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BOILER PERFORMANCE OF EMULSIFIED FUEL

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ABSTRACT

This research aims to show the performance of using emulsified fuel in a boiler. Bunker and three (3) fuel mixtures consisting of different proportions of bunker, water and catalyst were tested using three (3) nozzle sizes. Samples of the fuels tested including coal were subjected to fuel characteristic tests. A batch mixer was designed and fabricated to blend the fuel mixtures. The fuel mixtures were blended at the experimental sites using the formulated catalyst of the World Energy Extender Corporation.

The process of emulsification done and the performance tests conducted are discussed in this study. Fuel characteristic tests were performed based on the codes of the American Society for Testing Materials and the International Organization for Standardization. Boiler performance tests were conducted based on the power test codes of the American Society of Mechanical Engineers. A water tube boiler in conformity with Japanese Industrial Standard code was used. It was observed that the thermal efficiency was lower when firing the boiler with fuel mixtures of bunker, water and catalyst than when only bunker was used. This research only proves that these fuel mixtures can be used as alternative fuels. It is recommended that further study should be conducted to improve and realize the full potential of emulsified fuels.

I. Introduction

A fuel mixture of bunker and water can be burned with good results if the water is emulsified with the bunker before atomization. Emulsification forms tiny droplets of water that are encapsulated within a larger droplet of bunker. As the water droplets enter the combustion chamber or furnace, the heat causes the water droplets to suddenly flash to steam resulting in micro-explosions that shatter the larger bunker droplets into tiny particles. The micro-explosions result to a better mixing of bunker fuel and combustion air, which requires lesser time to burn.

However, there is a heat loss penalty for using bunker-water emulsions for improving fuel atomization. Heat is lost by the vaporization of water mixed with the bunker. The addition of water to the bunker may result in decreased thermal efficiency unless there is a compensating improvement in combustion efficiency. A reduction of the amount of carbon monoxide with the use of bunker-water emulsion leads to the reduction of the excess air needed for complete combustion and therefore increasing the amount of heat transferred. In order to realize the benefits of using emulsified fuels, the size of the water droplets encapsulated with the bunker should be very small and the emulsion must be stable.

The emulsion results in a cooler and/or shorter primary flame zone. Due to poor atomization by existing oil burning equipment, water-oil emulsions have been used in some installations, which reduced oxides of nitrogen in the flue gases [7]. An efficient emulsion can also optimize the use of heavy fuels for industries.

The objectives of the study are to compare the fuel characteristics and boiler performance characteristics of bunker to that of the three (3) different fuel mixtures consisting of bunker and water blended with a catalyst. Specifically, the study objectives determine the fuel characteristics particularly the kinetic viscosity, specific gravity, heating value, pour point, flash point, and percentages of water, water and sediment, ash, sulfur, carbon, hydrogen and nitrogen; and calculate the boiler performance characteristics particularly the total heat input, heat absorbed by the working fluid, heat losses, steam conversion ratio, and emissions (carbon dioxide, carbon monoxide and oxygen) of bunker, fuel mixture A, fuel mixture B and fuel mixture C at various nozzle sizes.

The fuel mixtures were blended at the experimental site using the catalyst formulated by the World Energy Extender Corporation. The fuel characteristic tests were conducted at the Fuels and Appliance Testing Laboratory (FATL) and the Energy Research Laboratory of the Department of Energy. The\boiler performance tests were performed at the FATL using a Goto Hamada water tube boiler.

The process of the combustion is dependent on various parameters such as the characteristics of the burner, configuration of the boiler, properties of the fuel, etc. The results of the combustion performance obtained are therefore applicable only to the equipment used by the specific fuels tested and the operating procedures and conditions during the experimental runs.

II. Methodology

The compositions of the fuels tested are shown in Table 1. The three (3) fuel mixtures were labeled A, B, and C. Fuel mixture A consisted of 85 kg of bunker, 15 kg of water and 0.4 kg of catalyst; fuel mixture B had 80 kg bunker, 20 kg water and 0.4 kg catalyst; and fuel mixture C contained 75 kg bunker, 25 kg water and 0.4 kg catalyst. Bunker and the catalyst were supplied by the World Energy Extender Corporation. Ordinary tap water was used. Bunker and coal were tested for comparison.

A batch mixer with a capacity of 200 litres was designed and fabricated. It is composed of a mixing drum, steel paddle and 2 kW electric motor.

Table 1
Fuel Composition

Fuel	Bunker kg	Water kg	Catalyst kg
Bunker	100	0	0
Fuel Mixture A	85	15	0.4
Fuel Mixture B	80	20	0.4
Fuel Mixture C	75	25	0.4

Each batch contained the exact proportion by weight of bunker, water and catalyst as shown in Table 1. The fuel mixture was thoroughly mixed for at least 30 minutes. Ten (10) batches at 100.4 kg per batch were mixed per fuel mixture before the experimental runs.

The fuel characteristic tests were based on the American Society for Testing Materials (ASTM) [2] and the International Organization for Standardization (ISO) [3, 4, 5, 6]. The characteristics tested were heating value (ASTM D240), specific gravity (ASTM D1298), kinematic viscosity (ASTM D445), pour point (ASTM D97), flash point (ASTM D93), and in percentages by weight of water (ASTM D95), water and sediment (ASTM D1796), sulfur (ASTM D129, ISO 351), ash (ASTM D482, ISO 1171), carbon (ISO 609), hydrogen (ISO 609) and nitrogen (ISO 333).

The samples were taken from the middle of each barrel containing the bunker and the various fuel mixtures. The fuel mixture samples were made to pass a 200 mesh or 75 micrometers sieve to determine the size of the water in the fuel mixtures.

The pilot scale boiler used in the research is a self-contained unit designed to burn solid and liquid fuels to determine the performance characteristics of using alternative fuels like hydro-oil. The schematic diagram shown in Figure 1 shows the experimental set-up and apparatus used.

The boiler was manufactured and fabricated by Goto Hamada in conformity with the Japanese Industrial Standard Code and acquired from Omega Industrial, Inc. in 1982. The boiler has the following specifications: model LGS300; water tube; heating surface area of 10 m^2; power rating of 24 brake horsepower; maximum working pressure of 10 kg/cm^2; normal steam evaporation of 300 kg per hour; and saturated steam quality. It has a furnace door to accommodate solid fuels, which was used in observing the burning characteristics of the fuels tested. The combustion chamber is about 2 m long by 1 m wide.

The boiler was fired with a forced-draft oil burner manufactured by Daito. Fuel oil is atomized by pressure jet nozzle with firing rate depending on the atomizing pressure and viscosity of the fuel. The fuel firing system consists of fuel pump, automatic monitoring equipment, combustion control, control console, fuel pre-heater and a positive displacement flowmeter with a resolution of 0.1 litre per hour. Combustion gasses make three (3) passes through the boiler tubes before it is withdrawn to the stack. An adjustable damper attains the control of combustion air and flue gas flows.

Small openings are provided upstream of the stack for temperature measurement and withdrawal of the gas sample for analysis. Flue gas temperature was monitored with a Yokogawa Hybrid Recorder. Direct readings of emissions (oxygen, carbon dioxide and carbon monoxide) in the dry flue gas were obtained with a Bacharach Portable Combustion Optimizer model 960 and were counter checked with a Fyrite Wet-Chemical Analyzer and an Orsat Gas Analyzer.

The feedwater system includes feedwater pump designed to handle preheated water, a positive displacement flowmeter, stop valves, check valves, water level gauge with drainpipe, sampling valve and drain valve. It has a water softener with built-in brink tank, raw water pump and chemical feed pump. Steam flow was measured using a combination of a Yokogawa Vortex flowmeter model YEWFLO and type YF104 with integrator/totalizer model YFTC-IST4.

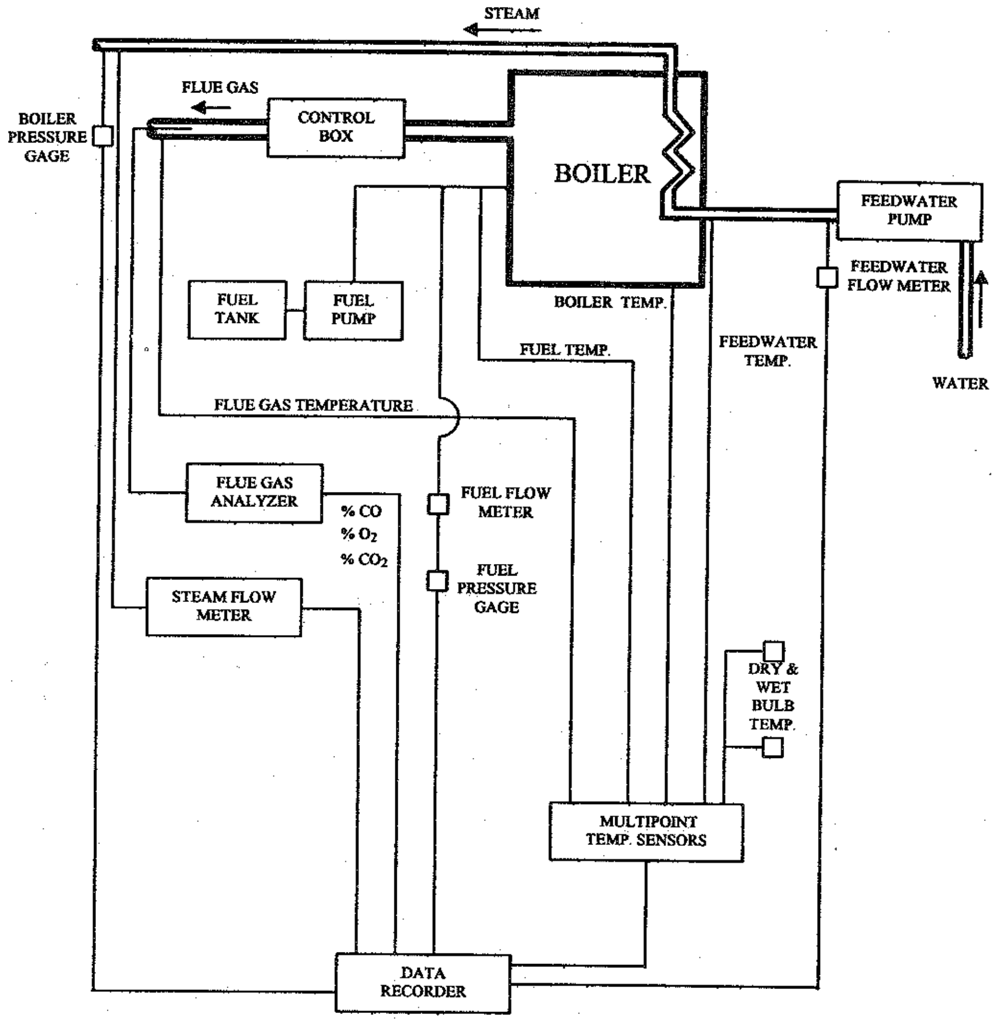

Figure 1. Experimental schematic diagram

A Yokogawa Hybrid Recorder model 3087 was used for recording. The recorder is programmable and can accept twelve (12) channels. It prints out analog traces in six (6) distinct colors and digital data.

The boiler performance tests were based on the American Society of Mechanical Engineers Power Test Codes [1}. Figure 2 shows the flow chart of the tests. The three (3) nozzle sizes used were 9.46 L/hr (2.5 gallons/hr), 13.25 L/hr (3.5 gallons/hr) and 17.03 L/hr (4.5 gallons/hr). A total of eight (8) experimental runs were conducted for the nozzle sizes as follows: three (3) runs for the bunker fuel using 9.46, 13.25 and 17.03 L/hr; two (2) runs for the fuel mixture A using 9.46 and 13.25 L/hr; two (2) runs for fuel mixture B using 17.03 L/hr, and one (1) run for fuel mixture C using 17.03 L.hr.

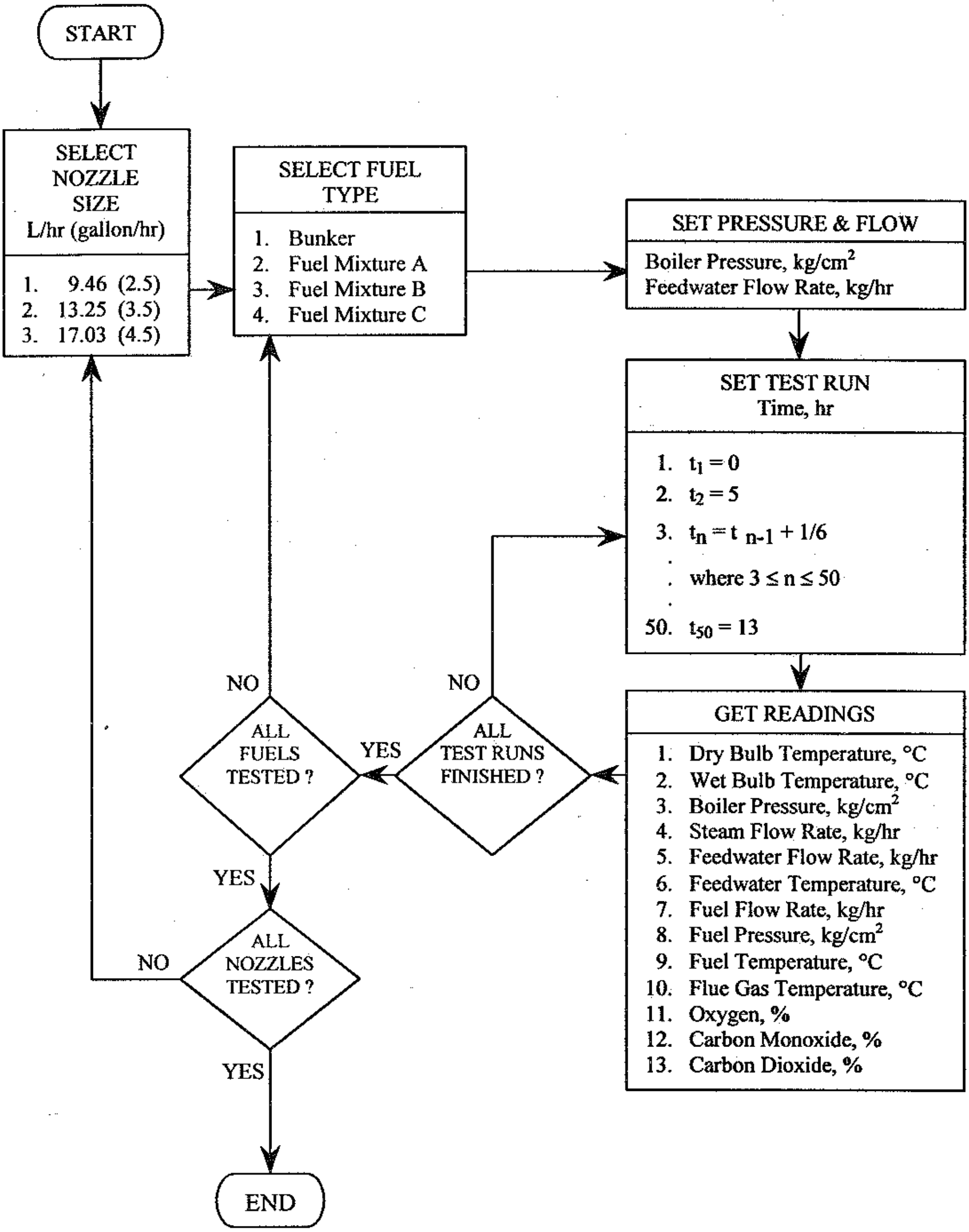

Figure 2. Flowchart of boiler performance test

The boiler was allowed to fire continuously for five (5) hours to attain equilibrium conditions before the experimental runs for each fuel. Each experimental run had duration of eight (8) continuous hours with readings taken at every ten (10) minutes. The readings recorded were dry bulb temperature in °C, wet bulb temperature in °C, boiler pressure in kg/cm^2, steam flow rate in kg/hr, feedwater flow rate in kg/hr, feedwater temperature in °C, fuel flow rate in kg/hr, fuel pressure in kg/cm^2, fuel temperature in °C, flue gas temperature in °C and stack gas levels of oxygen, carbon monoxide and carbon dioxide in percentages. Adjustment of the percentage oxygen level was limited by the percentage carbon monoxide in the dry flue gas, which should not exceed the acceptable limit of one (1) percent.

The boiler pressure was maintained at about 8 kg/cm ^{2}. The feedwater flow is controlled automatically by a drum level switch, which switches on and off the feedwater pump at intervals corresponding to the rate of steam conversion.

III. Findings and Analysis

The results of the fuel characteristic tests of the various fuel mixtures have been compared with the base fuel bunker and coal as shown in Table 2. Viscosity is a fluid property that measures its resistance to flow in the fuel system. The kinematic viscosity at 37.8 °C of bunker is 612 cSt while fuel mixture A is 954 cSt, a 55.9% increase. For fuel mixtures B and C, the increases are 70.4% and 103.8% respectively. It can be noted that the viscosity increased with the addition of water and catalyst.

Table 2
Fuel Characteristics

Fuel	Bunker	Fuel Mixture A	Fuel Mixture B	Fuel Mixture C	Coal
Kinematic Viscosity at 37.8 °C, cSt	612	954	1043	1247	-
Heating Value, kJ/kg	43182.6	36427.1	35475.7	32118.9	-
Water, %	0.17	16.16	21.16	25.93	
Water & Sediment, %	0.22	15.1	28.0	28.0	-
Pour Point, °C	14	18	17	22	-
Flash Point, °C	130	>110	>105	>100	-
Specific Gravity	0.955	0.963	0.987	0.966	-
Ash, %	0.02	0.004	-	-	18.63
Sulfur, %	2.96	3.07	2.65	2.65	0.18
Carbon, %	28.27	75.59	-	-	76.31
Hydrogen, %	9.11	9.22	-	-	1.25
Nitrogen, %	0.06	0.35	-	-	0.27

The heating value is a measure of the energy available from a fuel, which is essential when considering the thermal efficiency of equipment for producing either power or heat. The gross heating value of the fuel mixtures obtained by the bomb calorimeter method decreased by an amount about the same as the percentages of water added to the bunker. The percentage of water in each of the fuel mixtures was almost the same as the percentages of water added to each corresponding fuel mixtures. The gross heating value for fuel mixture A decreased by 15.6% while for fuel mixtures B and C, decreased by 17.8% and 25.6% respectively.

Pour point is an index of the lowest temperature that the fuel mixture can be used for certain applications. The pour point increased with the addition of water and catalyst.

Flash point measures the tendency of the fuel mixture to form a flammable mixture with air under controlled laboratory conditions. It is one of the factors to be considered in assessing the overall flammability hazard of a fuel. The flash point also increased with the addition of water and catalyst.

Specific gravity is the ratio of the mass of a given volume of fuel mixture at 15 °C to the mass of an equal volume of pure water at the same temperature. Specific gravity is necessary for the conversion of measured volumes to mass at the standard temperature of 15 °C. The specific gravity also increased with the addition of water and catalyst.

Measurements of the different levels of sulfur, carbon, hydrogen and nitrogen in the fuel mixtures enable better determination of the products of combustion. However, there were no significant changes in the percentages of sulfur, carbon, hydrogen and nitrogen in the fuel mixtures.

The fuel mixtures were made to pass through a 75 micrometers sieve to determine the size of water droplets in the fuel mixtures. It was observed that the droplets were approximately about 1-2 mm in size. It can be deduced that the mixing procedure is not efficient, as the water droplets were not fully encapsulated in the fuel. Theoretically, it is desirable to produce water droplets smaller than the size of the nozzle atomized bunker drops to produce better emulsion. Bigger water droplets may exit the nozzle totally free from bunker, thereby negating the benefits of secondary bunker atomization.

Table 3

Test Data Average Readings

Fuel	Bunker			Fuel Mixture A		Fuel Mixture B	Fuel Mixture C
Nozzle Size, L/hr (gallon/hr)	9.46 (2.5)	13.25 (3.5)	17.03 (4.5)	13.25 (3.5)	17.03 (4.5)	17.03 (4.5)	17.03 (4.5)
Dry Bulb Temperature, °C	30.5	29.9	33	32	29.3	29.5	29.6
Wet Bulb Temperature, °C	25.7	24.9	26.7	24.8	25.2	25.6	26.1
Boiler Pressure, kg/cm^2	8.4	8.3	8.3	8.1	8.5	8.7	8.4
Steam Flow Rate, kg/hr	141.3	145.8	169.9	110.3	151.1	178.4	144.8
Feedwater Flow Rate, kg/hr	118.3	124.0	143.8	116	125	161.7	123.7
Feedwater Temperature, °C	32.4	30.4	35.9	38.3	31.9	30.1	28.9
Fuel Flow Rate, kg/hr	13.3	14.5	16.2	14.6	18.4	22.5	20.2
Fuel Pressure, kg/cm^2	18	18	18	18	22	24	20
Fuel Temperature, °C	116.6	125.9	117.9	92.5	102.9	104.7	99.6
Flue Gas Temperature, °C	367.0	368.0	365.4	355.1	378.5	356.0	361.4
Oxygen, %	11.99	10.24	7.41	10.60	10.05	10.40	10.60
Carbon Monoxide, %	0.82	0.38	0.5	0.92	0.46	0.56	0.76
Carbon Dioxide, %	7.30	8.90	11.10	10.00	8.75	7.20	9.00

The catalyst appears like a greenish gel. The catalyst however was not tested in the laboratory. The values obtained in the fuel characteristics are also dependent on the sampling method used in getting the samples for testing

The data and results of the boiler performance tests using different fuels and different nozzle sizes are shown in Table 3. The energy balance using heat loss method is exhibited in Table 4. Table 5 presents the steam conversion ratio and the percentage difference of the fuel mixtures with respect to bunker.

Table 4
Energy Balance Using Heat Loss Method

Fuel	Bunker			Fuel Mixture A		Fuel Mixture B	Fuel Mixture C
Nozzle Size, L/hr (gallon/hr)	9.46 (2.5)	13.25 (3.5)	17.03 (4.5)	13.25 (3.5)	17.03 (4.5)	17.03 (4.5)	17.03 (4.5)
Total Heat Input, kJ/hr	597961	646133	725772	577152	714333	831830	685432
Heat Absorbed by Working Fluid, kJ/hr	388456	448736	531918	372016	460338	543207	386103
Heat Loss to Flue Gas, kJ/hr	158325	146343	138797	147915	181447	197129	209158
Heat Loss due to Moisture and Hydrogen in Fuel, kJ/hr	45201	44592	47800	51449	65406	83175	83316
Radiation Losses, kJ/hr	5980	6461	7258	5772	7143	8318	6854

Table 5
Boiler Performance Results

Fuel	Bunker			Fuel Mixture A		Fuel Mixture B	Fuel Mixture C
Nozzle Size, L/hr (gallon/hr)	9.46 (2.5)	13.25 (3.5)	17.03 (4.5)	13.25 (3.5)	17.03 (4.5)	17.03 (4.5)	17.03 (4.5)
Steam Conversion Ratio, kg steam / kg fuel	10.66	10.09	10.46	7.56	8.19	7.93	7.17
Difference, % (compared against the same nozzle size)				25.07	21.70	24.19	31.45

The thermal efficiency is defined as the percentage ratio of the heat absorbed by the working fluid (water) in the boiler to the total heat supplied to the boiler including the sensible heat of the fuel, water and combustion air. The heat loss method was used in the determination of thermal efficiency because of its better accuracy over the input/output method. The measurements used in the heat loss method calculation affect only the losses and measurement errors do not cascade in the computation. Heat loss method accounts for the total heat losses. The thermal efficiency in percent is computed [8] as follows:

Thermal Efficiency = 100 (Heat Input - Heat Losses) ÷ (Heat Input)

The heat losses considered were heat loss due to flue gas, heat loss due to moisture and hydrogen in the fuel and radiation losses. The radiation losses were assumed to be one (1) percent of the total heat input which is the commonly used value for liquid-fired boiler. The value was arbitrarily used because it would be very hard to mathematically calculate precisely the actual losses considering the inconsistency of heat distribution in the boiler walls.

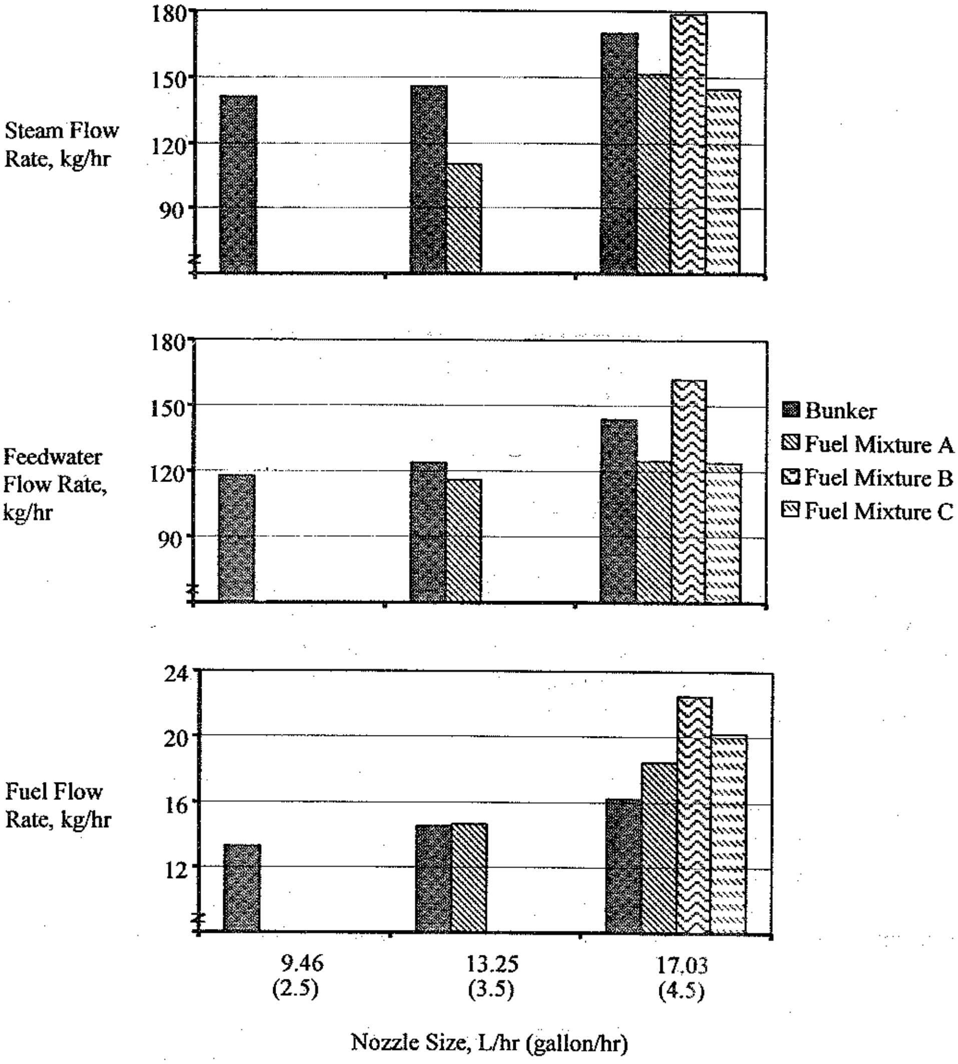

Figure 3. Steam, feedwater and fuel flow rates

The steam, feedwater and fuel flow rates are displayed in Figure 3. It can be seen that fuel mixture B consistently has the highest flow rates of steam, feedwater and fuel at 17.03 L/hr nozzle size. Fuel flow is higher for the fuel mixtures, which was implemented to eliminate the encountered problem of bunker and water separation at the burner pre-heater due to the increased fuel atomizing pressure. The fuel flow chart also shows that all fuel mixtures have higher fuel flow rates compared with bunker in the 13.25 and 17.03 L/hr nozzle sizes indicating faster fuel delivery and combustion.

Figure 4 presents the boiler pressure, which is almost constant at 8 kg/cm^2. It varies from 8.3 kg/cm^2 for bunker, 8.5 kg/cm^2 for fuel mixture A, 8.7 kg/cm^2 for fuel mixture B to 8.4 kg/cm^2 for fuel mixture C.

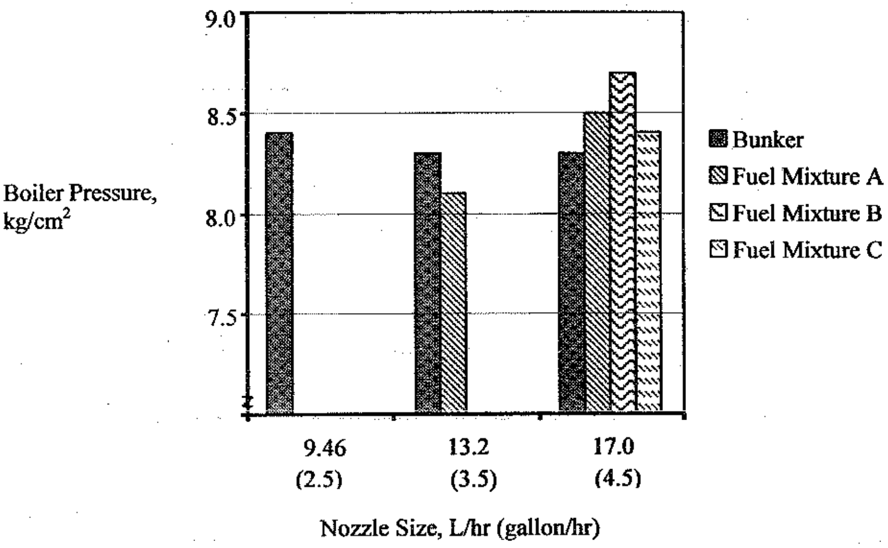

Figure 4. Boiler Pressure

The steam conversion ratio is shown in Figure 5. The steam conversion ratio is the amount of water converted to steam per unit weight of fuel input. It is a measure of the capacity of the fuel to convert water to steam. The percentage difference of the steam conversion ratio of the different fuel mixtures is computed against the base bunker fuel using the same nozzle size. The steam conversion ratio is lower for the fuel mixtures.

Comparing the fuel mixtures A and C at 17.03 L/hr nozzle size in Figure 3, it can be seen that even though the fuel flow rate of fuel mixture C is higher than that of fuel mixture A, fuel mixture A was able to produce a higher steam flow rate than fuel mixture C. This indicates a higher steam conversion ratio for fuel mixture A than fuel mixture C, which is reflected in Figure 5. It can also be seen that fuel mixture B has the highest steam flow rate but this does not conclude to a higher steam conversion ratio as illustrated in Figure 5 since its fuel flow rate as shown in the Figure 3 at the same nozzle size is very high.

It is also shown in Figure 5 that bunker still has the highest steam conversion ratio. This means that bunker has the highest capability of producing steam at the same amount of fuel, as compared to any of the fuel mixtures. It can be seen from Figure 3 that even though bunker had the lowest fuel flow rate, still bunker was able to produce a steam flow rate a little lower than fuel mixture B.

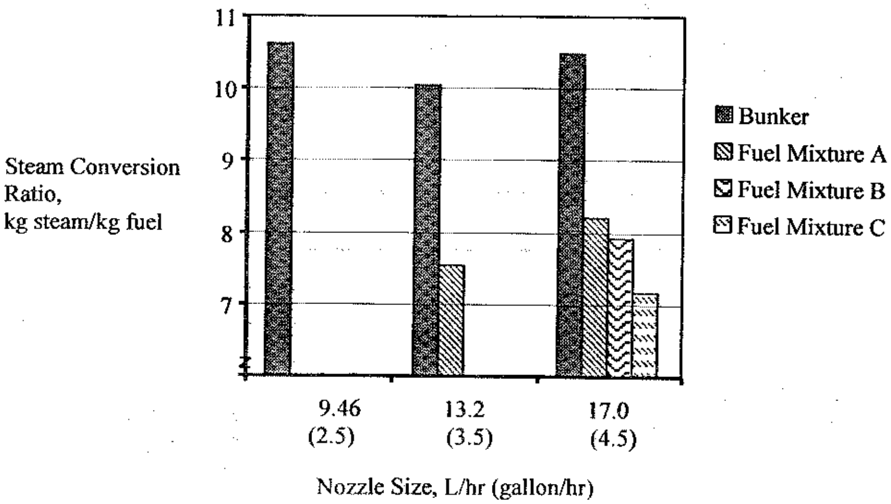

Figure 5. Steam Conversion Ratio

The total heat input is shown in Figure 6. It can be seen that fuel mixture B has the highest total heat input in the 17.03 L/hr nozzle size which is consistent to the fuel flow rate as shown in Figure 3 for the same nozzle size. Fuel mixture B was able to produce a significant increase in heat input of about 14.6% higher than bunker at 17.03 L/hr nozzle size. It can also be seen that fuel mixtures A and C have lower heat input than bunker which is consistent with their steam flow rates from Figure 3.

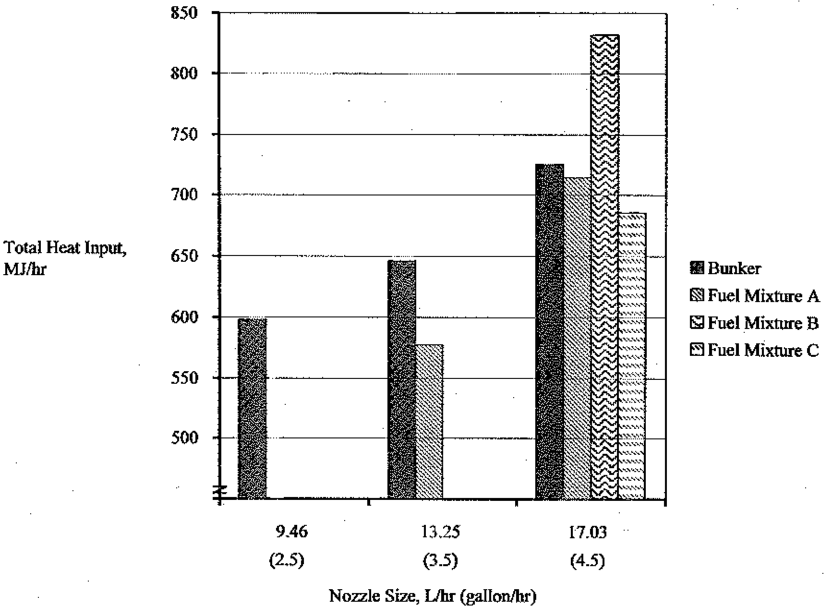

Figure 6. Total Heat Input

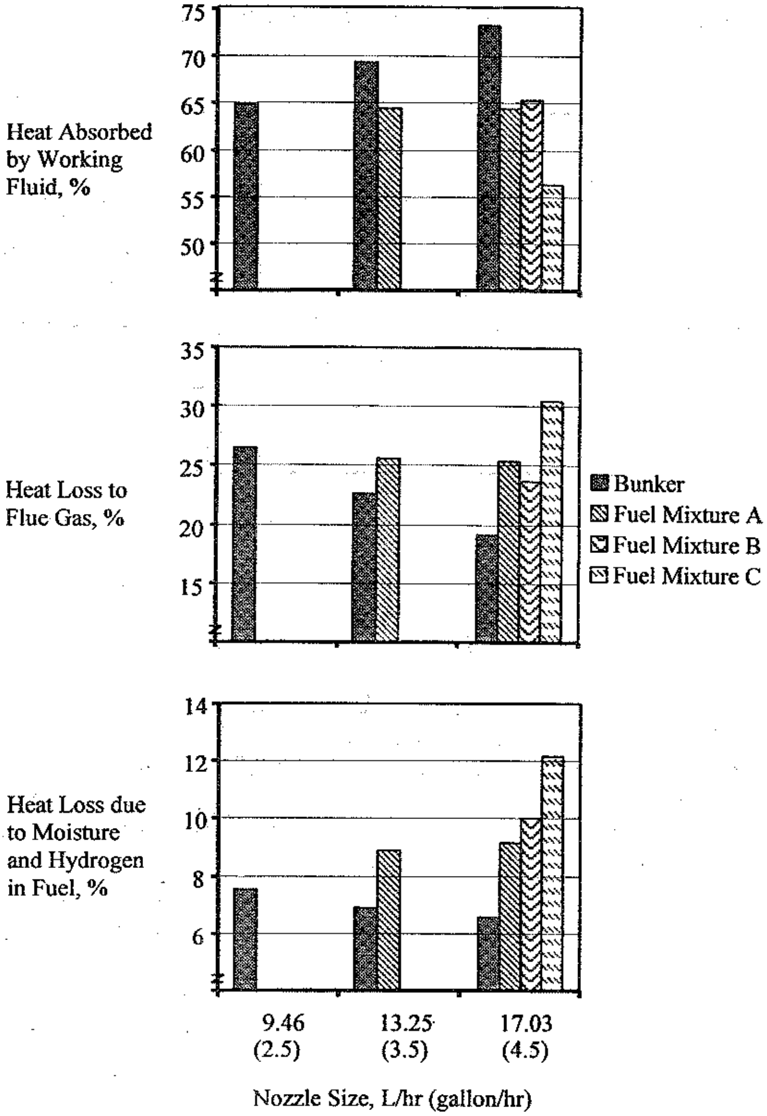

Figure 7. Heat absorbed and losses

Figure 7 shows the heat absorbed by the working fluid, the heat loss due to flue gas and the heat loss due to moisture and hydrogen in the fuel as a percentage of the total heat input. The heat loss due to moisture and hydrogen in fuel are higher for the fuel mixtures than for the bunker due to the amount of water added. The energy balance also shows the negative effect of the addition of water to the bunker. The amount of heat loss due to flue gas increased relative to the amount of water added to the bunker (Figure 7). Fuel mixture C has the highest heat loss since it has the highest amount of water as compared with the other fuel mixtures.

The percentages of oxygen, carbon dioxide and carbon monoxide are graphed in Figure 8. It shows that oxygen is higher than for bunker. It can also seen that carbon dioxide emission was significantly lowered when any of the fuel mixtures was used.

The slightly higher thermal efficiency obtained for the base fuel using 17.03 L/hr nozzle can be explained by the lower percent oxygen in the flue gas as shown in Figure 8. The percent oxygen in the dry flue gas in all test runs was about the same except for the base fuel. Adjustment of percent oxygen level was limited by the percent carbon monoxide in the dry flue gas which should not exceed the acceptable limit and the level obtained during the firing of the base fuel. Compared with the base fuel, there is no decrease in the minimum excess air requirement with the addition of water to the bunker.

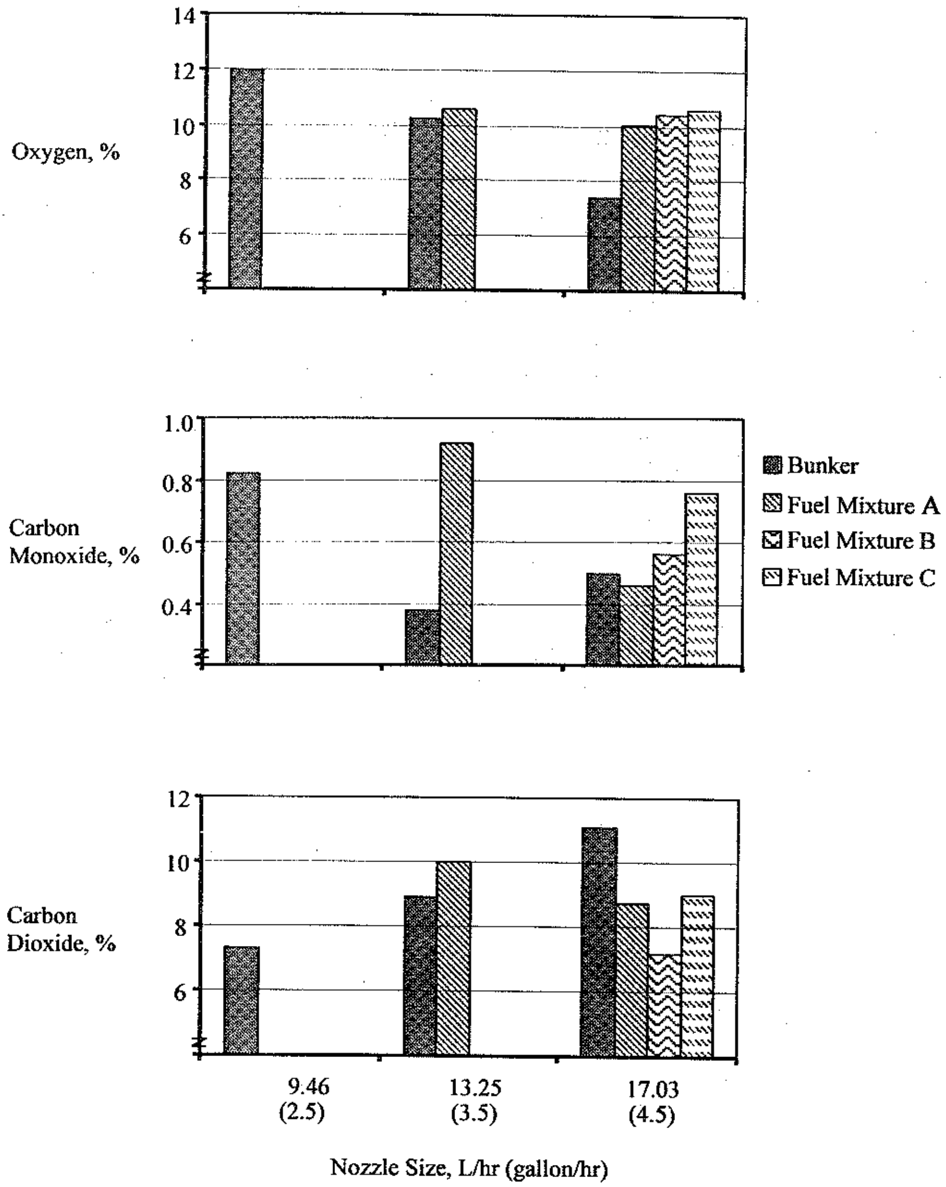

Figure 8. Emissions

The thermal efficiency for the fuel mixtures are lower compared to the base fuel, which indicates that there was no improvement with the use of the fuel mixtures. However, with the addition of water and better blending, heavier fuel may be used with slightly lower efficiency.

It was observed during the firing of the fuel mixtures that the separation occurred after the emulsion was pre-heated to atomizing temperature above 100 °C. This resulted in pulsating flame because the nozzle was blowing steam instead of spraying fuel. Fuel mixtures B and C were hard to ignite during cold starts. The fuel mixtures had to be pre-heated to about 130 °C before a flame can be established.

IV. Conclusions and Recommendations

The thermal efficiency of the boiler is lower when using fuel mixtures A, B and C as compared to bunker. The addition of water in the fuel increases the amount of heat loss due to the additional heat to evaporate the water. This should be made up by a resultant improvement in combustion efficiency to avail of savings in terms of fuel used. If there was improvement in the combustion efficiency, it could have been possible to lower the amount of oxygen in the dry flue gas without producing too much carbon monoxide. Lower oxygen in the dry flue gas could have made up for the inherent heat loss due to the addition of water to the bunker. The unsatisfactory combustion results could be attributed to the larger than ideal water droplet size produced during the blending of the bunker-water emulsion.

A study should be conducted to determine the optimum blending and proportion of bunker, water and catalyst; the size and type of nozzle; effective swirlers or diffusers; and fuel and air flow rates ratio in order to fully utilize the benefits of using emulsified fuels. Tests for oxides of nitrogen should be conducted to determine the decrease in the amount of pollution due to NOx since the emulsion results in cooler and/or shorter primary flame zone. An economic study on the cost effectiveness of the fuel mixtures should be conducted. Tests should also be done for the catalyst.

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