petrodiesel and soy bean methyl ester blends, in a semi industrial boiler and found that the blends were emitted lower emissions than that of petrodiesel. Biodiesel with 5% vegetable oil was found to be the best fuel for firing the boiler. Arumugan *et al.* [13] found the properties of rice bran oil methyl ester. The results shown that the rice bran oil and its blends with additives can be replaced in CI engine. Bazooyar *et al.* [14] made trails in a boiler with the biodiesel of various vegetable oils and found that the efficiency ranges from 14 -24%. Kermes and Belohradsky [15] carried out the experiments with preheated rapeseed oil methyl-ester at about 70 °C in a water-cooled horizontal combustion chamber. The emission of NO_x is more compared to extra light heating oil combustion. Kourmatzis *et al.* [16] investigated the atomization behavior of three biodiesels using phase Doppler anemometry and high speed microscopic imaging and identified that the structure of the spray was similar to the conventional air blast atomizer geometry. Agarwal *et al.* [17] examined a spray of Crude Jatropha oil, Jatropha methyl ester and diesel in an air-assist pressure-swirl atomizer. The results showed that atomizer performance depends on the quality of liquid cone, which affects the physical and flow properties.

Barroso *et al.* [18] analysed and compared the combustion of bioethanol in boilers with conventional liquid fuels. The feasibility of burning bioethanol in gasoil boilers has been analysed, and the results confirm that fuel switching is technically possible and offers some advantages in terms of pollutants reduction. Hosseini *et al.* [19] investigated the emission characteristics of a liquid burner system; the biodiesel can lower pollutant such as CO, CO_2, and particulate matter emissions while NO_x emission would increase in comparison with gas oil. Calugaru *et al.* [20] used low NO_x burner in industrial boiler and reduced NO_x emission up-to 10%. Lee *et al.* [21] conducted a test on a cylindrical multi-hole premixed burner for its potential use for a condensing gas boiler, which produce less NO_x and CO emissions. Jiru *et al.* [22] demonstrated that SHO20 (20% degummed soybean oil and 80% fuel oil) is suitable for residential furnaces without modification. The combustion of SHO20 resulted in a higher flue gas temperature which increased the NO_x emission than that of fuel oil.

Jose *et al.* [23] revealed that the combustion of biodiesel blends reduces the CO_2 and SO_2 by increasing the proportion of biodiesel in the fuel. Gonzalez-Gonzales *et al.* [24] focused on the use of sunflower biodiesel in a liquid fuel heating boiler of 26.7 kW. The CO emission was slightly higher and CO_2 emission decreased slightly when biodiesel content was increased in the mixture. When biodiesel is burnt, air-flow rate must be reduced, since oxygen content in biodiesel is higher than that in diesel. Lee *et al.* [25], made a combustion analysis in a residential oil-fired boiler with 20% soybean methyl ester mixed with diesel oil. The combustion of B20 blend exhibited similar gaseous emissions like NO_x emissions to those of diesel.

Tashtoush *et al.* [26] examined the combustion and emission analysis of palm oil biodiesel at two energy inputs in a water-cooled furnace. At the lower energy rate, combustion efficiency and exhaust temperature were higher and emitted less pollutant than diesel fuel at both energy levels. Hoon *et al.* [27] evaluated the combustion of palm oil methyl ester (POME) with diesel in a liquid burner-combustion chamber and observed that CO level was minimum, when equivalence ratio (ER) was within the 0.75-0.85 range. The CO and NO level improved across the tested ER range with increasing POME proportion in the fuel blends and pumping pressure.

Pereira *et al.* [28] made a combustion trails in a furnace by using biodiesel and diesel as a fuel through a commercial air-assisted atomizer. The CO emissions decreased rapidly and NO_x emissions increased with an increase in the excess air level for both liquid fuels. But NO_x emissions from biodiesel were lower than those from diesel combustion. Pandey *et al.* [29] analyzed the emission parameters of biodiesel of Jatropha or 30% blended Jatropha oil. The biodiesel has 20% less CO emission, 30% less HC emission, 50% less soot emission, 40% less particulate matter emission and about 10-15% higher NO_x emissions.

From the available literatures, it is clear that very little experimental results have been reported for the applications of burning straight vegetable oils and its blends at higher volume percentage for power generation and space heating. In the present work, experimental investigations have been made with a mini boiler to fire straight vegetable oils such as sunflower oil and rice bran oil blended with diesel with mixture proportions ranging from 0-50%.

Experimental set-up

The experimental set-ups used in the present study are shown in figs. 1 and 2. The mini boiler with the capacity of 35 L has been fabricated, with four fire tube of 58 mm diameter. Furnace is having a diameter of 30 cm and length of 37.5 cm. The furnace is fully insulated with glass wool and covered by asbestos rope and aluminum foil sheet. The set-up shown in fig. 1 consists of a commercial oil burner with a blower for primary air supply. Commercial burner is a local burner used to fire fuel oil in a furnace. It is the swirl type oil burner consuming a capacity of spraying 150 g per minute. In the set-up shown in fig. 2, a non-commercial burner is used to produce a fine spray through a number of holes of 0.8 mm diameter with the supply of compressed air at a pressure of 3-4 bar.

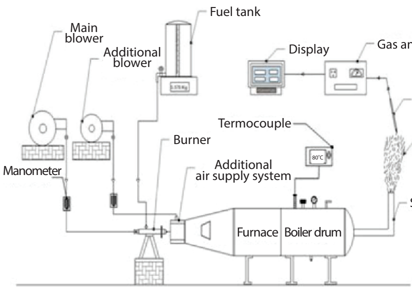

Figure 1. Experimental set-up of mini boiler with commercial burner

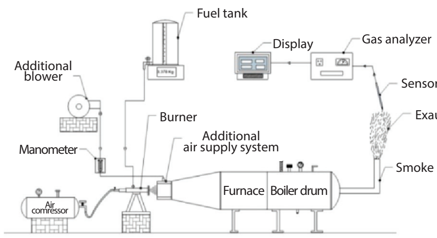

Figure 2. Experimental set-up of mini boiler with non-commercial burner

The fuel tank has been kept overhead on a digital weigh balance throughout the experiments. A digital weighing balance is used to measure the mass-flow rate of fuel consumed and an orifice meter with manometer is used for measuring the air supplied by the blower to the burner. The measurements have been taken carefully for each reading. To vary the mass of fuel consumption for different sets of readings, a ball valve is used to control the flow rate. The useful energy of the installation is the amount heat transferred to the water in the boiler shell, which is calculated from the rise in temperature of known quantity of water stored in the boiler shell. The temperatures of water and gases leaving the boiler have been measured using *K*-type thermocouples. Initial ignition is made manually with a small cotton piece soaked with diesel.

A separate air blower with an orifice meter has also been used for supplying additional air supply. Primary blower capacity is 0.0472 m^3/s. Additional blower capacity is 0.0708 m^3/s. Figure 2, presenting the experimental set-up 2, consists of a new burner with a compressor for primary air supply to atomize the fuel in mini boiler and an additional air supply system. The main air is supplied by a two-stage reciprocating air compressor having a capacity of 0.00417 m^3/s.

Measurements and results

Experiments have been conducted to study the combustion performance and emission levels in the exhaust gases. Table 1 presents the details of fuel blends used in the present study. Each fuel blend is named with the name of vegetable oil and its percentage in the blend. For example, 25% sunflower oil in the blend is named as SFVO 25 and 50% rice bran oil in the blend is named as RBVO 50.

Measurements have been made for, the rise in temperature of water, mass of fuel consumed, mass of air consumed and temperature of gases for blends of SFVO and RBVO. The levels of CO, CO_2, HC, and NO_x have also been measured using the CRYPTON gas analyzer. The *K*-type thermocouple (chrome/nickel) has been used to measure the water and gas temperature ranging between 0-1200 °C with resolution of 0.1 °C and accuracy of 0.5%. The accuracy of measured value for gases is 5%. Resolution of HC and NO_x is 1 ppm and for CO and CO_2 is 1%, and O_2 has 0.1% resolution and 0.2 % accuracy in their measured value.

Table 1. Details of fuel blends used in the study

Fuel	Vegetable oil proportion (by volume)	Diesel proportion (by volume)	Name of fuel blend	HCV [kJkg^{-1}]
Diesel + sunflower oil	Sunflower oil 0%	Diesel 100%	Pure diesel	42414
	Sunflower oil 25%	Diesel 75%	SFVO 25	40702
	Sunflower oil 50%	Diesel 50%	SFVO 50	38975
Diesel + rice bran oil	Rice bran oil 0%	Diesel 100%	Pure diesel	42414
	Rice bran oil 25%	Diesel 75%	RBVO 25	40118
	Rice bran oil 50%	Diesel 50%	RBVO 50	37810

The properties such as density, calorific value, flash and fire point and viscosity for diesel, sunflower and rice bran oil used in the work have been found and presented in the tab. 2. Calorific value measured by bomb calorimeter, flash and fire point temperatures measured by open cup cleave land apparatus and viscosity by viscometer.

Table 2. Properties of fuels

Fuel	Density [kgm^{-3}]	HCV [kJkg^{-1}]	Flash/Fire point [°C]	Viscosity [cSt]
Diesel	0.832	42414	72/77	3.9
Sunflower oil	0.918	35518	186/193	35.7
Rice bran oil	0.913	33192	183/189	33.4

Series of trail have been made for various fuel blends of SFVO and RBVO. During the trail hot water from the drum has been drained through the drain pipe and allowed the drum to cool down the atmosphere temperature. Again the fresh water has been added in the drum for next trial. The temperature of 30 °C of water in the boiler shell is increased by 40 °C to evaluate the thermal efficiency and emission level in the gases leaving the mini boiler when fired with sunflower and rice bran oil blended with different proportions, using a commercial burner with (WA) and without (WOA) additional air system.

Table 3 presents the variation in the mass of fuel consumption for the same amount of heat input to the water due to the change in the type of fuel, percentage of straight vegetable oil and use of additional air supply.

Table 3. Mass of fuel consumption (diesel and vegetable oil blends)

Fuel	Mass of the fuel [kg]			Rise in temperature of water [°C]
	Commercial burner WOA	Commercial burner WA	Non Commercial burner WA	
Diesel	0.295	0.280	0.292	40
SFVO25	0.440	0.368	0.348	40
SFVO50	0.560	0.464	0.408	40
RBVO25	0.408	0.344	0.332	40
RBVO50	0.528	0.404	0.392	40

Table 4 presents the amount of heat input, heat output, and thermal efficiency of mini boiler fired by the commercial oil burner with and without additional air supply [9].

Table 4. Results for combustion of fuel blends in a commercial oil burner with and without additional air supply

Fuel	Heat input [kJ]		Heat output [kJ]	Efficiency [%]	
	Without additional air	With additional air		Without additional air	With additional air
Diesel	12512.13	11875.92	4689.44	37.48	39.48
SFVO25	17908.88	14978.34	4689.44	26.18	31.31
SFVO50	21826.00	18084.40	4689.44	21.49	25.93
RBVO25	16368.14	13800.59	4689.44	28.65	33.98
RBVO50	19963.68	15275.24	4689.44	23.49	30.70

The maximum thermal efficiency is obtained for diesel compared to all other fuel blends in both the cases of commercial burner with and without additional air. The thermal efficiency is found to be increased in all fuel blends when the additional air is supplied. Table 5 presents the emissions of CO, CO_2, HC and NO_x in the exhaust gases for the blends considered in the study.

Table 5. Emissions in exhaust gases during combustion of fuel blends in a commercial oil burnerwith and without additional air supply

Fuel	Emissions in commercial burner without additional air				Emissions in commercial burner with additional air			
	CO [ppm]	CO_2 [%]	NO_x [ppm]	HC [ppm]	CO [ppm]	CO_2 [%]	NO_x [ppm]	HC [ppm]
Diesel	1900	13.23	52	131	1100	9.02	48	98
SFVO25	1800	12.94	38	269	1300	8.65	39	180
SFVO50	2700	12.55	24	391	1800	8.21	22	226
RBVO25	2100	12.81	45	239	1200	8.81	42	158
RBVO50	2800	12.65	34	365	1700	8.54	31	204

It is clear that CO emission decreases from 0.19-0.11%, when diesel is burnt with additional air supply. Similarly HC emission also reduces from 131 ppm to 98 ppm. Similar trend is seen in all the blends of SFVO and RBVO. But NO_x emission slightly decreases from 52 ppm to 48 ppm for diesel. Similar trend is seen in other fuels also.

Table 6. Results for combustion of fuel blends using a non-commercial burner with additional air supply

Fuel	Heat input [kJ]	Heat output [kJ]	Efficiency [%]
Diesel	12384.89	5024.4	40.57
SFVO 25	14164.30	5024.4	35.47
SFVO 50	15901.80	5024.4	31.60
RBVO 25	13319.18	5024.4	37.72
RBVO 50	14821.52	5024.4	33.90

Table 7. Emissions of fuel blends in a non-commercial burner with additional air supply

Fuel	Emission levels			
	CO [ppm]	CO_2 [%]	NO_x [ppm]	HC [ppm]
Diesel	800	10.29	69	72
SFVO25	800	8.6	47	78
SFVO50	1000	6.35	26	90
RBVO25	700	10.03	59	74
RBVO50	900	9.26	38	86

The study has been further extended using a new burner with a compressor for primary air supply and a separate blower for additional air supply. The results for the heat input, heat output and thermal efficiency of mini boiler fired with different fuels using the new burner (non-commercial type) have been presented in tab. 6.

The maximum efficiency is obtained for diesel. Increasing the percentage of vegetable oil in the fuel blends reduces the thermal efficiency of the system. Table 7 elucidates the exhaust emissions of CO, CO_2, HC, and NO_x measured in the exhaust gases for all fuel blends fired with the new non-commercial oil burner.

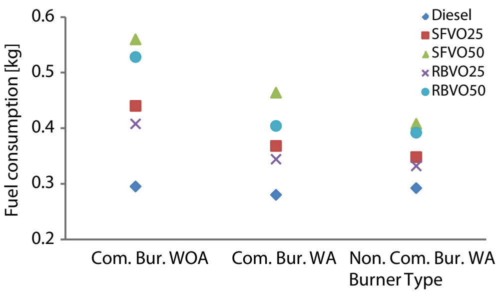

Figure 3. Fuel consumption for different type of burners

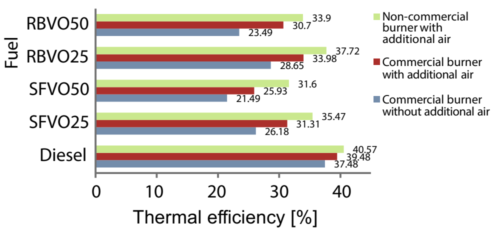

Figure 4. Thermal efficiency for commercial and non-commercial with and without additional air

Discussions

Figure 3 presents the comparison of consumption of various fuel blends fired by commercial and non-commercial burners with and without additional air.

The fuel consumption is low for diesel in all cases and it is found that it is increasing with the increase of percentage of vegetable oil in the fuel blends irrespective of the type of oil. It is also seen that the mass of fuel consumption of sunflower oil is more than that of rice bran oil. This may be due to the differences in the fuel properties such as calorific value, flash and fire point temperatures, viscosity and air fuel ratio and spray formation.

Performance analysis

Thermal efficiency of mini boiler fired with commercial burner has been presented in tab. 3. The comparison is also shown in fig. 4.

The thermal efficiency of diesel without additional air supply is 37.48%. The thermal efficiency decreases when the vegetable oil is mixed with diesel. This is due to the lower calorific value of vegetable oil, poor atomization and high viscosity, *etc.* Thermal efficiency of RBVO is better than that of SFVO when fired in the commercial burner without any additional air supply. About 2.47% for 25% blend and 2% for 50% blend, higher thermal efficiency is seen, even though the calorific value of SFVO is better than rice bran oil. This may be due to the better spray characteristics, flash and fire point temperatures of rice bran oil.

The thermal efficiencies for all fuels have increased when the additional air is supplied. About 2% rise for diesel, 4.43-5.13% rise for SFVO, 5.33-7.21% rises for RBVO have been found. This may be due to better mixing of air and fuel, making better combustion of fuel irrespective of fuel blend. The maximum rise in thermal efficiency due to additional air is found for 50% RBVO. Thermal efficiency of RBVO50 is 30.70%, which is about 77.76% of thermal efficiency of diesel. The comparison of thermal efficiencies of mini boiler when fired with commercial and non-commercial burners is presented in fig. 4.

The thermal efficiency of diesel is increased from 39.48-40.57% by using a non-commercial burner with compressed air atomization. The increase in thermal efficiency for rice bran oil is 3.2% for 50% blend and 3.74% for 25% blend, and similarly 5.67% for 50% blend, and 4.16% for 25% blend of SFVO have been found. The rise in thermal efficiency due to compressed air atomization is more effective in SFVO than RBVO. This may be due to the fact that SFVO is better atomized with new non-commercial burner.

Emission analysis

The emissions of CO, CO_2, HC, and NO_x for various fuel blends in a commercial and non-commercial burner have been presented in figs. 5-8.

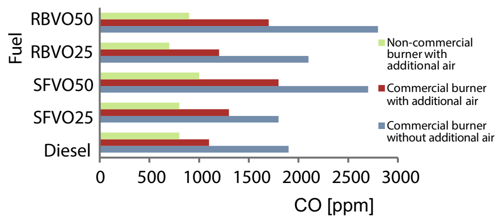

Figure 5. Comparison of CO emission in a commericial and non-commercial burner for various fuel blends

The CO emission is lower for diesel and 25% blend of vegetable oil in case of commercial burner. But 50% blends of vegetable oil produces about 30% more CO. The reduction in CO is found when the additional air is supplied for improving the combustion performance.CO emission reduces by 3.5% when the commercial burner is working with an additional air supply system. This could be attributed to the better mixing of fuel with air and supply of sufficient O_2 molecules for combustion.

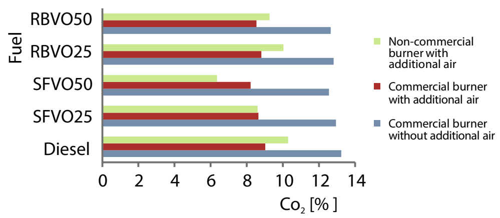

Figure 6. Comparison of CO_2 emission in a commericial and non-commercial burner for various fuel blends

Another 20-35% reduction in CO is made when the non-commercial burner is used for burning the fuels. This may be attributed to the better atomization of liquid fuel by the compressed air assisted non-commercial burner. In the non-commercial burner, the CO emission is almost the same for diesel and 25 % vegetable oil blends. 50% blend has marginally higher emission.

The emission of CO_2 is found more in diesel and it ensures that the combustion of diesel is better than that of vegetable oil and its blends. Even though, the additional air supply improves the combustion efficiency, the percentage of CO_2 decreases. This may be due to the dilution CO_2 in the additional amount of air supply. Further, the additional air supply and compressed air atomization in the non-commercial burner improves the combustion efficiency.

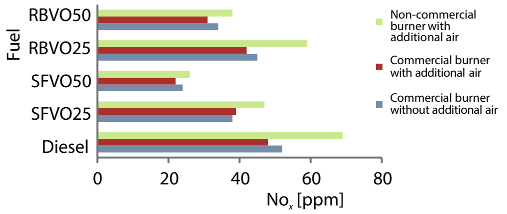

Figure 7. Comparison of NO$_x$ emission in a commericial and non-commercial burner for various fuel blends

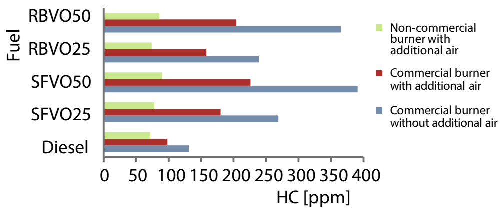

Figure 8. Comparison of HC emission in a commericial and non-commercial burner for various fuel blends

The HC emission is more for higher percentage blended vegetable oil. Particularly, the use of non-commercial burner produces large amount of emission for all types of fuel including diesel. The use of additional air and compressed air atomization reduces the HC emission by about 30% and 65%.

The NO$_x$ emission is more for diesel than that of other fuel blends of vegetable oil used and the emission with additional air supply is the same or slightly lower in commercial burner. This slight reduction may be due to the reduction in temperature of the combustion products by the excess air supplied by the additional air supply system. But, the NO$_x$ emission increases in non-commercial burner compared to commercial burner due to better atomization and complete combustion for all fuel blends.

Conclusions

The effects of additional air and compressed air for combustion of straight vegetable oil blends with diesel on emission levels and thermal efficiency of the mini boiler have been investigated. The conclusions from the present study are summarized as:

- Thermal efficiency of mini boiler is high for diesel irrespective of the burner used and air supply system. It is found to be reduced when straight vegetable oil is mixed with diesel to form the blends of vegetable oil.
- However, thermal efficiency has increased by 2-7% for the case of the commercial oil burner, when the additional air is supplied for the combustion of different blends of straight vegetable oil. About 2% increase is found in diesel and a maximum of 7% is seen in RBVO50.
- The efficiency of the combustion system was quite low, in the range of 21.49-37.48% and 25.93-39.48 % when the mini boiler fabricated with four fire tubes is fired with and without additional air supply. This range is comparable to report of literatures that, Daho *et al.* [7] show only 22-27% for cotton seed oil and 14-24% for biodiesel Bazooyar *et al.* [14]. If it is commercialised with the design modification optimize the number of tubes and passes, the thermal efficiency will further increase.
- The use of newly developed burner with compressed air atomization has improved the efficiency to 31.6-40.57%.
- The CO and HC emissions have also reduced by 28-43 % and 25-44% when additional air is used for better mixing. The CO emission has been recorded in the range of 1900 ppm to 2800 ppm (0.19-0.28 %) for the mini boiler fabricated with only four fire tubes and fired with locally available commercial burner for burning viscous vegetable, which is high as per the norms. The design modification in the new burner with compressed air atomization set up reduces the emission a lower level. The CO emission from the same boiler with the newly developed burner has lowered to 0.07-0.1 % (in the range of 700-1000 ppm).

- In general the combustion characteristics are good for RBVO. But, better atomization with compressed air improves the combustion characteristics in SFVO and the thermal efficiency is improved by 4% in non-commercial new burner.

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