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Effects of Jatropha oil blending with C-heavy oil on soot emissions and heat absorption balance characteristics for boiler combustion

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Abstract

This study investigated the effect of crude *Jatropha* oil (CJO) blending with C-heavy oil on the combustion characteristics of oil-fired boilers. Combustion experiments were conducted using a 550 kW liquid fuel combustion test facility equipped with a steam-atomizing burner. The results indicated that the flame radiation intensity is decreased by the CJO blending with C-heavy oil. Consequently, the heat absorption of the sections near the burner decreases. Due to the lower nitrogen and sulfur contents in CJO, the NOx and SO₂ emissions are decreased by the CJO blending with C-heavy oil. It was also found that both the particulate matter concentration and the particle size in the exhaust gas are decreased by the CJO blending. This is attributed by the low carbon residue content of CJO. The results of this study imply that when CJO is introduced into oil-fired thermal power stations, considerable attention should be paid to changes in the heat absorption balance and the possibility of a decrease in the particle collection efficiency of the electrostatic precipitator.

Key words: spray combustion; Jatropha oil; heavy oil; soot formation; heat absorption balance

Nomenclature

C_1 :	first Planck's constant, $3.742 \times 10^{-16} \text{ Wm}^2$
C_2 :	second Planck's constant, 1.439×10^{-2} mK
C _{p,water} :	specific heat of water, J/(kg K)
E:	flame radiation intensity, W/m ²
$E_{\lambda \iota}$:	monochromatic radiation intensity for λ_i , W/m ³
<i>K</i> :	absorption coefficient, 1/m
L:	line-of-sight path length through flame, m
<i>m</i> water,i:	mass flow rate of cooling water supplied to section i, kg/s
\dot{Q}_{i} :	heat absorption rate of section i, W
<i>T</i> :	temperature of soot particles in the flame, K
T_{in} :	temperature of cooling water supplied to each section, K
T _{out,i} :	temperature of cooling water discharged from section i, K
<i>X</i> 4%02,i:	volumetric concentration of species i corrected to 4% O ₂ , ppm
X _{measured} ,	i: volumetric concentration of species i measured in exhaust gas, ppm
<i>X</i> _{m,O2} :	volumetric concentration of O2 measured in exhaust gas, %

Greek Symbols

α:	constant
$\mathcal{E}_{\lambda i}$:	monochromatic emissivity for λ_i
λ_i :	wavelength, m

1 1. Introduction

 $\mathbf{2}$ Biomass fuel attracts considerable attention as a renewable energy source from the viewpoint of global 3 warming. Vegetable oil can be used as an alternative biomass-derived fuel in oil-fired thermal power 4 stations. The vegetable oil from Jatropha curcas is a promising biomass-derived fuel as it does not $\mathbf{5}$ directly influence food prices because of its toxicity. Another advantage of Jatropha is the wider 6 latitude range in which it can be cultivated compared with that of palm [1]. In addition, Jatropha is a 7drought-resistant perennial plant that grows well even in marginal soil [1]. According to a report by the Global Exchange for Social Investment (GEXSI) [2], there are considerable areas of land where 8 Jatropha can be cultivated, whereas other edible crops cannot be cultivated. Although the oil yield of 9 10 palm trees exceeds that of Jatropha [3], a report indicated that the net energy ratio (ratio of energy 11 output to energy input) of *Jatropha* oil was higher than that of palm oil when considering the energy 12content of the co-products [4]. Therefore, the fundamental combustion characteristics have been 13investigated using basic burners by some researchers [5,6].

As Jatropha oil can be utilized as an alternative fuel for automobiles, stationary gas turbines, and airplanes, previous researches have investigated its combustion characteristics for IC engines [7-24] and gas turbine combustors [25-31]. However, IC engines and gas turbine combustors require the purification and/or esterification of Jatropha crude oil to eliminate impurities and/or to decrease the viscosity to achieve acceptable atomization characteristics. In contrast, purification and esterification are not required for boilers as they have higher tolerance for impurities and the viscosity of the fuel compared with IC engines and gas turbine combustors. However, there are very few studies

21	investigating the combustion characteristics of Jatropha oil for boilers. A study by Kang et al. [32] is
22	one of the few studies in which direct burning of crude Jatropha oil (CJO) in a commercial boiler
23	system using a burner designed for commercial home-heating oil was conducted. The study revealed
24	that CO, NOx and soot emissions from CJO combustion were comparable to the emissions from the
25	commercial home-heating oil. However, it is necessary to investigate the combustion characteristics of
26	CJO using a burner designed for C-heavy oil in order to introduce CJO into oil-fired thermal power
27	stations. Since the spray combustion is a complicated phenomenon, the various fundamental researches
28	have been conducted by many researchers [33-38]. Such fundamental researches are important to
29	clarify the basic mechanism of the spray combustion. On the other hand, the evaluation whether there
30	will be problems or not when a new type of fuel is introduced.
31	The aim of this study is to evaluate the effect of CJO blending with C-heavy oil in oil-fired thermal
32	power stations. A 550 kW liquid fuel combustion test facility equipped with a burner designed for C-
33	heavy oil [39] was used for the evaluation. Two combustion tests involving pure C-heavy oil and a
34	mixed fuel of 50% CJO and 50% C-heavy oil on a lower heating value (LHV) basis were conducted.
35	
	The NOx, SO ₂ and particulate matter emissions were compared for the two cases. Furthermore, the two
36	The NOx, SO_2 and particulate matter emissions were compared for the two cases. Furthermore, the two cases were also compared with respect to the particle size distributions in the exhaust gas, the flame
36 37	The NOx, SO_2 and particulate matter emissions were compared for the two cases. Furthermore, the two cases were also compared with respect to the particle size distributions in the exhaust gas, the flame radiation intensities, and the heat absorption balances. Although the number of combustion tests were

39 examinations of introducing biofuels into oil-fired thermal power stations, were obtained.

2 Experimental apparatus and conditions

2.1 Fuel properties

43	The properties of the fuels investigated in this study are listed in Table 1. The density and LHV
44	of CJO are lower than that of C-heavy oil. This indicates that the volumetric flow rate of CJO
45	exceeds that of C-heavy oil for the same thermal input to the boiler. The viscosity of CJO is much
46	lower than that of C-heavy oil. The temperature of CJO needed to achieve the required atomization

Fuel		C-heavy oil	CJO	
	@30°C	g/cm ³	0.9635	0.9097
Density	@50°C	g/cm ³	0.9492	0.8962
	@75°C	g/cm ³	0.9317	0.8793
	@30°C	mm ² /s	392.0	52.6
Viscosity	@50°C	mm ² /s	110.0	25.8
viscosity	@75°C	mm ² /s	36.8	13.1
Surface	@23°C	dyn/cm	30.6	31.7
tension	@50°C	dyn/cm	29.2	29.6
HHV		J/g	42,820	39,670
LHV		J/g	40,450	37,026
Flash point		°C	93	248
Ignition poi	nt	°C	408	417
Water conte	ent	wt-ppm	300	1,100
	Carbon content	wt%	86.9	76.5
T.TL	Hydrogen content	wt%	10.7	11.7
Ultimate analysis	Oxygen content	wt%	< 0.5	11.1
	Nitrogen content	wt-ppm	2,000	55
	Sulfur content	wt-ppm	23,000	2
Carbon resi	Carbon residue		10.9	0.27
	Saturated	wt%	21.7	-
Type	Aromatics	wt%	58.7	-
analysis	Resin	wt%	10.8	-
	Asphaltene	wt%	8.8	-
	Palmitic (C16:0)	vol.%	-	13.8
	Palmitoleic (C16:1)	vol.%	-	0.8
	Margaric (17:0)	vol%	-	0.1
E-4	Stearic (C18:0)	vol.%	-	6.8
Fatty acids	Oleic (C18:1)	vol.%	-	44.5
	Linoleic (C18:2)	vol.%	-	33.6
	Linolenic (C18:3)	vol.%	-	0.2
	Arachic (C20:0)	vol.%	-	0.2

Table 1Fuel Properties.

viscosity is lower than that of C-heavy oil. This indicates that employing CJO can reduce heating 47energy required for atomization of the fuel. The flash point of CJO is much higher than that of C-48heavy oil, but the ignition points of both fuels are almost identical. It should be noted that CJO 4950contains more than 10 wt.% oxygen in its molecular composition. The oxygen content of the fuel 51molecules has been found to affect the sooting tendency [40]. The nitrogen and sulfur contents and the carbon residue of CJO are considerably lower than that of C-heavy oil. Hence, the NOx, SOx 52and particulate matter emissions from CJO combustion are expected to be lower than that from C-53heavy oil combustion. 54

55

56 2.2 Liquid fuel combustion test furnace

57 Figure 1 is a schematic diagram of the liquid fuel combustion test facility at the Central Research
58 Institute of Electric Power Industry (CRIEPI). This facility was designed to evaluate the liquid fuel



Fig. 1. Schematic of liquid fuel combustion test facility.

59combustion characteristics of oil-fired thermal power stations. Two types of fuels in arbitrary mixing ratios could be supplied to the furnace. The steam heater heated the tanks and fuel lines. The fuel 60 61temperature supplied to the burner nozzle could be controlled up to 150 °C by the electric heater in 62 front of the fuel nozzle. The furnace was divided into five sections to measure the heat absorption 63 balance using the inlet and outlet temperatures of the cooling water and the flow rates of each section. 64The detailed procedure to measure the heat absorption balance was as follows. Cooling water at room 65temperature (20-30 °C) was supplied to each section during the combustion experiment. The flow rate 66 of the cooling water to each section was adjusted to be sufficiently large to avoid boiling the cooling 67 water. As indicated in Fig. 1, the temperature and the flow rate of the cooling water to each section 68 were measured by a thermometer and flowmeters. The temperatures of the return cooling water from 69 each section (40-60 °C) were also measured by thermometers. The heat absorption rate of each section 70 was then calculated using the following formula:

71

72
$$\dot{Q}_i = \dot{m}_{water,i} c_{p,water} \left(T_{out,i} - T_{in} \right).$$



(1)

Fig. 2. Details of burner.

73

74	Here, Q_i , $m_{water,i}$, $T_{out,i}$, and T_{in} are the heat absorption rate of section i [W], the mass flowrate of cooling
75	water supplied to section i [kg/s], the temperature of cooling water discharged from section i [K], and
76	the temperature of cooling water supplied to each section [K], respectively. The combustion air was
77	supplied from a forced draft fan. Mixing the exhaust gas with the air supply line allowed the
78	recirculation of a portion of the exhaust gas. The air temperature could be heated up to 280 °C by the
79	electric heaters.
80	Figure 2 shows the details of the burner (Volcano Co., Ltd) that was designed to combust C-heavy oil.
81	The burner contained swirl vanes for stabilizing the flames. An electric discharge from a spark igniter
82	resulted in ignition. A flame detector was installed to monitor the extinction of the flames during the
83	experiment.
84	Figure 3 shows the details of the fuel-atomizing nozzle. A steam atomizer with a mixing chamber was
85	employed as the fuel-atomizing nozzle. The supplied steam pressure was controlled at a constant value
86	during the experiment.



Fig. 3. Details of fuel atomizing nozzle.

88 2.3 Measurement instruments and methods

A two-color pyrometer (Thermera-Turret, Mitsui Optics Co., Ltd.) was used to measure the flame radiation intensity through the optical window of the furnace as indicated in Fig. 1. The flame radiation intensity was calculated from the KL value and the temperature which were measured by the two-color method. The two-color method for the KL value and the temperature was based on the work of Hottel and Broughton [41]. The thermal radiation intensity from the soot particles was expressed by Planck's equation with Wien's approximation law as follows:

95

96
$$E_{\lambda i} = \frac{C_1 \varepsilon_{\lambda i}}{\lambda_i^5} \exp\left[-\frac{C_2}{\lambda_i T}\right]$$
(2)

97

98 Here, $\varepsilon_{\lambda i}$ is expressed by the following empirical equation [41]:

99

100
$$\varepsilon_{\lambda i} = 1 - \exp\left[-\frac{KL}{\lambda_i^{\alpha}}\right]$$
 (3)

101

102 In this study, the value of 1.38 was employed for α , as proposed by Matsui et al. [42]. Eq. (3) and the 103 measured thermal radiation intensities for two different wavelengths were substituted into Eq. (2), to 104 obtain the following equation:

106
$$\left[1 - \frac{\lambda_1^5 E_{\lambda 1} (\exp[C_2/\lambda_1 T] - 1)}{C_1}\right]^{\lambda_1^{\alpha}} - \left[1 - \frac{\lambda_2^5 E_{\lambda 2} (\exp[C_2/\lambda_2 T] - 1)}{C_1}\right]^{\lambda_2^{\alpha}} = 0$$
(4)

107

In this study, to avoid the superposition of the radical emission and chemiluminescence on the thermal radiation, 550 and 650 nm were employed for λ_1 and λ_2 , respectively. The temperature, *T*, was calculated from Eq. (4). The value of *KL* was calculated from Eqs. (2) and (3) using previously calculated *T*. The flame radiation intensity *E* was calculated by integrating E_{λ} with respect to λ as follows:

113

114
$$E = \int_0^\infty E_\lambda d\lambda = \int_0^\infty \left(\frac{C_1 \left(1 - \exp\left[-\frac{KL}{\lambda^{\alpha}} \right] \right)}{\lambda^5} \exp\left[-\frac{C_2}{\lambda T} \right] \right) d\lambda$$
(5)

115

116 The maximum uncertainty for the measurement value of E_{λ} is 3%.

117 A gas analyzer measured the concentrations of CO, NOx, and SO₂ in the furnace exhaust gas. The 118 maximum uncertainty for the measurements of CO, NOx, and SO₂ was 5 ppm. In the current research, 119 NOx, CO, and SO₂ emissions were evaluated as their volumetric concentration in the exhaust gas was 120 corrected to 4% O₂. The corrected concentration was calculated by Eq. (6):

121

122
$$X_{4\%O2,i} = X_{measured,i} \frac{(20.99 - 4)}{(20.99 - X_{m,O2})}$$
(6)

124	Here, $X_{4\%02,i}$, $X_{measured,i}$, and $X_{m,O2}$ were the concentrations corrected to 4% O ₂ of species i [ppm], the
125	measured concentration of species i in the exhaust gas [ppm], and the measured concentration of O_2 in
126	the exhaust gas [%], respectively.
127	The concentrations and size distributions of the particles in the exhaust gas were measured based on
128	the Japanese Industrial Standards JIS-Z8808 [43], which prescribes the method for measuring dust
129	concentrations of an exhaust gas in a flue, stack or duct, and JIS-K0302 [44], which prescribes the
130	method for measuring particle size distribution of dusts in flue gas, respectively. In addition, a scanning
131	electron microscope (SEM) was used to analyze the collected particles in detail.
132	
133	2.4 Experimental conditions
$133\\134$	2.4 Experimental conditions Table 2 shows the experimental conditions in this research. In Case 1, 100% C-heavy oil was used as
133 134 135	2.4 Experimental conditions Table 2 shows the experimental conditions in this research. In Case 1, 100% C-heavy oil was used as a fuel. A mixed fuel containing 50% CJO and 50% C-heavy oil on an LHV basis was used in Case 2.
133 134 135 136	2.4 Experimental conditions Table 2 shows the experimental conditions in this research. In Case 1, 100% C-heavy oil was used as a fuel. A mixed fuel containing 50% CJO and 50% C-heavy oil on an LHV basis was used in Case 2. The fuel mass flow rates of CJO and C-heavy oil were controlled by small size rotary flow meters

	Case 1	Case 2
	(100% C-heavy oil)	(50% CJO/50% C-heavy)
Thermal input [kW]	5	50
Staged combustion air ratio [%]	1	5
Exhaust gas recirculation ratio [%]	1	5
Excess air ratio [-]	1.	26
(Oxygen mole fraction at exit [%])	(4.5)	
CJO flow rate [kg/h]	0	27
C-heavy oil flow rate [kg/h]	47	24
Air flow rate [Nm ³ /h]	624	648
Fuel viscosity at nozzle [mm²/s]	6.5	
Fuel temperature at nozzle [°C]	140	124
Atomization steam flow rate [kg/h]	0.	01

Table 2Experimental conditions.

138	the liquid fuel density based on Table2, the temperatures of the flow meters were controlled at 50 °C.
139	The maximum uncertainty for the flow meters is 1.5% for full scale (200 L/h). Therefore, the maximum
140	uncertainty for the flow meters was $5.1 - 5.7\%$ for actual fuel flow rates ($52.4 - 58.4$ L/h). The fuel
141	mass flow rate of CJO was higher than that of C-heavy oil in Case 2 because of the lower LHV of CJO.
142	Both cases used the same values for the thermal input, the staged combustion air ratio, the exhaust gas
143	recirculation ratio, the excess air ratio, the fuel viscosity at the nozzle and the atomization steam flow
144	rate. The values of the staged combustion air ratio (15%) and the exhaust gas recirculation ratio (15%)
145	were based on the common operating conditions across heavy oil-fired thermal power stations in Japan.
146	As the spray characteristics of liquid fuel exert a strong effect on the combustion characteristics [45-
147	47], the liquid fuel temperature was controlled such that there was no difference in liquid fuel viscosity
148	between the two cases.

150 **3 Results and discussion**

151 **3.1 Flame radiation intensity and heat absorption balance**

Figure 4 shows a comparison of the direct photographs of the flames in Case 1 and Case 2. The same exposure time was used for both cases. Evidently, the flame luminosity in Case 1 is higher than that in Case 2. This indicates that the soot volume fraction of the flame in Case 2 is lower than that in Case 1. This tendency is consistent with that of the measured flame radiation intensity, as shown in Fig. 5.

156 Figure 5 shows the flame radiation intensity obtained by the two-color method described in detail in



Fig. 4. Direct images of the flame (the same exposure time was used in both cases).

157	section 3.2. The measurement was conducted through the optical window nearest to the burner exit.
158	The location and size of each measurement region is indicated in Fig. 5 (a). Although there are some
159	differences in the absolute values between the regions, it is obvious that the flame radiation intensity
160	in Case 2 is lower than that in Case 1. This could be because CJO has no aromatic ring in its molecules.
161	The sooting tendency of the biofuel is lower than that of fossil fuel. In a previous study on the
162	combustion of pure Jatropha oil in gas turbine combustors, although the combustion conditions were
163	different, the same trend was observed [25]. The same tendency was also observed for the combustion
164	of other biofuels [48, 49]. Wang et al. [50] and Cignoli et al. [51] reported that the sooting tendency
165	of a fuel containing aromatic rings in its molecular composition was higher than that of a fuel
166	containing no aromatic rings. Additionally, Song et al. [40] found that the soot from a biofuel had a
167	high reactivity during combustion because of the presence of oxygen in the biofuel molecules. Figures
168	4 and 5 and the previous results cited above indicate that the mixing of a biofuel with a fossil fuel has
169	the effect of reducing the flame radiation intensity. This reduction in the flame radiation intensity might
170	affect the heat absorption balance of the furnace.

171	Figure 6 shows the heat absorption balances in Cases 1 and 2. The heat absorption ratios of the burner
172	section and the furnace section 1 (the nearest furnace section to the burner, as indicated in Fig. 1) in
173	Case 2 are lower than that in Case 1. This is caused by the lower flame radiation intensity in Case 2
174	due to the mixing of CJO, as observed in Fig. 5. The difference in the heat absorption balance between
175	two cases in this study is relatively small. Nevertheless, it is considered that the actual difference in
176	large scale boilers will exceed that in this study, because the proportion of the heat absorption quantity
177	due to thermal radiation to the heat absorption quantity due to thermal convection in large-scale boilers
178	is larger than that in small test furnaces [52]. In other words, due to the lower specific surface area of
179	the water wall, the radiation heat transfer plays a more important role in large scale boilers compared
180	with small furnaces. Because the flame radiation intensity has a strong correlation with the fuel spray
181	droplet diameter [25], the flame radiation intensity might be increased by increasing fuel spray fuel
182	droplet size. However, an increase in the fuel droplet size beyond a certain point could cause other
183	problems, such as flame extinction or an increase in the particulate matter concentration in the exhaust



Fig. 6. Heat absorption balance of burner and furnace sections.

gas. Thus, there are limitations to increasing the fuel droplet size. Therefore, when CJO is introduced
at a high blending ratio into large-scale boilers, careful attention should be paid to the heat absorption
balance for operational safety.

187

3.2 Emissions

189 In both Cases 1 and 2, the concentration of CO in the exhaust gas was less than 10 ppm, and there
190 were no significant differences between the two cases.

Figure 7 shows the NOx emissions in Cases 1 and 2. The NOx emissions in Case 2 are lower than 191 192those in Case 1. This is attributed to the lower nitrogen content of CJO compared with C-heavy oil. 193The NOx is formed by both the thermal NOx mechanism and the fuel NOx mechanism in the spray 194combustion field. Due to the inclusion of CJO with its lower nitrogen content, the amount of NOx 195formed by the fuel NOx mechanism was decreased in Case 2. As the nitrogen content of CJO (55 wt. 196 ppm) is significantly lower than that of C-heavy oil (2000 wt. ppm), the nitrogen content of the mixed 197fuel in Case 2 is almost half of that in Case 1. In spite of the fact mentioned above, the NOx emission 198in Case 2 was not reduced by half compared with that in Case 1 (the NOx emission in Case 2 was 199approximately 62% of that in Case 1). This is because a portion of the NOx is formed by the thermal 200NOx mechanism. The amount of NOx formed by the thermal NOx mechanism is not significantly 201affected by the fuel type, because the flame temperature does not significantly change for the fuel type 202under the same excess air ratio. Therefore, the decrease in NOx emission in Case 2 is caused by the 203reduction of NOx formed by the fuel NOx mechanism.

204Figure 8 shows the SO₂ emissions in Case 1 and Case 2. The SO₂ emission in Case 2 is lower than 205that in Case 1. This is caused by the lower sulfur content of CJO compared to that of C-heavy oil. In 206contrast to the NOx emissions (Fig. 7), the SO_2 emission in Case 2 was approximately half that of Case 2071 (the SO₂ emission in Case 2 was approximately 53% of that in Case 1). It has been established that 208all the sulfur present in fuel appears as SO2 or SO3 in the combustion products (the amount of SO3 209produced is typically only a few percent of the amount of SO₂) [53]. Hence, the SO₂ emission in Case 2102 was reduced solely by the decrease in the sulfur content of the mixed fuel compared to 100% C-heavy 211oil. Slight difference between the measured value for Case 2 (53% of Case 1) and the expected value 212(50% of Case 2) is considered to be due to the uncertainty of flow meter of fuels (5.1 - 5.7%).

213Figure 9 shows the particulate matter concentration in the exhaust gas. The particulate matter 214concentration in Case 2 is lower than that in Case 1. This is because, as indicated in Table 2, the carbon



Fig. 9. Fagtiquiato matters formission.



Fig. 10. Rosin-Ramplar plots for particles

215residue of CJO is significantly lower than that of C-heavy oil. Generally, when the carbon residue in 216the liquid fuel is high, the particulate matter concentration in the exhaust gas tends to be high [54,55]. 217Figures 10 and 11 show Rosin-Rammlar plots for the particles collected from the exhaust gas and the 218SEM images of the particles. The particle sizes in Case 2 is entirely smaller than that in Case 1. This 219is because of the higher porosity of the particles in Case 2 compared with that in Case 1, as discussed 220below. Two types of particulate matter are emitted from liquid fuel combustion fields, namely, soot and 221cenospheres [56,57]. Soot is formed by the incomplete combustion of hydrocarbons in the gas phase 222due to a local lack of oxygen. Cenospheres are formed from the remaining heavy aromatic constituents 223of the fuel following thermal decomposition of the fuel. In general, the shapes and sizes of the soot 224particles and cenospheres from liquid fuel combustion fields are significantly different [58]. It is 225evident from the SEM images in Fig. 11 that most of the particulate matter collected from the exhaust 226gas consist of cenospheres, i.e., almost no soot particles can be observed in Fig. 11. There are also no 227significant differences in the basic sizes of the large cenospheres between the two cases (Fig. 11 (a) 228and (b)). This is because there are no significant differences in the spray characteristics between the 229two cases, as the fuel viscosities at the atomizing nozzle for the two cases are consistent. Thus, there 230was no significant difference in the size distribution of droplets injected from the fuel nozzle to the 231combustion field between the two cases. However, the number and sizes of the open holes on the 232cenosphere surface in Case 2 (Fig. 11 (d)) are greater than that in Case 1 (Fig. 11 (c)). This is because 233the carbon residue content of CJO is significantly lower than that of C-heavy oil. The concentration of 234heavy aromatic constituents of the fuel in Case 2 was diluted by the mixing with CJO. Hence, the

proportion of volatile matter in the fuel droplets in Case 2 is larger than that in Case 1. Consequently,
the porosity of the cenospheres in Case 2 was higher than that in Case 1. Many collapsed cenospheres
are observed in Case 2 (Fig. 11 (b)), while there are fewer collapsed cenospheres in Case 1 (Fig. 11
(a)). The particle sizes of the collapsed cenospheres are smaller than that of the original cenospheres.
This is considered to explain why the particle sizes in Case 2 are consistently smaller than that in Case
1, as observed in Fig. 10.

As per the above discussion, this study verified that the emissions of NOx, SO₂ and particulate matter from the furnace could be decreased by the mixing of CJO with C-heavy oil. However, it should be

(a) Case 1 (100% C-heavy), ×600



(c) Case 1 (100% C-heavy), ×2500



(b) Case 2 (50% CJO/50% C-heavy), × 600



(d) Case 2 (50% CJO/50% C-heavy), $\times\,2500$

Fig. 11. SEM images of particles collected from exhaust gas.

243	noted there is a possibility of decreasing the particle collection efficiency of the electrostatic
244	precipitator (ESP). This is because a penetration window from a few percent up to tens of percent exists
245	in the size range from 0.1 to 5 μ m for a normally operating ESP [59]. Therefore, careful attention to
246	the particle size distributions in the exhaust gas is required when introducing CJO into oil-fired thermal
247	power stations.

248

2 49 4. (Conclusions
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250This study investigated the effect of crude Jatropha oil (CJO) blended with C-heavy oil on the 251combustion characteristics of oil-fired boilers. The combustion experiments were conducted using a 252550 kW liquid combustion test facility equipped with a steam atomizing burner. The flame radiation 253intensity, the heat absorption balance of the furnace and the emissions of NOx, SO2, and the particulate 254matter in the 50%CJO + 50% C-heavy oil case were compared with that in the 100% C-heavy oil case. The size distributions of the particles collected from the exhaust gas were also analyzed. The principal 255256findings are as follows.

257

2581. The flame radiation intensity was decreased using CJO blended with C-heavy oil. This was 259considered to be due to the low sooting tendency of CJO. The low sooting tendency of CJO is due to that CJO has no aromatic ring in its molecules and it has higher oxygen content than C-heavy 260261oil.

2622. The heat absorption of the section near the burner was decreased using CJO blended with C-heavy oil. This was caused by the decrease in the flame radiation intensity. The decrease in the flame
radiation intensity is due to the low sooting flame tendency of CJO. As this effect is greater in
actual large scale boilers, careful attention should be paid to the heat absorption balance when
CJO is introduced into large scale boilers at a high blending ratio.

3. The NOx and SO₂ emissions were greatly decreased using CJO blended with C-heavy oil. This
was because the nitrogen and sulfur contents of CJO were significantly lower than that of C-heavy
oil. The SO₂ emission in the 50% CJO + 50% C-heavy oil case was approximately half that of the
100% C-heavy oil case. However, the NOx emission in the 50% CJO + 50% C-heavy oil case was
more than 60% of that in the 100% C-heavy oil case. This was because a portion of the NOx was
formed by the thermal NOx mechanism, and the nitrogen content of fuel did not affect this
mechanism.

4. Both the particulate matter emission and the size of the particulate matter were decreased using
CJO blended with C-heavy oil. This was due to the lower carbon residue in CJO compared to Cheavy oil. The decrease in the particle size was caused by the fact that the cenospheres in the CJO
blending case were broken into small particles because of their high porosity. Hence, careful
attention should be paid to the possibility of a decrease in the particle collection efficiency of the
electrostatic precipitator due to the decrease in particle size when CJO is introduced into oil-fired
thermal power stations.

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Figure and table captions

- Fig. 1. Schematic of liquid fuel combustion test facility.
- Fig. 2. Details of burner.
- Fig. 3. Details of fuel-atomizing nozzle.
- Fig. 4. Direct images of the flame (the same exposure time was used in both cases).
- Fig. 5. Flame radiation intensity.
- Fig. 6. Heat absorption balance of burner and furnace sections.
- Fig. 7. NOx emission.
- Fig. 8. SO₂ emission.
- Fig. 9. Particulate matter emission.
- Fig. 10. Rosin-Rammlar plots for particles collected from exhaust gas.
- Fig. 11. SEM images of particles collected from exhaust gas.
- Table 1 Fuel Properties.
- Table 2 Experimental conditions.