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Combustion Properties of Fuelwood in Hot-Air Heaters

By

Toshimi HIRATA[1] and Yasuo FUKUI[2]

Summary : Following previous studies on hot-water boilers, the combustion properties of fuelwoods of sugi and konara and Ogalite of wood briquette were obtained for two hot-air heaters manufactured for trial. This was to yield basic data for the development and the improvement of household combustion appliances. The furnace of heater I has a maximum capacity of six Ogalite briquettes. Heater II has a smaller furnace, which can contain one Ogalite briquette but has an automatic supplier of Ogalite. Since these heaters produce hot air heated by inner heat exchangers, it is not dangerous to touch the outside surface of the heaters. Both the heaters are highly practical because of sustained production of hot air at a stable temperature, though the hot-air temperature of heater II fluctuated more than that of heater I. The thermal efficiency is higher in heater I than heater II, but the initial heating rate of hot air is larger in heater II than heater I. The emissions of carbon monoxide and smoke are greater in heater II than heater I, but these emissions are considerably less than those from previously reported hot-water boilers. The initial rising rate of the hot-air temperature and the emission of carbon monoxide with sugi are the largest. The initial rising rate of the hot-air temperature with Ogalite is the smallest due to the smallest combustion rate, and Ogalite is appropriate for heating for long time. Konara showed, for the most part, intermediate properties between sugi and Ogalite, but the emission of nitrogen oxide from konara is the largest. The thermal efficiency and the emission of nitrogen oxide generally increased with increases in exhaust temperature. However, excessively high exhaust temperature made the thermal efficiency lower. Therefore, a mechanism to control combustion, depending on exhaust temperature, should be developed for the future.

1. Introduction

Potential combustion heat per unit volume of wood is generally equivalent to one fourth to one sixth of that of fossil fuels, such as petroleum and coal. This can be shown by comparing the specific gravity and the calorific value of wood and the fossilfuels. Wood's smaller combustion heat creates some disadvantages for the transportation and design of furnaces using its solid state. Furthermore the solid shape makes exact control of the combustion rate difficult. We have long used charcoal, which has high calorific values, and controlled the combustion rate. Now gasification and liquefaction of wood have been studied on the basis of the pyrolysis to solve those difficulties.

On the other hand, processes using direct combustion of wood for industrial and household appliances are spreading since the rapid increase in oil prices. In spite of wider use, few research papers about the direct combustion of wood in household appliances have been published. It is necessary to develop household appliances more suitable to the combustion of wood for more effective use of fuelwood. Following previous papers on hot-water boilers[1)2)], this paper describes combustion properties of the same sorts of fuelwood in the most popular hot-air

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heaters. The aim was to obtain basic data for the development and improvement of household combustion appliances.

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2. Experimental

2. 1 Fuels

The same fuels used in the previous studies[1)2)], namely, woods of Konara (*Quercus serrata* THUNB.) and Sugi (*Chryptomeria japonica* D. DON), and Ogalite of wood briquette produced in Japan, were used for comparison among the studies. They had been kept at a constant temperature and humidity of 19°C and 42 r. h. %, respectively, for one year. The length of konara and sugi woods in strage was about 30 cm, and that of Ogalite was about 40 cm. The shapes, and the average values of the moisture content, the calorific value, and the specific gravity of these fuels at time of use are listed in Table 1. The lower calorific value in the table was obtained according to the well known equation,

$$H_l = \frac{H_h - 600(9h + \mathrm{MC})}{1 + \mathrm{MC}} \qquad \cdots\cdots (1)$$

where H_l is the lower calorific value, H_h the higher calorific value in the oven-dry condition, h the hydrogen content which was assumed to be 6%[3)] in the present study, and MC the moisture content on a dry weight basis.

2. 2 Hot-air heaters

Two sorts of heaters were used in the study. Both were manufactured for trial as household appliances by Rocket Boiler, Inc. of Tsuchiura, Japan, and Isolite Juki, Inc. of Osaka, Japan. These heaters were designed for combustion of Ogalite, but fuelwoods other than Ogalite can be used in them. They are shown in Figs. 1 and 2.

Heater I in Fig. 1 is about 68 cm high, 81 cm wide, and 38 cm deep. To supply fuelwood to the furnace the front lid, which has the hot-air outlet, must be removed and then put back in its place after igniting the fuelwood. The furnace has a maximum capacity of six Ogalite briquettes. During combustion it is not dangerous to directly touch the outside of the heater due to insulation applied to the inside face of the furnace. Air for combustion is automatically supplied by an electric fan, with a controlled rate, from the top of the furnace. The rate at

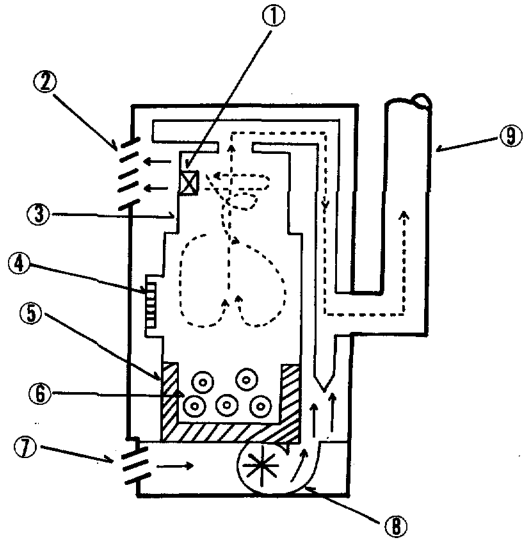
Table 1. Fuels used in the study.

Fuels	Shape at the use	MC*1 (%)	H_h*2 (kcal/kg)	H_l*3 (kcal/kg)	r*4
Ogalite	About 20 cm long and 5.5 cm diametrical octagonal column with about 2 cm diametrical empty cylinder at the center	6. 6	4, 839*5	4, 198	1. 1～1. 3[4)]
Sugi	Rectangular parallelepiped, about 30 × 3 × 3 cm	8. 7	4, 960*6	4, 217	0. 3～0. 35[4)]
Konara	Logs or split ones, the approximate mean size, 30 × 3 cm	10. 7	4, 562*6	3, 770	0. 62[4)]

*1 MC is the moisture content based on oven-dry weight, *2 H_h the higher calorific value at the oven-dry condition, *3 H_l the lower calorific value, *4 r the specific gravity in oven dry[4)], *5 the value was determined by means of Shimadzu Bomb Calorimeter CA-3, and *6 the values were cited from SATONAKA[5)].

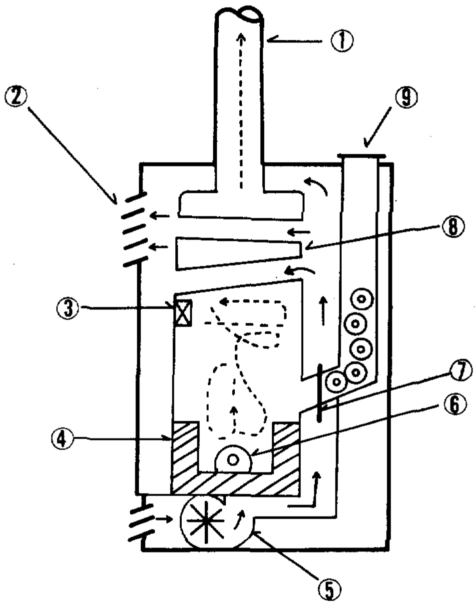
which air is supplied can be changed with the rotation number of the fan, but all the runs in this study were conducted at a constant rate of supply. The hot air is expelled from the heater with a constant velocity. Air in the room is introduced into the heat exchanger through an opening in the bottom of the heater, heated there, and sent back to the room as hot air by an electric fan.

Heater II in Fig. 2 has a mechanism for automatically supplying fuelwood into the furnace.



① Blowed air inlet into furnace
② Hot-air outlet
③ Heat exchanger
④ Observation window
⑤ Heat insulating grate (non-combustible)
⑥ Fuelwood
⑦ Air inlet
⑧ Blower
⑨ Smokestack

Fig. 1. Schematic diagram of heater I.



① Smokestack
② Hot-air outlet
③ Blowed air inlet into furnace
④ Heat insulating grate (non-combustible)
⑤ Blower
⑥ Fuelwood
⑦ Gate for fuelwood supply
⑧ Heat exchanger
⑨ Fuelwood reservoir

Fig. 2. Schematic diagram of heater II.

Ogalite, which is piled in a line in the fuel reservoir within the heater, is automatically fed one-by-one to the furnace depending on the hot-air temperature. Air for combustion is drown into the furnace from the top with an electric fan in a way similar to that of heater I. Air in the room is introduced through an opening under the furnace, heated in the heat exchanger, and returned to the room as hot air. At its lower temperature, the hot air is expelled by one electric fan, and by two fans at its higher temperature. The furnace can be cleaned through an ash door on the side face. Heater II is about 78 cm high, 85 cm wide, and 46 cm deep, and somewhat larger than heater I. Also heater II is not dangerous for touching directly with hands and so forth.

Smooth ignition is necessary for good reproducibility of the combustion of the fuelwoods. Therefore, bits of fuelwood, which absorbed kerosene with immersion, were placed on a fuelwood pile within the furnace and then ignited with matches. The amount of absorbed kerosene ranged from 10 to 30 g, depending on the type of fuelwood.

2. 3 **Measurements**

2. 3. 1 Temperature and velocity of hot air and thermal efficiency

A wooden duct was closely inserted the heaters' hot-air outlet to minimize turbulence in the hot-air flow for determination of its velocity. The inner sizes of the ducts are 150 cm long, 70 cm wide, and 9 cm high for heater I, and 150 cm long, 47 cm wide, and 12 cm high for heater II. A velocity distribution was obtained by measuring velocities on the centers of small squares or rectangles which were given by dividing an opening section of a duct with a 4 or 5 cm distance in both sides of the width and of the height. The velocities were measured with a hot-wire anemometer, the KANOMAX Anemomaster 1000 (Nippon Kagaku Kogyo, Inc., Osaka). From the velocity distribution, average velocities of heater I and II were respectively calculated to be 1.70 m/s, and 0.77 m/s with one fan and 1.12 m/s with two fans. Average hot-air flow rates were obtained from the opening areas of the ducts and these mean values.

Temperatures of hot air in the outlets and supplied air in the inlets of the heaters were measured with copper-constantan thermocouples. By integrating the difference between these two temperatures for the combustion duration, total heat obtained in the hot air was determined with the average flow rate, and the assumed values of 1.16 J/(g·°C) of the specific heat and of 1.093 g/l of the density of the hot air at 50°C of the temperature. The total heat divided by the amount of the consumed fuel is called the obtained heat here. The ratio of the obtained heat against the lower calorific value was calculated as the thermal efficiency.

2. 3. 2 Temperatures within the furnace and of the exhaust

To obtain information about the combustion behaviors, the temperature of the exhaust and temperature within the furnaces were measured by using chromel-almel thermocouples. The temperature of the exhaust for both the heaters was measured at about 10 cm above the smokestack base in the center of the smokestack. The furnace temperatures of heater I and II were measured at an upper or side portion within the furnaces, respectively.

2. 3. 3 Emissions of gases and smoke

With the flow rate of about 1 l/min, a part of the exhaust was first introduced from the smokestack into a photometer, as shown in Fig. 3, and the concentration of the emitted smoke was determined as the optical density D, expressed as

$$D=\frac{1}{L}\log\frac{I_0}{I} \qquad \cdots\cdots(2)$$

where L is the light path length in the photometer, I_0 and I the illumination intensities before

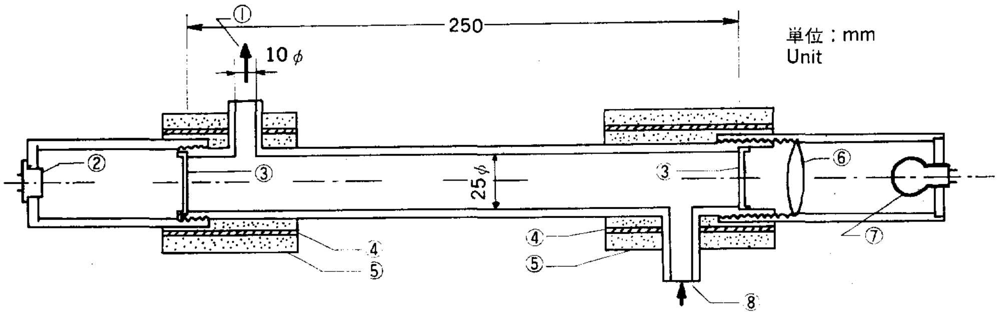


Fig. 3. Photometer for measuring smoke density.
① Smoke outlet, ② Light receptor, ③ Glass plate, ④ Heating wire, ⑤ Heat insulating glass fiber, ⑥ Lens, ⑦ Incandescent lamp, ⑧ Smoke inlet.

and during the combustion. This method was cited from the Japanese Industrial Standard (JIS) A 1321-1975. Furthermore, the exhaust flow passing through the photometer was sent into a Shimadzu Infrared Gas Analyzer URA-2S to measure the concentrations of carbon monoxide and carbon dioxide. and then into a Shimadzu Magnetic Oxygen Analyzer MAGNOS-2 to measure the concentration difference of oxygen between the exhaust and the atmosphere, and was finally released into the atmosphere.

On the other hand, with the flow rate of about 3 l/min, a part of the exhaust was first introduced from the smokestack into Fuji Electric Infrared Gas Analyzer ULTRAMAT-S ZAL to measure the total amount of two concentrations of nitrogen monoxide and nitrogen dioxide, and the concentration of sulfur dioxide, respectively. The exhaust introduced into the Shimadzu and Fuji Electric systems was dehydrated by magnesium perchlorate before the measurements.

It is difficult to obtain absolute amounts of these gases from the measured concentration. The gas concentrations were measured under the above constant flow rates while the flow rate of the actual exhaust did not remain constant due to change in the combustion rate with time. In addition, nitrogen dioxide and sulfur dioxide would be somewhat condensed in the paths to the analyzers. However, values of the concentrations integrated for the combustion times per unit weight of fuel consumption were calculated after the manner of the previous studies[1)6)], and assumed to be proportional to the actual amounts of these gases.

3. Results and Discussion

3. 1 Temperature of hot air

The changes in the temperature of the hot air generated from heater I and II are respectively shown by representative examples in Figs. 4 and 5. In heater I, in Fig. 4, the fuelwood was supplied only one time at the beginning of the run, while in heater II, in Fig. 5, the fuelwood was supplied two or three times including one before the ignition. It is found from comparison between Figs. 4 and 5 that heater I generated hot air more stable in temperature than heater II. The fuel capacity of the furnace of heater II is about one fifth or sixth of that of heater I. It was necessary several times to supply fuels to the furnace of heater II for sustained generation of hot air. Therefore, the temperature of hot air from heater II changed greatly for every supply of the fuels, as compared with heater I.

It is seen also in these figures that the initial elevation rates of the hot-air temperature

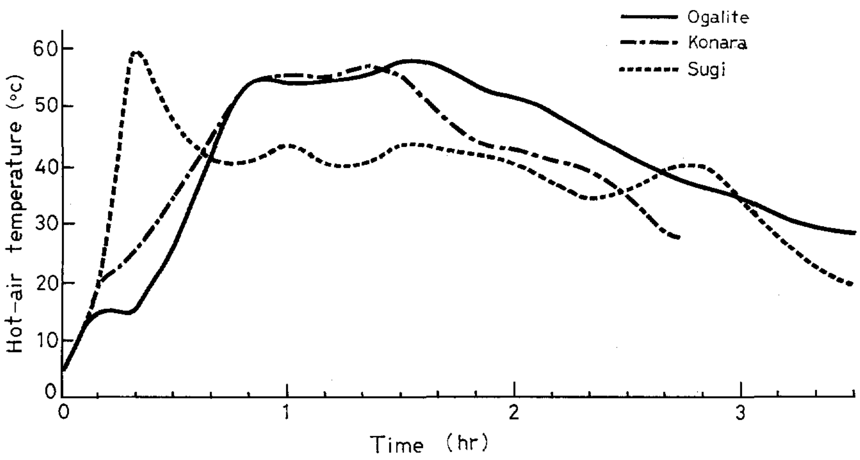


Fig. 4. Temperature of hot air from heater I.
Consumptions of Ogalite : 6,285 g, of Sugi : 5,239 g, and of Konara : 6,060 g.

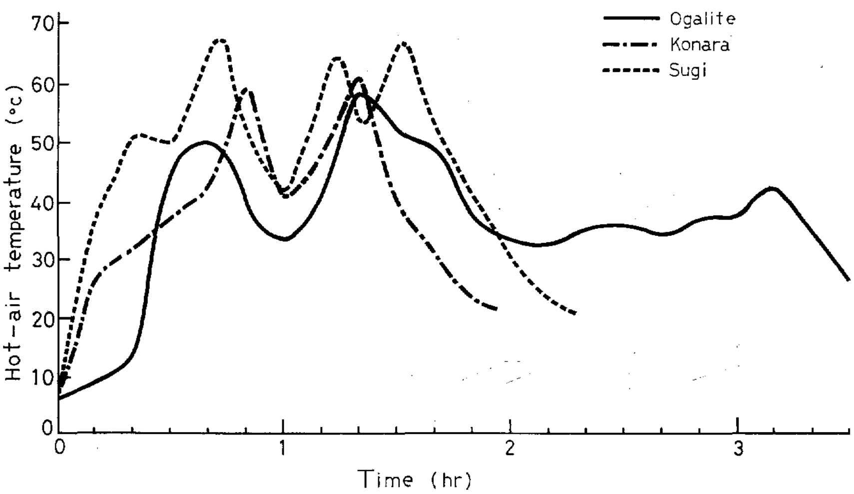


Fig. 5. Temperature of hot air from heater II.
Consumptions of Ogalite : 2,346 g, of Sugi : 2,878 g, and of Konara : 2,410 g.

of both the heaters is greatest for the combustion of sugi and smallest for Ogalite. Stable combustion of the fuels was usually established after the hot-air temperature rose over 37°C. Therefore, the initial combustion time until the temperature of the hot air rose to 37°C was one of indicators for evaluating the practicalities of the heaters. The mean values of these initial combustion times to 37°C are listed in Table 2. From the table the initial heating properties of sugi and of Ogalite are found to be the best and worst, respectively. Moreover, the initial heating property of heater II is seen to be better than that of heater I.

The initial heating property may be interpreted as depending on the pyrolysis rates of the fuels. The specific heat of oven-dry wood was found to be practically independent of species and is expressed as 1.113 J/g at 0°C[7]. The differences in specific heat among the present fuels is easily estimated to be less than 10% by using the specific heat of this value and of water.

Therefore, the heat capacity per unit volume of Ogalite is conjectured to be larger than those of other fuels, and that of konara is probably larger than that of sugi from the specific gravity in Table 1. The larger this heat capacity of the fuels, the later the rise in the temperature, especially in the inner part of them. For the reason of large temperature dependency, namely, many reported high values of Arrhenius activation energy of the overall pyrolysis of wood, probably sugi was most easily pyrolyzed and Ogalite most slowly pyrolyzed of all the fuels. This interpretation of the initial heating property as dependent on the pyrolysis rate, which was controlled not by the chemical property but by the physical property of the fuels, agrees with results by Akita[8]. He has shown ignition time of woods to increase with the specific gravity.

3. 2 Thermal efficiency, obtained heat, and temperatures within the furnace and of the exhaust

The mean values of the thermal efficiencies and of the obtained heats calculated from individual runs are listed in Table 2. It is found from the table that the thermal efficiency of heater I differes slightly among the fuels, while that of heater II shows the large difference of about 12% between the largest value for sugi and the smallest one for konara. On the other hand, for the obtained heat per unit weight of the consumed fuel of both the heaters, sugi gave the largest value and konara the smallest. These values for thermal efficiency are generally larger than previously reported for a quick heating hot-water boiler[1] and smaller than reported for a hot-water storage boiler[2]. The values of obtained heat for the most part are larger than corresponding values of the two boilers, probably because of the lower moisture contents of the present fuels, except Ogalite, compared with ones in the previous studies.

The mean values of the maximum temperature within the furnace of heater I are higher than 700°C for all the fuels, while in heater II only one given by konara of the corresponding values rose over 700°C, as shown in Table 2. In heater I sugi and Ogalite gave respectively the highest and the lowest mean value for the maximum furnace temperature, agreeing with previous results with hot-water boilers[1)2]. The insulating material, Kaowool (produced by Isolite Juki, Inc., Osaka), which is applied to the inside faces of the furnaces of the two heaters, can be used continuously at temperature up to 1,100°C and for a moment at 1,260°C. Hence, these values for the maximum temperature suggest good maintenance of the applied insulating material.

The mean values of the maximum exhaust temperature of heater II are considerably higher than those of heater I, as shown in Table 2. The largest mean value of the exhaust

Table 2. Mean values of initial combustion time to 37°C of hot air, of thermal efficiency, of obtained heat, and of maximum temperatures within furnace and of exhaust.

Measurements \ Heater / Fuel		I			II	
		Ogalite	Konara	Sugi	Ogalite	Konara	Sugi
Time to 37°C	(min)	41	15	11	17	10	7
Thermal efficiency	(%)	43.8	45.8	45.6	39.9	32.9	44.7
Obtained heat	(cal/g)	2,302	2,169	2,378	2,132	1,578	2,483
Furnace temperature	(°C)	709	739	752	501	790	514
Exhaust temperature	(°C)	221	248	228	412	436	383

temperature was given by konara in both heaters. The flaming combustion of konara has been shown to be the strongest in previous studies on hot-water boilers[1)2)]. Also in the present study the highest mean value of this temperature for konara is considered to indicate the point of most active flaming combustion of all the fuels.

3. 3 Effects of exhaust temperature and fuel amount on thermal efficiency and obtained heat

It is interesting that the thermal efficiency of heater I slightly increased with the increase in the maximum exhaust temperature, while the efficiency of heater II decreased with the increase in the maximum exhaust temperature, as shown in Table 2. Furthermore, the maximum exhaust temperatures of heater I range from 221 to 248°C, and those of heater II from 383 to 436°C. The exhaust temperature is interpreted as rising with the growth of the flaming zone. From the above observations the thermal efficiency of hater I seems mainly to depend upon the growth of the flaming zone, but that of heater II seems mostly determined by heat loss through high temperature exhaust.

Excessively active flaming combustion would increase heat lost into the atmosphere, but too small a flaming zone would make the heat exchanger work unsatisfactorily. In order to check on this estimation, the relationships between the thermal efficiency and the maximum exhaust temperature as an indicator of degree of the flaming combustion are shown in Figs. 6—8 for heater I and Fig. 9 for heater II. For Ogalite, in Fig. 6, the thermal efficiency has an obvious tendency to increase with increases in the maximum exhaust temperature in the whole range studied. For konara and sugi the efficiencies increased with the maximum exhaust temperature in its lower range, and in its higher range they decreased with the increase in this temperature. The maxima of the efficiency are shown in the temperature range 240 to 270°C, but the maximum for konara seems to be presented in a little higher range than for sugi, from a comparison between Figs. 7 and 8. Concerning heater II in Fig. 9, although it may involve some uncertainty to derive the following observations from the small number of the plots, the maxima of the efficiencies are found in the ranges 390 to 400°C for Ogalite and 370 to 380°C for sugi. However, such a maximum for konara cannot be found in the figure.

The thermal efficiency is thought to have been affected also by the flow rate of the exhaust, in addition to the temperature. As stated above, the pyrolysis rate and then the combustion rate may generally decrease with the increase in the specific gravity of the fuels. The flow rate of the exhaust properly increases with the pyrolysis rate. Therefore, the smaller the specific gravity, the larger the rate of heat loss with the atmosphere due to exhaust results at the constant temperature. This suggests that in fuel of smaller specific gravity the minimum effect of the heat loss on the thermal efficiency should be found at the lower maximum exhaust temperature, as shown as maxima in Figs. 7—9. It is thought from this suggestion that the probable maximum thermal efficiency for Ogalite in Fig. 6 is at a higher temperature than for konara, which may be out of the range studied. Furthermore, the corresponding maximum for konara in Fig. 9 is estimated to lie between those for sugi and Ogalite. The thus observed and estimeted optimum maximum exhaust temperatures for the highest thermal efficiency are listed in Table 3.

For heater I, which is not equipped with an automatic fuel feeder, the runs were carried out at three levels of the fuel supply, namely, about 2.4, 4.4, and 6.4 kg (5.4 kg for sugi), to investigate the effects of the amount of fuel. These levels correspond to about one fourth, one half, and two thirds of furnace capacity, respectively. The runs were usually completed with the hot-air temperature was lowered under 30°C. At all levels the thermal efficiency is

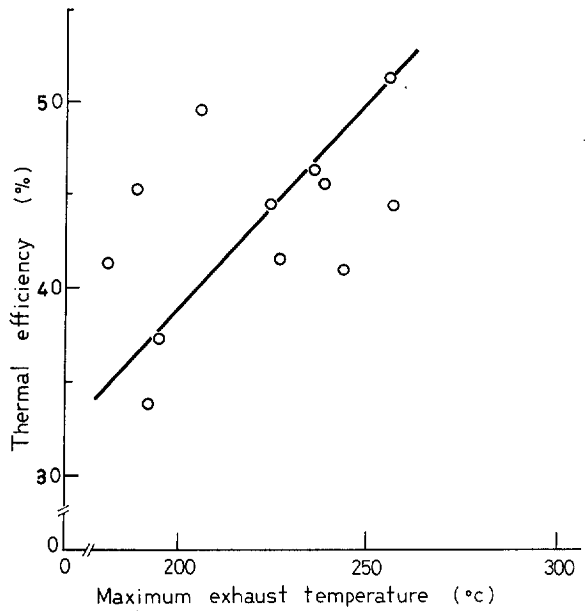


Fig. 6. Dependency of thermal efficiency on exhaust temperature for combustion of Ogalite in heater I.

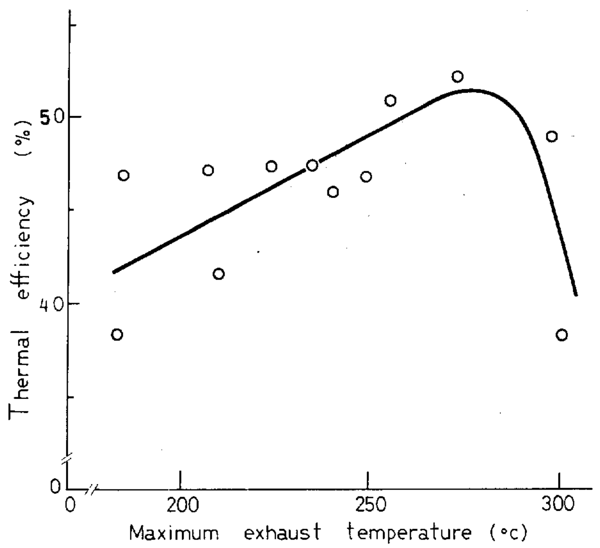


Fig. 7. Dependency of thermal efficiency on exhaust temperature for combustion of Konara in heater I.

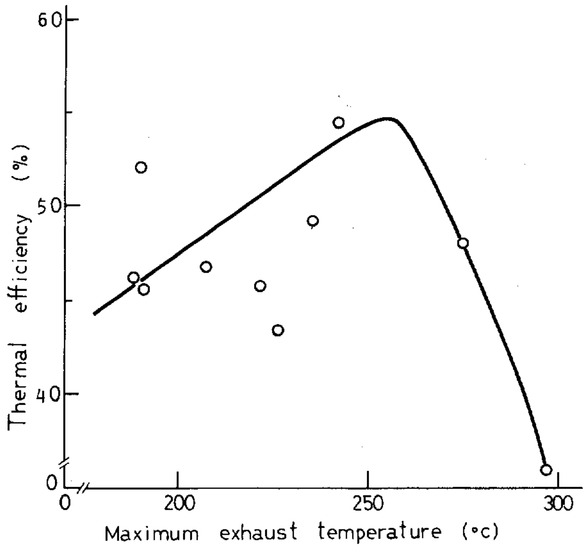


Fig. 8. Dependency of thermal efficiency on exhaust temperature for combustion of Sugi in heater I.

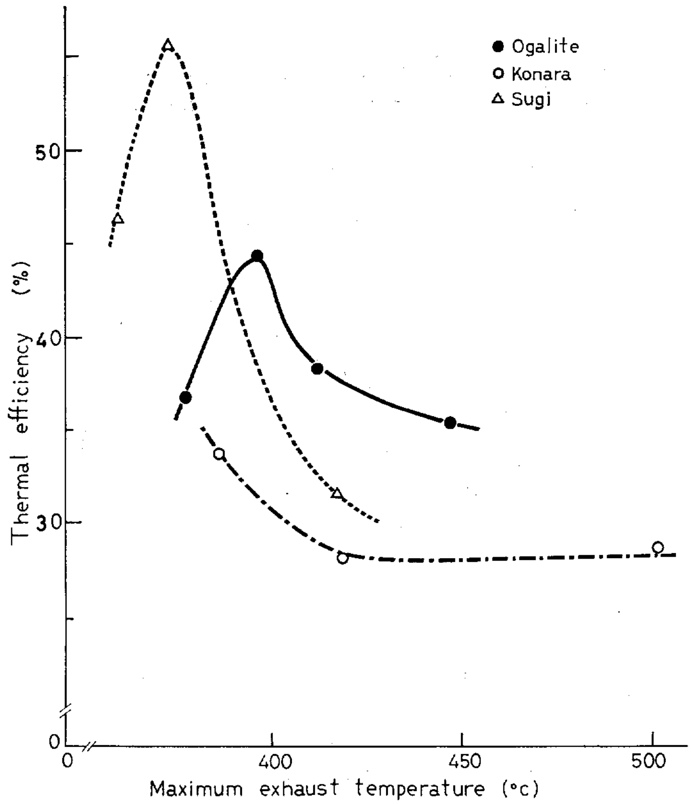


Fig. 9. Dependency of thermal efficiency on exhaust temperature for heater II.

Table 3. Optimum conditions of combustion for thermal efficiency.

Conditions \ Heater / Fuel	I			II		
	Ogalite	Konara	Sugi	Ogalite	Konara	Sugi
Maximum exhaust temperature (°C)	Higher than 270	260 to 270	250 to 260	390 to 400	(380 to 390) ?	370 to 380
Amount of fuel supply (kg)	Above 6	About 4	Under 2	—	—	—

Table 4. Linear regression functions between thermal efficiency and fuel consumption in heater I.

Fuel supply level (kg)	$Y(\%)^{*1} = a$	$X(g)^{*2} + b(\%)$	r^{*3}
2.4	0.038	−38.4	0.907**
3.4	0.0037	31.0	0.269
6.4	0.013	−32.3	0.695*

*1 Y is the thermal efficiency, *2 X the fuel consumption, and *3 r the co-efficients of correlation, where the values marked with ** and * are significant with the 1 and 5% levels of significance in the test of hypothesis, respectively.

found to increase with the consumption of the fuels, as shown in Fig. 10, where this tendency is expressed with three lines by the linear regression. The regression functions are shown in Table 4. The statistical results in the table show that the dependence of the thermal efficiency on the fuel consumption is large at the lower and higher levels of the fuel supply, but that at the middle level this dependence is small and cannot be judged to be significant at the 10% level. It is noted for the design of a furnace that the dependence of the thermal efficiency on fuel consumption changes with the amount of fuel supplied.

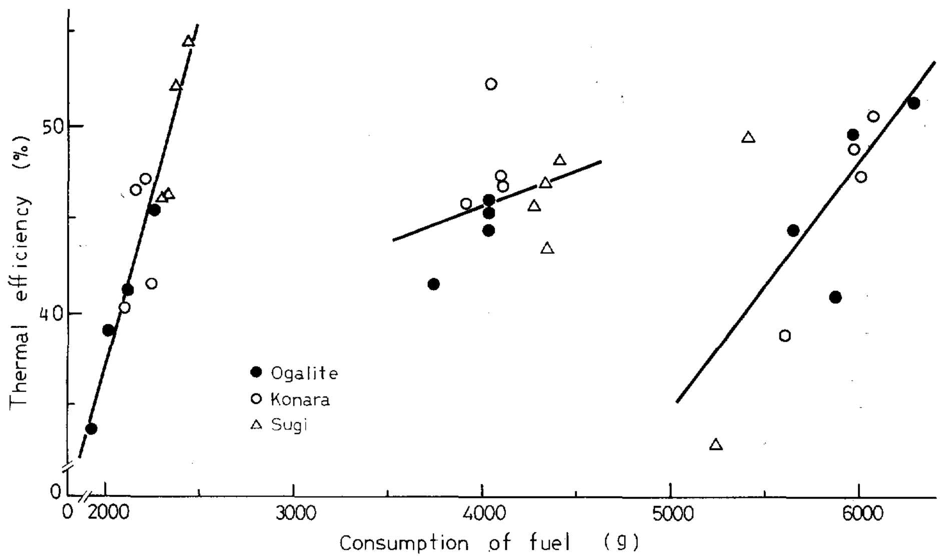


Fig. 10. Changes in fuel-consumption dependency of thermal efficiency with three fuel supply levels.

The mean values of the obtained heat per unit fuel consumption were calculated for each supply level, and the changes in the mean values with the amount of fuel supplied are shown in Fig. 11. Except for the highest fuel supply level, the largest obtained heat and the smallest one were respectively given by sugi and konara. Furthermore, the optimum fuel supply level for the largest obtained heat and then the highest thermal efficiency is suggested for each fuel from the figure. It is noted that this optimum fuel supply level rose with the specific gravity of the fuel.

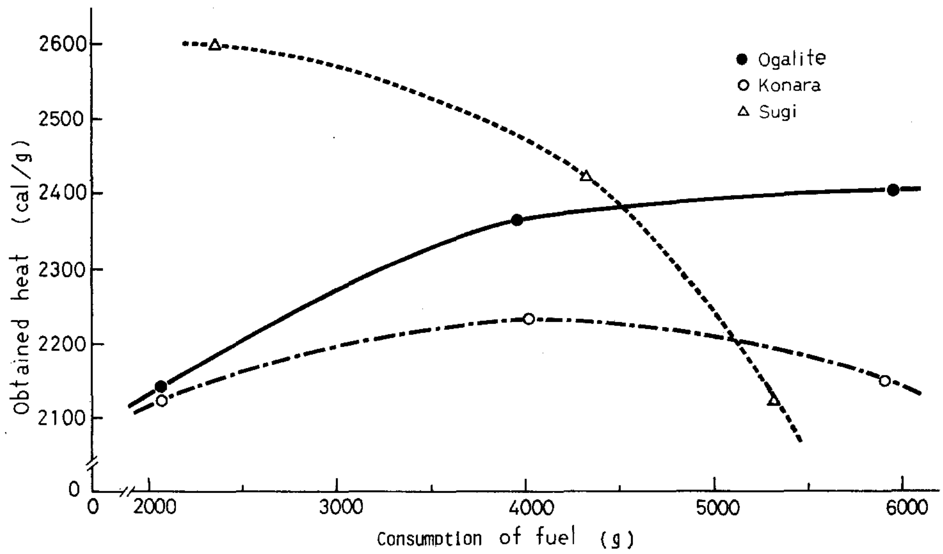


Fig. 11. Changes in obtained heat with fuel supply amount.

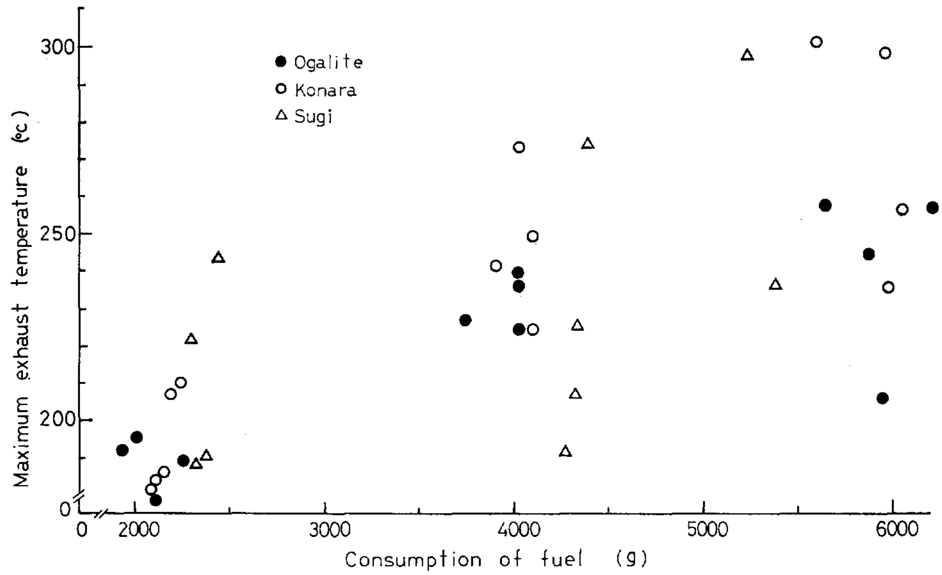


Fig. 12. Plots of fuel consumption vs. maximum exhaust temperature in heater I.

The maximum exhaust temperature generally rose with the fuel amount, as shown in Fig. 12. The rise in the exhaust temperature not only raises the efficiency of the heat exchanger but also increases the heat lost by the exhaust. For fuelwood of the higher specific gravity, such as Ogalite, the rise in the exhaust temperature may have more contribution to heat exchange than to the heat loss in the studied range. But for sugi of the lower specific gravity, if this rise is high, it may increase the heat loss rather than the heat exchange.

Also the optimum fuel supply amounts for the highest thermal efficiency are listed in Table 3, where the optimum combustion conditions are found to differ considerably among the fuels. Therefore, a hot-air heater must be designed to suit the different optimum conditions of various fuelwoods.

3. 4 **Emissions of gases and smoke**

Mean values of the maximum concentrations of gases and smoke, and of the maximum differences in concentrations of oxygen between the exhaust and the atmosphere are listed in Table 5. Furthermore, mean values of the integrated concentrations per unit fuel consumption are listed as the emissions of the gases and the smoke, and the oxygen consumption in the same table.

For both the heaters the maximum concentration of carbon monoxide is the highest in the combustion of konara and the lowest in Ogalite, while the emission of this gas is the largest in sugi and the smallest in Ogalite, as shown in the table. In addition, heater II emitted more carbon monoxide than heater I. The emissions from the heaters are considerably smaller than the 2,000 to 8,000 ppm·min·g^{-1} from the previously reported hot-water boilers[1)2)].

The emission of carbon dioxide and the consumption of oxygen depend on the efficiency of the combustion. These two quantities should increase with the growth of the flaming combustion. From Table 5 the emission of carbon dioxide and the consumption of oxygen are found to be larger in heater II than in heater I. For both the heaters the differences of the two quantities among the fuels are small. Since air for combustion was sent into the furnaces

Table 5. Mean values of emissions of gases and smoke, and oxygen consumption.

Gas	Heater / Fuel	I Ogalite	I Konara	I Sugi	II Ogalite	II Konara	II Sugi
CO	Maximum (ppm)*1	4, 371	6, 465	5, 277	11, 876	16, 581	14, 150
	Total(ppm·min·g^{-1})*2	52	75	113	209	284	320
CO_2	Maximum (%)	3. 2	3. 8	3. 3	8. 4	10. 3	6. 0
	Total(%·min·g^{-1})	0. 059	0. 061	0. 061	0. 26	0. 23	0. 25
O_2	Maximum (%)	4. 2	5. 2	4. 8	12. 3	13. 7	10. 4
	Total(%·min·g^{-1})	0. 095	0. 097	0. 110	0. 36	0. 38	0. 31
SO_2	Maximum (ppm)	18	32	21	55	86	45
	Total(ppm·min·g^{-1})	0. 31	0. 61	0. 68	1. 91	1. 56	1. 46
NOx	Maximum (ppm)	29	86	25	56	139	57
	Total(ppm·min·g^{-1})	0. 25	1. 17	0. 40	1. 41	3. 86	1. 35
Smoke density	Maximum (m^{-1})	0. 17	0. 24	0. 31	0. 72	0. 65	0. 65
	Total (m^{-1}·min·g^{-1})	0. 0082	0. 0057	0. 0055	0. 039	0. 021	0. 031

*1 For all the gases and the smoke, the maximum means the maximum concentration (for O_2 the maximum concentration difference between the exhaust and the atmosphere), and *2 the total means the emission or consumption per unit consumption of the fuel.

at constant rates, the combustion would proceed at a constant rate in comparison with furnaces without fans. Therefore, it is not thought that the overall growth of the flaming combustion was very different among the fuels.

For the maximum concentration of sulfur dioxide, konara gave the highest values in both heaters. For the emission of this gas, however, sugi and Ogalite gave the largest value in heater I and Heater II, respectively, as shown in Table 5. Sulfur dioxide is a pollutant in its own right, and also can combine with rain to form dilute sulfurous acid. The average sulfur content of wood is 0.013%[9], and can be calculated to be less than two hundredths and one hundredth of those of coal[9] and of crud oil[10], respectively. Therefore, the emission of sulfur dioxide from wood is not thought to have as important an environment impact as other fuels.

For smoke emission, Ogalite gave the largest values in both heaters. In heater I, however, Ogalite gave the lowest value of all the maximum concentrations, as shown in Table 5. This may be caused by Ogalite's relatively lowest combustion rate. The smoke emission in heater II is larger than in heater I, but even the emission in heater II is considerably smaller than the above-mentioned boilers.

3. 5 **Emission of nitrogen oxide**

Both the maximum concentration and emission for konara are remarkably greater than those for the other fuels, as shown in Table 5. Emission of nitrogen oxide (NOx) from combustion generally refers to nitrogen in the fuel and in the air. Nitrogen oxide from the former source is called fuel NOx and that from the latter is called thermal NOx. The emission of the thermal NOx increases with the temperature of the combustion.

The remarkably high emission of this gas from konara may be attributable to the fuel NOx. Nitrogen content of a tree differs considerably among the species[11)~14)]. Most of the reported values[11)~16)] are less than 1%. Oak has been reported by NIKITIN[11] to be one of the woods with the highest nitrogen content, and the bark has been found to contain twice nitrogen as much as pine bark[15]. Thus, the present fuel, konara with its bark, contains more nitrogen than the other fuels.

The emission of the thermal NOx is thought to increase with the growth of the flaming combustion. For each fuel, plots were made of the maximum concentration of nitrogen oxide against the maximum exhaust temperature, as shown in Figs. 13—15. These figures show that the maximum concentration of emitted nitrogen oxide generally increases with the rise in the maximum exhaust temperature. Regression lines between these two quantities were determined, as shown by the solid lines in the figures. The corresponding linear regression functions are given in Table 6. The emission of nitrogen oxide from konara has a prominently higher dependency on the exhaust temperature than those of the other fuels, as shown in the table. The coefficients of correlation for konara and sugi are both highly significant, while that for

Table 6. Linear regression functions between maximum concentration of NOx and maximum exhaust temperature.

Fuel	Y(ppm)*1 = a	X(℃)*2 + b(ppm)	r
Ogalite	0.14	− 2.5	0.468
Konara	0.51	−37.3	0.740**
Sugi	0.11	− 1.0	0.699*

*1 Y is the maximum concentration NOx and *2 X the maximum exhaust temperature.

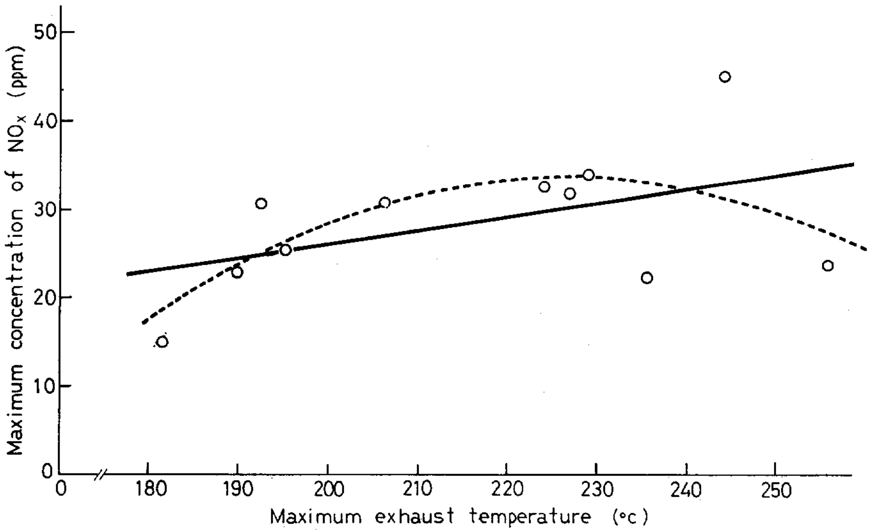


Fig. 13 Relationship between maximum concentration of NOx and maximum exhaust temperature for Ogalite in heater I.

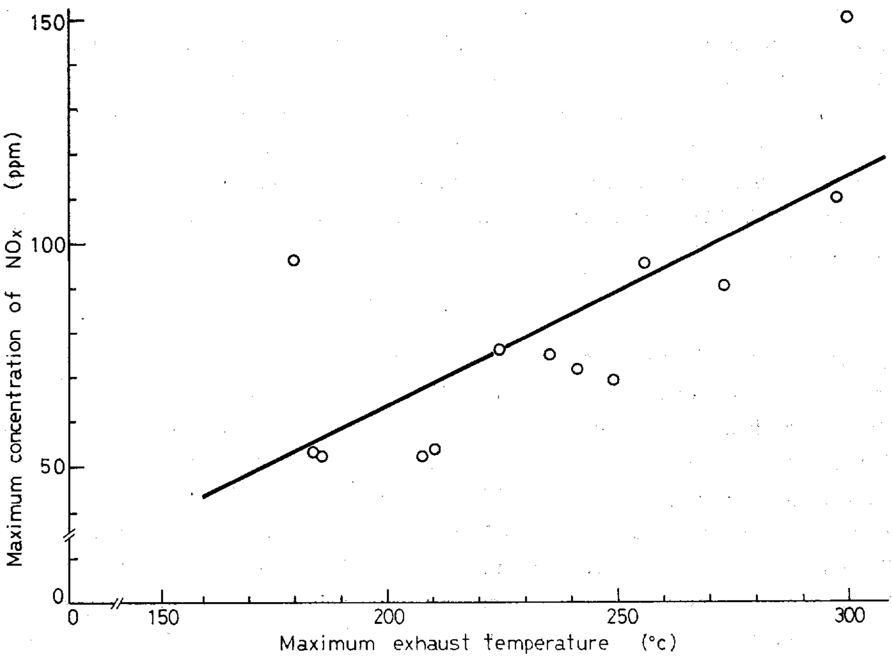


Fig. 14. Relationship between maximum concentration of NOx and maximum exhaust temperature for konara in heater I.

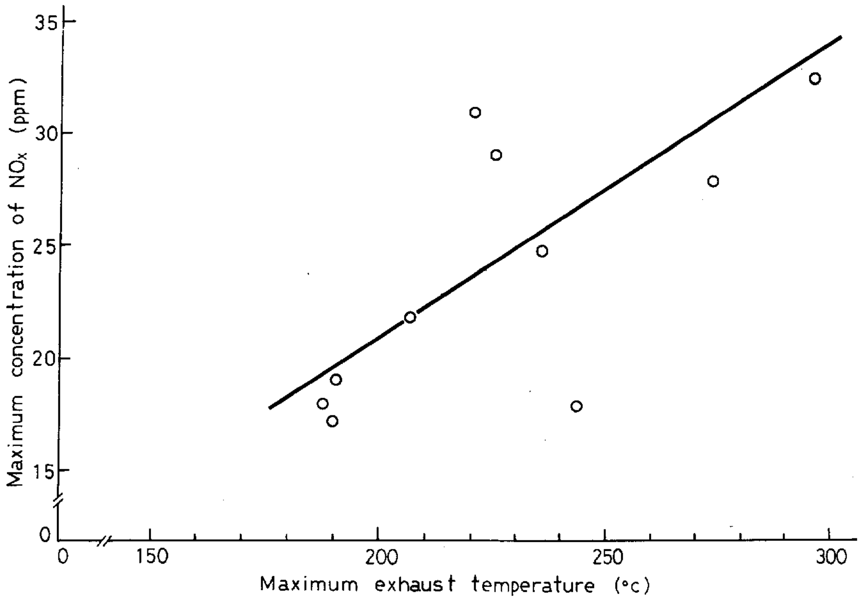


Fig. 15. Relationship between maximum concentration of NOx and maximum exhaust temperature for sugi in heater I.

Ogalite lies within the acceptance region, also seen in the same table. The relation between the maximum concentration of nitrogen oxide and the maximum exhaust temperature for Ogalite may more correctly be expressed by a polynomial regression curve rather than the straight line, as shown by a broken line in Fig. 13. The corresponding function is

$$Y = -345.8(\mathrm{ppm}) + 3.34(\mathrm{ppm/^\circ C}) \cdot X - 0.0074(\mathrm{ppm/^\circ C^2}) \cdot X^2 \cdots\cdots\cdots (3)$$

where Y is the maximum concentration of nitrogen oxide in ppm and X the maximum exhaust temperature in °C. The correlation coefficient for Ogalite was calculated to be small, probably for this reason.

4. Conclusions

1) Two household hot-air heaters, which were manufactured for trial, yielded hot air at a considerably stable temperature for a long time, by burning wood of sugi and konara, and Ogalite of wood briquettes. Therefore, both heaters are judged to be highly practicable.

For heater I the mean thermal efficieny is almost equal among the fuels, while for heater II that of sugi is the largest and that of konara the smallest. The initial rising rate of hot-air temperature is the largest in the combustion of sugi and the smallest in Ogalite.

2) For both the heaters, generally, the thermal efficiency increased with increases in the maximum exhaust temperature, due to increases in efficiency of the heat exchange. Too high an exhaust temperature, however, made the thermal efficiency lower because of increased heat loss into the atmosphere. Furthermore, the optimum fuel amount for obtaining the highest thermal efficiency of heater I was found to be different among the fuels used. Therefore, from consideration of thermal efficiency, combustion conditions should be different among fuelwoods.

3) For both heaters the emission of carbon monoxide from sugi is the largest and that

from Ogalite the smallest. But the smoke emission from Ogalite is larger than those of sugi and konara, despite Ogalite having the lowest value of the maximum concentration of all the fuels. These two emissions, however, are considerably smaller than those for the previously studied hot-water boilers.

4) Sulfur dioxide was produced from the combustion of the fuelwoods, but the emission is not considered serious in comparison with that from coal and petroleum. The emission of nitrogen oxide from konara is remarkably greater than from the other fuels in both heaters. This may be attributed to the high nitrogen content of konara. In general the maximum concentration of nitrogen oxide increased with the maximum exhaust temperature because of the increase in the thermal NOx.

5) For the future a control system for combustion of fuelwood needs to be developed to obtain reasonable exhaust temperature, and consequently high thermal efficiency and the suppression of the emission of nitrogen oxide.

Furthermore, it is desirable to use sugi and konara in the initial heating for a rapid rise in hot-air temperature, and then to use Ogalite for sustained heating with fewer fuel-supply problems.

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温風暖房機における木質燃料の燃焼特性

平 田 利 美[1]・福 井 康 夫[2]

摘 要

小型燃焼器具の改良，開発に資するため，本研究では既報の温水ボイラーの燃焼試験に続き，温風暖房機における木質燃料の燃焼特性を求めた。

使われた試作の2機種は，木質燃料を用いるものとしては，初めての本格的な温風暖房機である。両機種の主な相違は，暖房機Ⅰがオガライトを最高6本収容出来る大きな燃焼炉を有し，燃料の中途補給が不可能なのに対し，暖房機Ⅱはオガライトを1本収容可能な炉を有し，温風温度に応じてオガライトを1本ずつ自動供給する機構を備えている点にある。燃料として，スギ，コナラ，およびオガライトを用いた。

暖房機Ⅱの温風温度は暖房機Ⅰより変動するが，実用性を損なうほどではない。しかし，温風の初期昇温速度は暖房機Ⅱの方が大きい。暖房機Ⅱは熱効率では暖房機Ⅰより小さく，煙と一酸化炭素の発生量は暖房機Ⅰより多いが，既報の温水ボイラーよりは少ない。両機種に共通した各燃料の特性を示すと次のとおりである。スギでは温風の初期昇温速度は大きいが，一酸化炭素発生量も多い。オガライトでは燃焼速度が小さいため，温風の初期昇温速度は小さいが，長時間暖房に適している。コナラの燃焼特性は，スギとオガライトの特性の中間に相当するが，酸化窒素発生量が著しく多い。一般に，熱効率は排気温度が高くなるにつれて大きくなるが，排気温度が高過ぎると，大気への放出熱のため減少する。酸化窒素は排気温度に比例して多く発生する。以上のことから，排気温度によって燃焼を制御する機構の開発が望まれる。

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