Performance of Small Steam Engine Operating on Wood and Rice Husk

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ABSTRACT

This paper presents results of a study which examined the feasibility of using a small-scale steam engine for the production of mechanical power using wood and rice husk as fuel. Steam was produced in a water-tube boiler and fed into a two-cylinder oscillating steam engine. The boiler was installed in a wood furnace and a simple natural draft rice husk furnace which was developed specially for this boiler-engine system. Tests were performed to investigate the performance and technique of operation and maintenance of the system.

Details of the systems tested are presented. The performances of the systems operating on wood and rice husk were evaluated and are also presented. The technical and economic feasibility of the steam engine to produce mechanical power from wood and rice husk and some practical aspects concerning the operation and performance of the systems are discussed.

INTRODUCTION

Despite the fact that the price of oil has not risen for the past few years, liquid fossil fuels are still far too expensive for people in the rural areas of developing countries. There is still a pressing need to develop indigenous renewable energy sources which can make a significant contribution to the economy and well-being of their rural populations. In the rural areas of developing countries, the ability to produce very small amounts of mechanical power by utilizing locally available renewable fuel is extremely valuable, regardless of the efficiency.

The development process is closely linked with an increase in the demand for energy. Often this is associated with processes of mechanization requiring mechanical or electrical energy. Steam engines played a widespread and important role in industrialization in the past and continue to have some specific applications at present. Although small steam engines have a low efficiency, they have some advantages over other renewable energy technologies such as biomass gasification and Stirling engine technologies. Steam engines are very reliable and require little maintenance. Unlike biomass gasification systems, the fuels for which have to meet strict specifications, steam engines can be operated on nearly all types of fuels.

Because of their reliability and flexibility regarding the fuel to be used, steam engines are still being used, particularly in industries such as rice mills and saw mills which produce by-products. At present over 1000 steam engines are used in rice mills in Thailand. A search for possible equipment suppliers concluded that steam power units of output below 10 kW are scarce, and either of unproven reliability or very expensive.

The U.K. based Intermediate Technology Development Group (ITDG) has been trying to promote 3.7 kW (5 hp) steam engines built by the Thames Steam Launch Co. (TSL) of Chiswick of U.K. for rural uses in developing countries. The Food and Agriculture Organization of the United Nations (FAO) is also interested in promoting the use of steam engines for power production using wood wastes and rice husk as fuels.

With funding support from FAO, Prince of Songkla University (PSU), through its Department of Mechanical Engineering, carried out an assessment of a 3.7 kW (5 hp) steam engine built by TSL in collaboration with ITDG. The main objectives of the project were to assess the technical and economic feasibility of this steam engine using wood and rice husk as fuels. The project activities included:

(i) Testing and evaluation of the performance of the steam engine with wood as fuel;
(ii) Development of a rice husk furnace so that the engine could be operated on rice husk;
(iii) Organization of a training course on the operation and maintenance of the steam engine and furnaces; and
(iv) Installation of the steam engine for water pumping using wood as fuel in the field for 9 months.

This paper presents the results of the assessment of the steam engine when operated on wood and rice husk in the laboratory.

DESCRIPTION OF EQUIPMENT

Test Set-up

Test set-up without condenser: The test set-up when the condenser was not used and when wood was used as fuel is shown in Fig.1. When operating on rice husk, the test set-up is shown in Fig. 2.

For these tests, the condenser was not used and the steam was discharged into the atmosphere after doing work on the pistons.

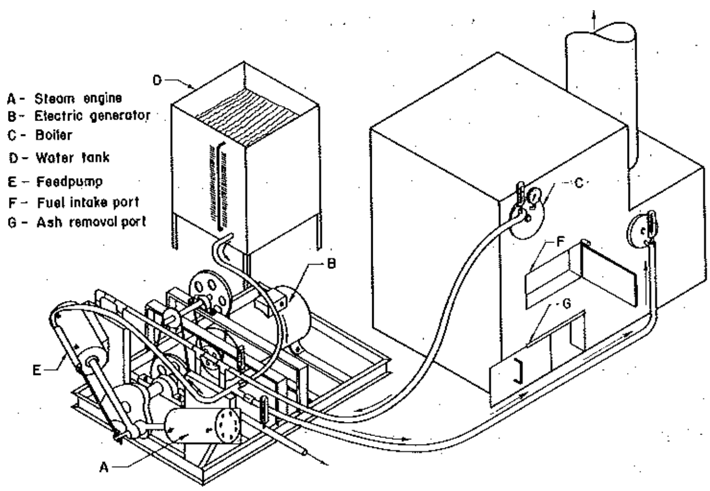


Fig. 1. Test set-up for steam engine without condenser using wood as fuel.

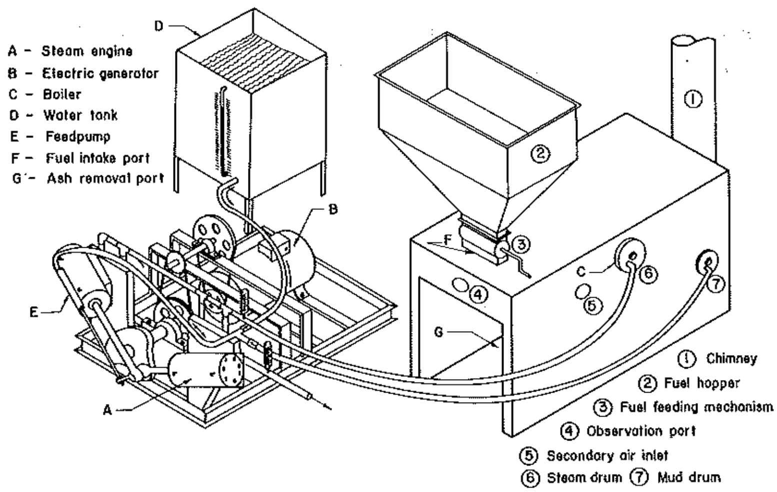


Fig. 2. Test set-up for steam engine without condenser using rice husk as fuel.

Test set-up with condenser: Tests with condenser installed to the exhaust of the steam engine were carried out only when wood was used as fuel. The test set-up is shown in Fig. 3.

The rate of heat transfer from the condensing steam to air was enhanced by forcing the air through the condenser (which was an air cooled heat exchanger) by using a blower driven by the steam engine. To increase the combustion efficiency, part of the hot air from the condenser was passed into the furnace.

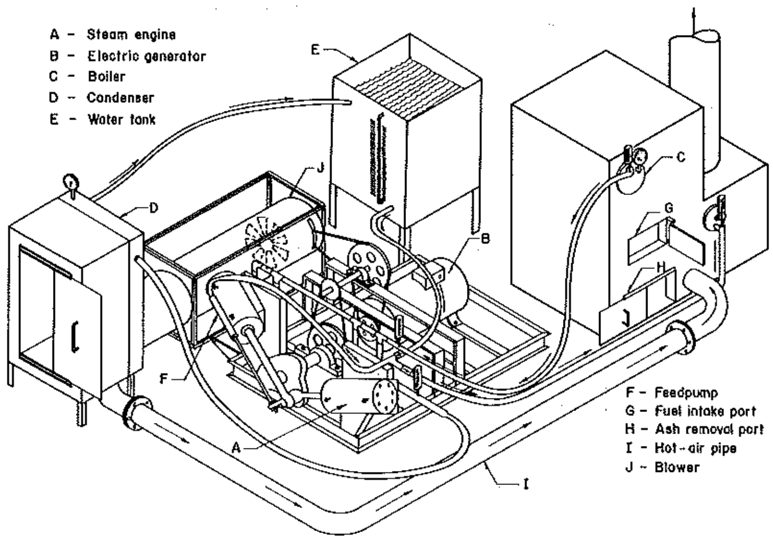


Fig. 3. Test set-up for steam engine with condenser using wood as fuel.

Steam Engine

The engine used in this study was a double acting, oscillating, two cylinder steam engine built by TSL of Chiswick, U.K. Each cylinder has a bore and stroke of 6.35 cm (2.5 inch) and 12.7 cm (5 inch) respectively. The steam engine is shown in Fig. 4, and its ideal indicator diagram is shown in Fig. 5.

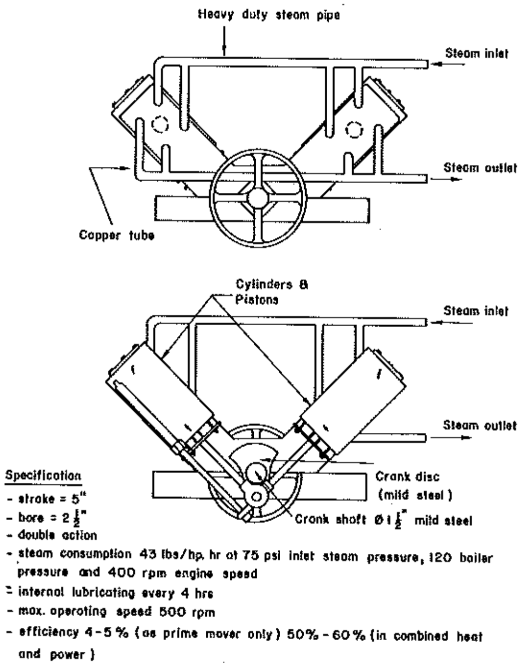


Fig. 4. Steam engine.

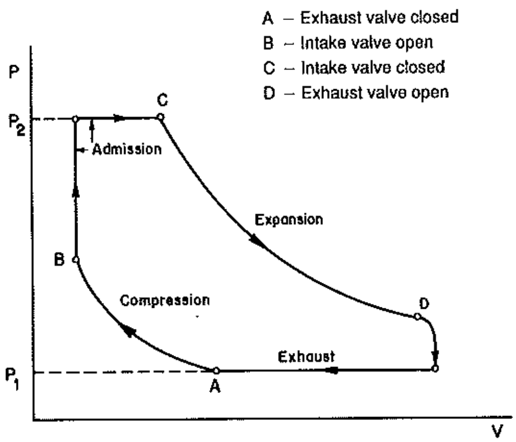


Fig. 5. Ideal indicator diagram of steam engine.

Boiler

The boiler used was a water-tube boiler built by TSL. It had a heat transfer surface of 3.252 m^2 (35 ft^2).

The boiler, shown in Fig. 6, consisted of two horizontal steel drums linked by copper tubes used as a heat transfer surface. Stayed end plates were rebated to drum ends. All fittings threaded into drum ends. All the major dimensions of the boiler are given in Fig. 6.

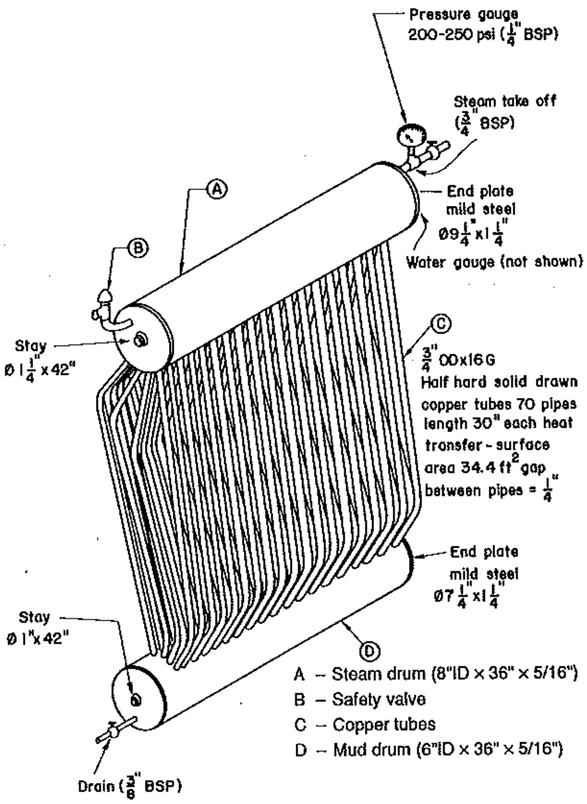


Fig. 6. Boiler.

The copper tubes were bent and expanded into reamed holes in the horizontal steel drums. This type of boiler is particularly appropriate to applications where high steam output and low plant weight are important.

Due to the method of construction, i.e. fabrication rather than welding, the risk of explosion is minimal. If water level is allowed to fall below the required level, the expanded copper tube joints in the top drum anneal and allow the steam to escape and the pressure to reduce to a safe value.

The boiler was fitted with a pressure relief valve which could be set to give the required value.

Condenser

A car radiator was used as the condenser. The radiator was 70 cm in height, 57 cm in width and 7 cm in thickness. The radiator was connected to the circular air conduit in which a blower was installed. The blower driven by the steam engine through a belt was used to force the air through the radiator to enhance the rate of heat transfer.

The other side of the radiator was connected to a square steel box, the outlet area of which could be varied to regulate the pressure of the hot air in the box. A 10 cm diameter steel pipe was used to connect the steel box with the furnace so that part of the hot air from the condenser could be used to enhance the combustion process in the furnace (see Fig. 3). The quantity of air flow to the furnace could be regulated by varying the pressure of the hot air in the box.

Feedwater Pumps

Two feedwater pumps were used in pumping water into the boiler.

The first feed was a small reciprocating pump with a cylinder diameter of 12.7 mm (See Fig. 1). This feedpump was fitted to one of the engine's cylinders and was powered by the engine. A check valve was installed in the liquid line connecting the feedwater tank and the boiler to stop water from flowing from the boiler. This feedpump could be put into operation by allowing the water from the feedwater tank to enter the pump by opening the valve installed in the liquid line between the feedwater tank and the pump.

The second pump was a hand operated reciprocating pump. This pump was an emergency pump which could be operated if the first pump failed to operate.

Feedwater Tank

The feedwater tank was made of 3.175 mm thick steel sheet. It had a square cross section of 61 cm x 61 cm and height of 150 cm.

Governor

A mechanical governor was provided with the steam engine. The governor was supposed to be installed to maintain the rotational speed of the engine.

Furnaces

Wood furnace: The wood furnace was designed by The Thames Steam Launch Company (TSL). Construction of the furnace and the installation of the boiler at the Department of Mechanical Engineering were carried out by departmental staff and technicians with the help of an engineer from TSL.

The furnace was made from bricks covered internally with clay and chicken wire and covered externally with concrete blocks and clay. The perspective view of the furnace is shown in Fig. 7. The cross section of the furnace together with the main dimensions of the wood furnace are shown in Figs. 8 and 9.

The grate was made from five pieces of 3.75 cm x 3.75 cm x 0.476 cm x 72.4 cm steel angles. The space between the angles is 2.5 cm.

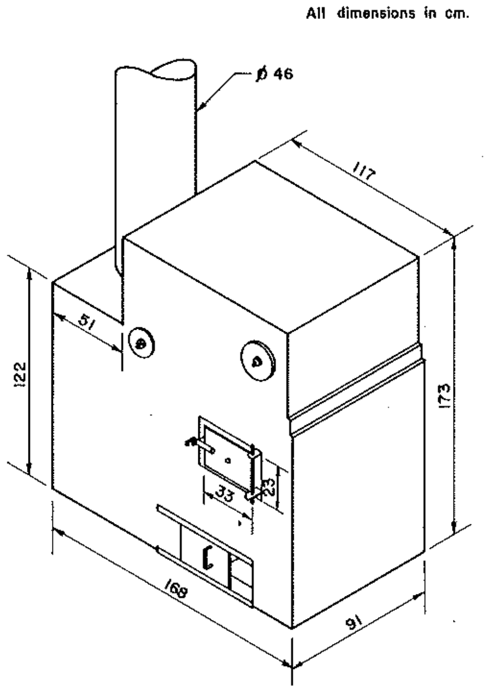


Fig. 7. Perspective view of the wood furnace.

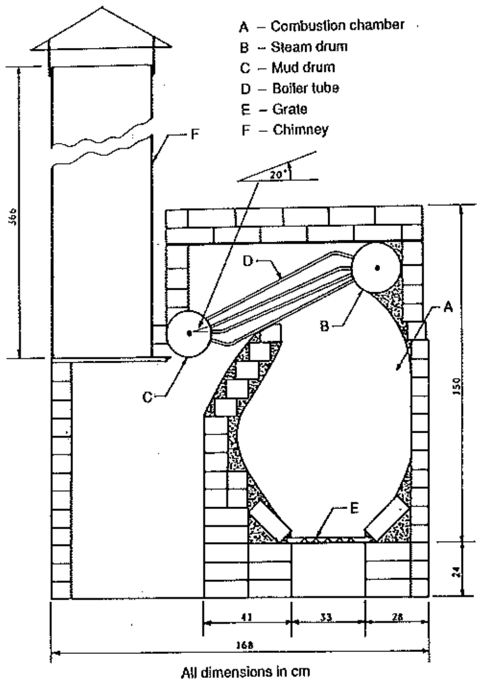


Fig. 8. Cross section of the wood furnace.

Other main dimensions of the furnace are given as follows:

Chimney diameter	46	cm
Chimney height	3.66	m
Grate area	2700	cm^2
Grate air space	1200	cm^3
Area of air inlet port	790	cm^2
Dimensions of combustion chamber (width x depth x height)	73.5 cm x 73.5 cm x 70.0 cm	

The flue gas made two passes through the boiler tubes before entering the chimney. Arrangements were made to enable the areas of the fuel port and the air inlet port to be regulated.

Rice husk furnace: To develop a rice husk furnace suitable for operations with the existing steam engine, a cyclone was first tried. It was found that there were several problems associated with the operation of a small cyclone furnace and it is not suitable for operation in rural areas. A simple natural draft furnace with inclined grate was designed and constructed by staff members of the Department of Mechanical Engineering and was found to operate quite satisfactorily.

The perspective view of the rice husk furnace is shown in Fig. 10. It was a natural draft type with chimney of 30 cm in diameter and 10 m in height. The furnace was made from ordinary bricks covered with locally made cement mixed with rice husk ash with the ratio of cement to rice husk ash of 1:3 by volume.

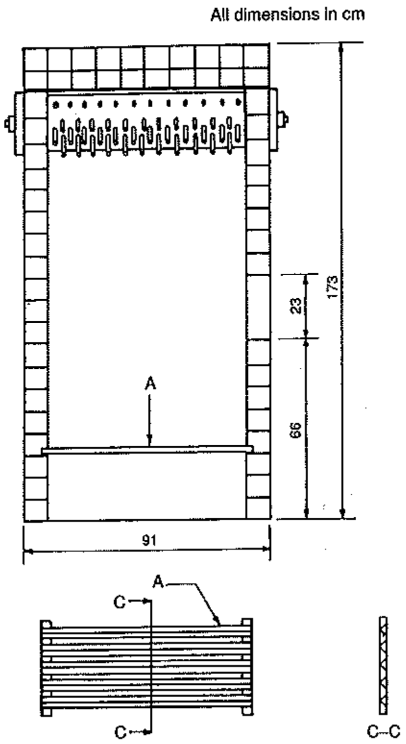


Fig. 9. Section of the wood furnace.

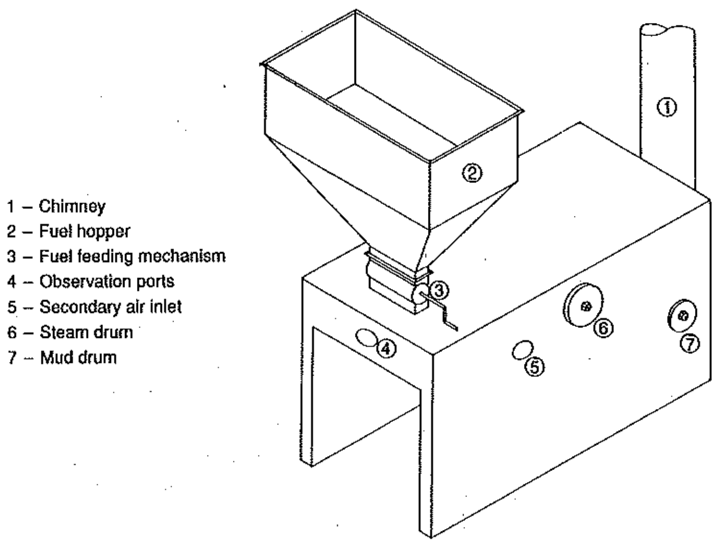


Fig. 10. Perspective view of the rice husk furnace.

The cross section of the furnace is shown in Figs. 11 and 12. An inclined removable grate making an angle of 45 degrees to horizontal (see Fig. 11) was adapted. The grate was made of 7 pieces of steel channels supported by steel angle as shown in Fig. 12. Holes of 1 cm in diameter were drilled in these channels to provide openings for the primary combustion air to enter the furnace. These holes also served as ash removal ports.

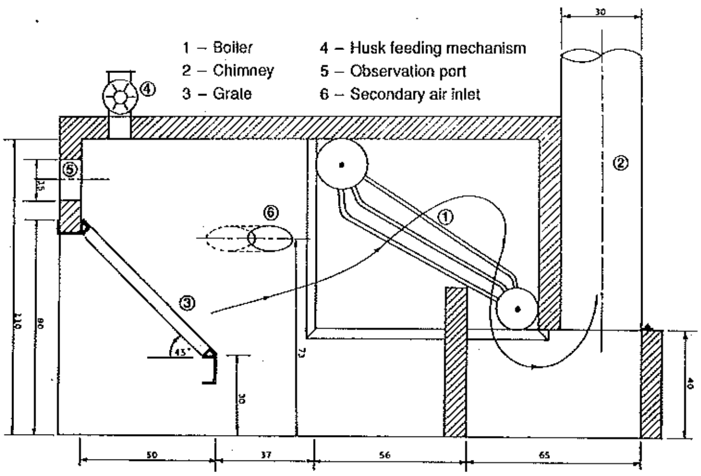


Fig. 11. Cross section of the rice husk furnace.

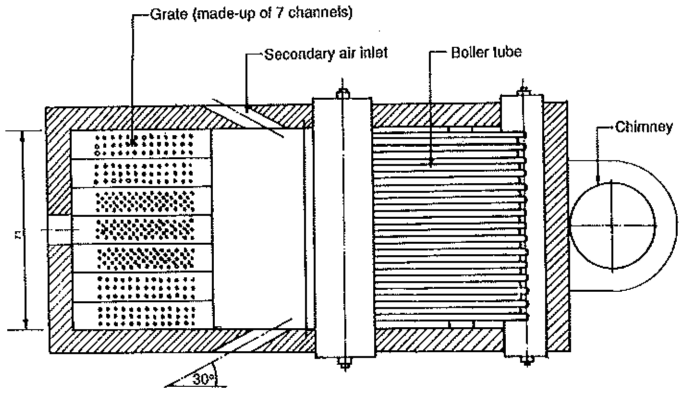


Fig. 12. Cross section of the rice husk furnace.

Combustion air can also enter the furnace through the secondary air ports provided at the walls of the furnace as shown in Figs. 11 and 12. The secondary air was introduced into the furnace to achieve a more complete combustion in the furnace.

An observation port was also provided at the front of the furnace as shown in Fig. 11 to enable the operator to observe the strength of combustion during the operation.

Rice husk was stored in the fuel hopper and fed into the furnace by a feeding mechanism installed underneath the fuel hopper as shown in Fig. 13. The feeding mechanism was operated

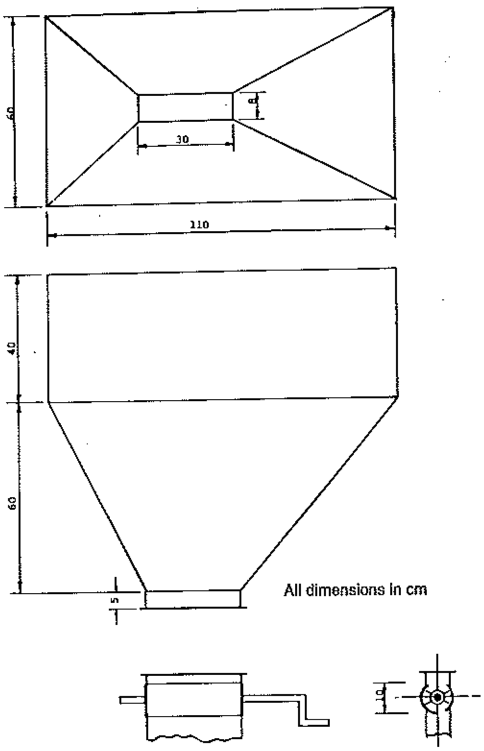


Fig. 13. Details of hopper and feeder.

manually. An electric motor could be installed to operate the mechanism automatically if desired.

The water tube boiler was mounted on a steel frame made from 3.81 cm x 0.635 cm (1.5 inch x 0.25 inch) steel angle, which was placed in the furnace as shown in Figs. 11 and 12.

Other main dimensions of the furnace are given as follows.

Chimney diameter	30	cm
Chimney height	10	m
Grate area	4402	cm^2
Area of primary air inlet ports	400	cm^2
Area of secondary air inlet port	91	cm^2
Area of fuel intake port	240	cm^2

Like the wood furnace, arrangement was made for the flue gas to make two passes through the boiler tube before entering the chimney.

Loading

The steam engine was loaded by connecting it to a 3 kW single phase electric generator via V-belts. The electrical energy generated was used to power a light board fitted with ten 300 watts light bulbs which could be switched on independently.

Instrumentation

Pressure gauges and thermometers were installed at the outlet of the boilers, and also at the inlet and the outlet of the engine. Arrangements were also made for the temperatures of the flue gas to be monitored with thermocouples before entering and after leaving the boiler and in the chimney.

The electrical energy from the electric generator was measured with a voltmeter and an ammeter.

The fuel consumption rates were determined by weighing the amount of wood or rice husk used over a period of time.

For tests without condenser, the flow rate of steam was obtained by measuring the flow rate of the make-up water from the feedwater tank. For tests with condenser, the steam production rate was obtained by weighing the condensate. In this case the condensate was discharged into a vessel for the purpose of weight determination before being poured into the feedwater tank.

The brake horse power of the engine was not monitored, but it can be determined fairly accurately from the measured values of manifold pressure, the dimensions of the cylinder, and the speed of the engine as will be shown in the section "Test Data" subsequently.

The contents of carbon monoxide and oxygen in the flue gas in the chimney were also monitored with an electronic analyzer capable of examining their transient values.

TEST PROCEDURE

The performance of the steam engine was examined at different values of steam pressure at inlet to the engine, i.e. 652.93 kPa (80 psig) to 790.81 kPa (100 psig). By varying the pressure of the steam at inlet to the engine, the fuel consumption rate and the speed of the engine could also be varied, which enabled the performance of the engine to be examined at different fuel consumption rates and speeds of the engine. It should be pointed out that the main aim of this work was to examine only the basic parameters of the system, i.e. specific fuel consumption, furnace efficiency and engine efficiency. These parameters and other parameters will be examined in greater detail in future work.

When using wood as fuel, the fire was started up in the furnace and the pressure of the steam in the boiler was allowed to build up to 990.76 kPa (130 psig) before the steam was allowed to enter the engine's cylinder. With the use of a ball valve at the exit of the boiler, the pressure of steam before entering the intake manifold of the engine can be set at any required value. Usually it took about 20 minutes to start the system (from firing to starting of the engine). By regulating the rate of feeding the fuel, the speed of the engine could be maintained at a particular loading without having to use the governor.

After the system reached the steady state condition, (i.e. after about one and a half hours of operation), values for the following parameters were recorded :

(a) Steam temperature at the boiler,
(b) Steam pressure at the boiler,
(c) Steam temperature at the engine's outlet,
(d) Steam pressure at the engine's inlet,
(e) Steam temperature at the engine's inlet,
(f) Feedwater temperature,
(g) Inlet air temperature,

(h) Stack temperature (temperature of the flue gas in the chimney),
(i) Steam production rate,
(j) Fuel consumption rate,
(k) Engine speed, and
(l) Electrical energy output.

When using rice husk as fuel, the procedures for start-up of the system and data acquisition were the same as for using wood fuel. The start-up time when rice husk was used as fuel was about 25 minutes.

For each test the system was operated at a steady state for at least 3 hours during which data acquisition was carried out.

The carbon monoxide and oxygen contents in the flue gas and the temperature of the flue gas in the chimney were also examined for some selected tests.

TEST DATA

Data and Derived Values

When operated with wood fuel, a total of 7 tests were carried out: two tests were carried out with the condenser being installed and the rest without the condenser. When operated with rice husk, all 5 tests were carried out without using a condenser.

The data obtained from tests carried out with wood are shown in Table 1 while those obtained from tests carried out with rice husk are shown in Table 2.

Using the experimentally determined values of various parameters, i.e. items (a) to (l) in the "Test Procedure" section, values for the following parameters were calculated:

(i) The engine shaft power (BHP)
(ii) The furnace efficiency (η_p)
(iii) The specific fuel consumption (*sfc*)
(iv) The specific steam consumption (*ssc*)
(v) The overall engine efficiency (η_o)
(vi) The overall electrical efficiency ($\eta_{o,e}$)

The engine shaft power or the brake horse power of the engine was calculated from the equation

$$BHP = \frac{PLANMF}{33000}$$

where,

P = Pressure of the steam in the gauge at engine's manifold in psig
L = Length of stroke in feet
A = Area of piston in in.^{2}
N = Number of revolutions per min
M = Number of power strokes per revolution
F = Efficiency factor = 0.8 for $200 < N < 500$

This equation has been recommended by the manufacturer of the steam engine (TSL) for

Table 1. Summary of parameters of all tests for wood furnace.

Parameters		Test No.						
		1	2	3	4	5	6	7
Boiler Pressure	(kPa) (abs)	998	998	998	998	1136	998	998
Boiler Steam Temperature	(°C)	175	175	175	175	180	177	175
Feed Water Temperature	(°C)	52.3	65.5	37.0	34.0	31.0	32.0	34.5
Inlet Air Temperature	(°C)	77.0	80.0	60.0	63.0	32.5	33.5	34.8
Flue Gas Temperature	(°C)	227	264	210	268	240	247	317
Steam Production Rate	(kg/hr)	76.8	92.4	82.8	100.8	97.2	105	141
Fuel Consumption Rate	(kg/hr)	25	35	30	40	40	40	67
Steam Engine Manifold Pressure	(kPa) (abs)	653	791	653	791	791	653	791
Engine Inlet Steam Temperature	(°C)	160	170	160	165	168	168	170
Engine Outlet Steam Pressure	(kPa) (abs)	101.3	101.3	101.3	101.3	101.3	101.3	101.3
Engine Outlet Steam Temperature	(°C)	110	110	105	105	105	105	105
Engine Speed	(rpm)	210	219	227	228	230	296	341
Engine Shaft Power	(hp)	3.35	4.37	3.62	4.55	4.59	4.72	6.80
Specific Fuel Consumption	(kg/hr hp)	7.46	8.01	8.29	8.79	8.72	8.48	9.85
	(kg/hr kW)	10.00	10.74	11.11	11.78	11.69	11.37	13.20
Specific Steam Consumption	(kg/hr hp)	22.91	21.14	22.87	22.15	21.18	22.25	20.74
	(kg/hr kW)	30.71	28.34	30.66	29.69	28.39	29.83	27.80
Electrical Power Output	(kW)	0.68	1.01	1.40	1.95	2.01	2.02	2.92
Furnace Efficiency	(%)	57.80	48.60	53.20	48.82	47.38	51.02	40.74
Overall Engine Efficiency	(%)	2.65	2.47	2.38	2.24	2.26	2.33	2.00
Overall Electrical Efficiency	(%)	0.72	0.76	1.24	1.29	1.33	1.34	1.15
Steam to Fuel Ratio		3.07	2.64	2.76	2.52	2.43	2.62	2.11
Remarks		C	C	N-C	N-C	N-C	N-C	N-C

Note: C = Test with condenser installed at engine exhaust
N-C = Test without condenser

evaluating the shaft power of the engine. It has been verified by the Department of Engineering at the South Bank Polytechnic, London.

The specific fuel consumption (sfc) was calculated by the equation

$$sfc = \frac{\text{Fuel consumption rate}}{\text{Brake horse power}}$$

The specific steam consumption rate (*ssc*) was calculated by the equation

Table 2. Summary of parameters of all tests for rice husk furnace.

Parameters		Test No.				
		1	2	3	4	5
Boiler Pressure	(kPa) (abs)	745	841	765	772	869
Boiler Steam Temperature	(°C)	166	170	170	170	170
Feed Water Temperature	(°C)	30.0	30.0	30.0	30.0	30.0
Inlet Air Temperature	(°C)	34.0	35.0	35.0	34.0	34.0
Flue Gas Temperature	(°C)	360	400	400	400	450
Steam Production Rate	(kg/hr)	98	112	111	123	123
Fuel Consumption Rate	(kg/hr)	49	59.4	65	61	63
Steam Engine Manifold Pressure	(kPa) (abs)	612	689	750	756	791
Engine Inlet Steam Temperature	(°C)	158	165	165	165	165
Engine Outlet Steam Pressure	(kPa) (abs)	101.3	101.3	101.3	101.3	101.3
Engine Outlet Steam Temperature	(°C)	105	105	105	105	105
Engine Speed	(rpm)	306	318	297.4	313	308
Engine Shaft Power	(hp)	4.52	5.41	5.58	5.93	6.15
Specific Fuel Consumption	(kg/hr hp)	10.84	10.98	11.65	10.30	10.25
	(kg/hr kW)	14.5	14.70	15.625	13.77	13.7
Specific Steam Consumption	(kg/hr hp)	21.68	20.70	19.89	20.74	20.00
	(kg/hr kW)	29.06	27.72	26.68	27.77	26.74
Electrical Power Output	(kW)	1.725	2.28	2.30	2.45	2.5
Furnace Efficiency	(%)	39.23	37.50	33.51	39.58	38.38
Overall Engine Efficiency	(%)	1.84	1.82	1.71	1.94	1.95
Overall Electrical Efficiency	(%)	0.94	1.03	0.95	1.07	1.06
Steam to Fuel Ratio		2.0	1.87	1.71	2.02	1.95

$$ssc = \frac{\text{Steam production rate}}{\text{Brake horse power}}$$

The furnace efficiency (η_F) was calculated by the following equation

$$\eta_F = \frac{\text{Energy absorbed by steam}}{\text{Energy input to the furnace}}$$

The overall engine efficiency (η_o) was calculated by the following equation

$$\eta_o = \frac{\text{The engine shaft power}}{\text{Energy input to the furnace}}$$

The overall electrical efficiency ($\eta_{o,e}$) was calculated by the equation

$$\eta_{o,e} = \frac{\text{The electrical output}}{\text{Energy input to the furnace}}$$

The values of shaft horse power, *sfc*, *ssc*, η_F, η_o and $\eta_{o,e}$ were evaluated for all tests and are also shown in Tables 1 and 2.

Presentation of Data

Apart from the presentation of the data and the derived values in Tables 1 and 2, a graphical presentation is also made. The furnace efficiency (η_F) and the overall engine efficiency (η_o) are

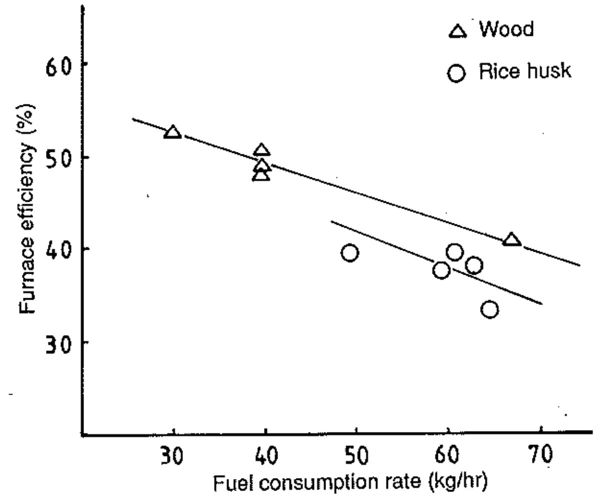


Fig. 14. Furnace efficiency (η_F) as a function of fuel consumption rate ($\dot{m}_f$).

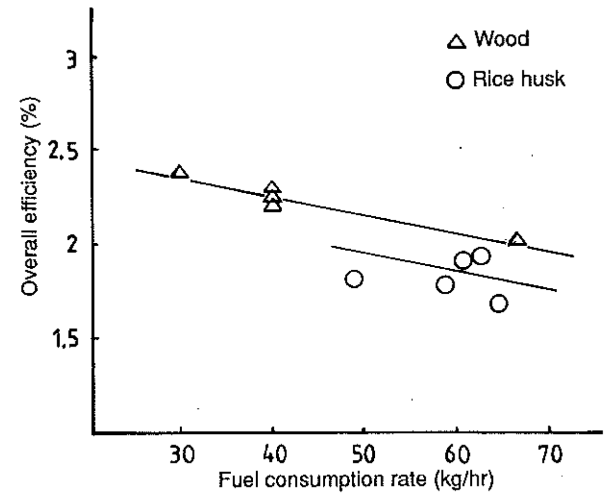


Fig. 15. Overall engine efficiency (η_o) as a function of fuel consumption rate ($\dot{m}_f$).

plotted as a function of the fuel consumption rate as shown in Figs. 14 and 15. The overall engine efficiency (η_o) is shown as a function of the engine speed in Fig. 16. The engine shaft power (BHP) is shown as a function of the speed of the engine in Fig. 17. The specific fuel consumption (sfc) and the specific steam consumption (ssc) are shown as a function of engine shaft power in Figs. 18 and 19.

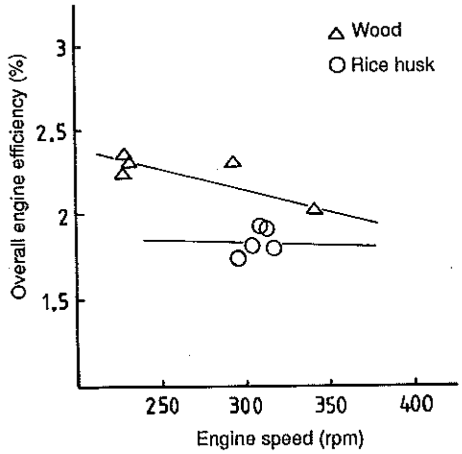


Fig. 16. Overall engine efficiency (η_o) as a function of engine speed (rpm).

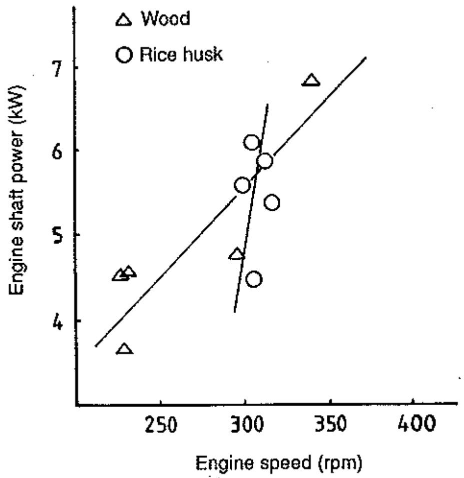


Fig. 17. Engine shaft power (BHP) as a function of engine speed (rpm).

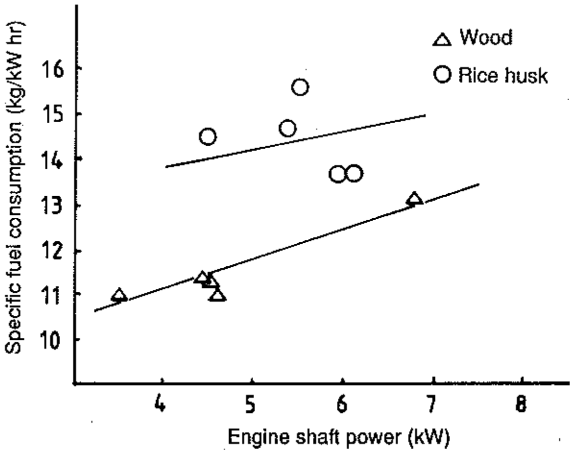


Fig. 18. Specific fuel consumption (sfc) as a function of engine shaft power (BHP).

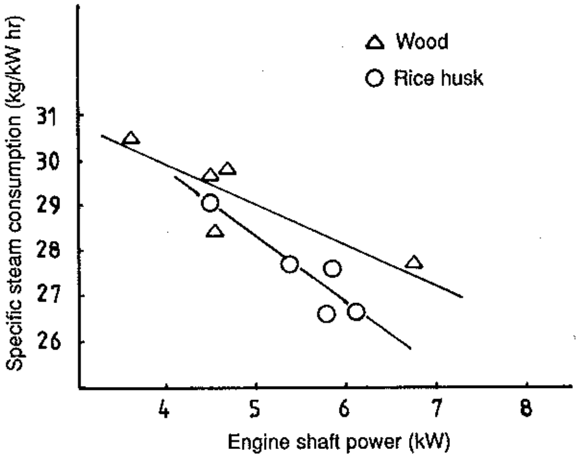


Fig. 19. Specific steam consumption (ssc) as a function of engine shaft power (BHP).

DISCUSSION OF TEST RESULTS

Operation and Maintenance

Tests carried out in the laboratory have shown that small steam engines can be operated using wood and rice husk as fuel without any major technical problem. For wood, a simple conventional wood furnace can be used. For rice husk, a simple natural draft furnace can be used.

Starting up the system was fairly simple and usually took only about 20-25 minutes after the furnace was ignited. The systems could be started and operated with only one operator. Onc attendant had to be on duty all the time during the operation. The duties of the attendant included : (a) feeding fuel to the furnace, (b) regulating the valve on the steam pipe leading to the engine so that the pressure of the steam entering the engine manifold is constant, (c) regulating the feedwater flow rate into the boiler at the required level and (d) raking the ash from the furnace.

The steam engine systems required little maintenance. The maintenance of the systems included filling the cylinders with 2 - 3 cm^3 of lubricating oil every 3 hours of operation and cleaning the boiler tubes every week (about 40 operating hours per week) with high velocity steam jet.

Performance

Combined heat and power (CHP): Table 1 shows that the electrical output of a steam engine with a condenser is much lower than that of the steam engine without a condenser, although the shaft power developed by the engine is about the same. This is due to the fact that a large proportion of mechanical power produced was used to force the air through the condenser. It could be estimated that about 1.5 kW (2 hp) of mechanical power was needed to operate the condenser.

Although the steam engine with condenser (shown in Fig. 3) produced much less mechanical work compared with the one without condenser, it produces a lot of hot air at 60°C - 90°C, which can be utilized for heating purposes. The system with condenser offers an excellent opportunity for both heat and power to be provided by the system.

It can be estimated from the data in Table 1 that this steam system can provide about 2 kW (3 hp) of mechanical power and about 100 kW of heat. The heat available is in the form of hot air at 60°C - 90°C, which is very useful for drying purposes.

Power output: Table 1 and Fig. 17 show that when operating on wood the engine can develop a maximum shaft power of 3.5 kW (4.7 hp), for the manifold pressure of 80 psig and 5.1 kW (6.8 hp) for the manifold pressure of 100 psig. The corresponding electrical energy outputs for the manifold pressure of 80 psig and 100 psig are 1.40 kW and 2.92 kW respectively. It can be said that this engine can develop a maximum shaft power of about 5.0 kW (7 hp) when operating with wood as the fuel.

Table 2 shows that the output power of the engine when using rice husk as the fuel is lower than when using wood. This was due to the fact that the furnace efficiency is lower when rice husk is used, resulting in lower rate of steam output.

Efficiency: Fig. 14 shows that the furnace efficiency decreases with the fuel consumption rate for both wood and rice husk, although the furnace efficiency decreases more rapidly for wood. The furnace efficiency decreases from 57 % at the fuel consumption rate of 25 kg/hr to 41 % at the fuel consumption rate of 67 kg/hr when wood is used. The furnace efficiency decreases very slowly for rice husk, giving the maximum value of 40 % at the fuel consumption rate of 50 kg/hr and the minimum value of 33 % at the fuel consumption rate of 65 kg/hr as shown in Fig. 14.

It is interesting to note that the efficiency of the rice husk furnace is about 12 % lower than that of the wood furnace on average, as shown in Fig. 14. This is due to the fact that the rice husk was not completely burnt and there was a substantial amount of carbon remaining in the ash, which was not taken into account in calculating fuel energy input.

Figures 15 and 16 show that the overall engine efficiency of the system operating using wood decreases with fuel consumption rate and the engine speed. The overall engine efficiency decreases from 2.65 % to 2.00 % as the speed of the engine increases from 210 rpm to 350 rpm as shown in Fig. 16.

With regard to rice husk, the overall engine efficiency remains substantially constant with the engine speed as shown in Fig. 16. As to be expected, the overall efficiency for rice husk is lower than that of wood due to incomplete burning of husk.

Fuel and steam consumptions: Table 1 shows that the specific fuel consumption for the system operated using wood fuel is around 11.6 kg/kW hr (8.7 kg/hp hr), which is very high. This is because the efficiency of the steam engine is very low. Table 2 shows that the specific fuel consumption for the system operated using rice husk is about 14.0 kg/kW hr (10.6 kg/hp hr), which is much higher than that of wood. This was due to the incomplete combustion of rice husk.

Tables 1 and 2 show that the specific steam consumptions of system fuelled by wood and system fuelled by rice husk are approximately the same (29 kg/kW hr or 22 kg/hp hr), which is to be expected.

Speed Governing

Although a mechanical governor was also provided for the purpose of speed control, this governor was not used. The speed control was achieved by regulating the feeding rate of fuel so that the steam pressure in the boiler was fairly constant. A ball valve installed in the steam pipe connecting the boiler and the engine's manifold was used to control the pressure in the engine's manifold.

It was found that by regulating the fuel feeding rate and the valve installed in a pipe leading the steam to the engine, the speed of the engine could be kept within ± 10 % of the required value. With this technique of speed control, the engine could be used for water pumping, electricity generation and propulsion of agricultural machinery.

CONCLUSIONS

(i) The small steam engine manufactured by TSL can be installed and operated by local technicians. The wood furnace can be built with locally available materials and skills.

(ii) A simple natural draft rice husk furnace was successfully developed by the Department of Mechanical Engineering, Prince of Songkla University. This furnace could be used to operate the TSL steam engine quite successfully.

(iii) The maximum mechanical output of the steam engine is 4.85 kW (6.5 hp) when operating without condenser and 3.35 kW (4.50 hp) when operating with condenser.

(iv) In general this steam engine can provide about 2 kW of mechanical power and 100 kW of heat in the form of hot air from the condenser which consumes about 1.5 kW of mechanical power. This set-up provides an excellent opportunity for the system to be used for providing both heat and power(CHP).

(v) The furnace efficiency, i.e. the fraction of combustion energy that is converted to energy in the steam, decreases with the capacity of the furnace. The furnace efficiencies for wood furnace and rice husk furnace are about 50 % and 37 % respectively.

(vi) The specific fuel consumptions when operated on wood and rice husk are 11.6 kg/kW hr and 14.0 kg/kW hr respectively.

(vii) The overall efficiencies, i.e. the fraction of energy in the fuel that is converted to shaft power, when operated on wood and rice husk are 2.5 % and 1.9 % respectively.

(viii) In the operation one attendant is needed to look after the engine. Operation and maintenance of the engine are quite simple and can be carried out by an unskilled labour.

REFERENCES

[1] *Assessment of Small Steam Engine for Field Application in Thailand,* RAPA Bulletin on Rural Energy, 1981/1.

[2] *Report on the Installation and Performance Evaluation in the Laboratory of A Small Steam Engine Using Wood as Fuel,* submitted to FAO by the Department of Mechanical Engineering, Prince of Songkla University, June, 1987.

[3] *Final Report on the Installation and Performance Evaluation in the Laboratory of A Small Steam Engine Using Rice Husk as Fuel,* submitted to FAO by the Department of Mechanical Engineering, Prince of Songkla University, December, 1987.

APPENDIX

Sample Calculation

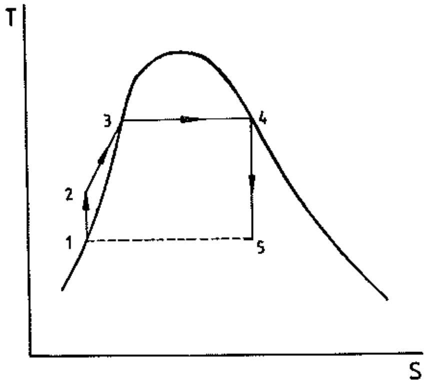
Data from a particular test are shown as follows:

Test condition

Boiler		
Steam Pressure (P_{steam})	998	kPa(abs) (130 psig)
Steam Temp.	175	°C
Feed Water Temp.	52.3	°C
Inlet Air Temp.	77.0	°C
Flue Gas Temp.	227	°C
Steam Production Rate	1.28	kg/min
Fuel Consumption Rate	25	kg/hr
Steam Engine		
Inlet Steam Pressure	653	kPa(abs) (80 psig)
Inlet Steam Temp.	160	°C
Outlet Steam Pressure	101.325	kPa(abs) (0 psig)
Outlet Steam Temp.	110	°C
Engine Speed	210	rpm
Condenser		
With Condenser		
Generator		
Voltage	205	V
Current	3.3	A

From the data various parameters can be calculated as follows:

(In the calculation, it is assumed that the states of the working fluid leaving the boiler and condenser are saturated as shown in Fig. 20).



1–2 Compression process by the pump

2–3–4 Constant pressure heat transfer process in the boiler

4–5 Expansion process through the steam engine

Fig. 20. T-s diagram for processes in the steam power plant.

From the Thermodynamic Table of Properties for Steam, the enthalpy and specific volume of saturated liquid at 52.3 °C are :

$$h_{f,l} = 218.9 \text{ kJ/kg and } v_{f,l} = 0.001 \text{ m}^3\text{/kg}$$

The pump work can be calculated by the equation

$$W_p = V_{f,l}(P_{boiler} - P_{atm})$$

$$P_{boiler} = 130 \text{ psig} = 998 \text{ kPa}, P_{atm} = 101 \text{ kPa}$$

$$W_p = 0.001(998 - 101)$$

$$= 0.906 \text{ kJ/kg}$$

The enthalpy of the feedwater at the boiler inlet is given by

$$h_2 = h_{f,i} + w_p = 218.9 + 0.906$$

$$= 219.81 \text{ kJ/kg}$$

The enthalpy of steam at the boiler outlet, which is assumed to be dry saturated, is given by

$$h_3 = 2778.02 \text{ kJ/kg}$$

The rate of heat transferred to the steam is given by

$$Q_{2\text{-}3} = m_s(h_3 - h_2)$$

$$= \frac{1.28}{60} \quad (2778.02 - 219.81)$$

$$= 54.58 \text{ kW}$$

Assuming that the net heating value of wood (i.e. after taking into account the moisture content in the fuel) is 13600 kJ/kg

The rate of heat supplied to the furnace is given by

$$Q_f = \frac{25}{3600} \times 13600$$

$$= 94.44 \text{ kW}$$

The furnace efficiency is given by

$$\eta_F = \frac{Q_{2\text{-}3}}{Q_f} = \frac{54.58}{94.44} = 57.8 \text{ \%}$$

The brake horse power is given by

$$BHP = \frac{P\,L\,A\,N\,M\,F}{33000}$$

where

P = 80 psig
L = Length of the stroke = 0.417 ft
A = Area of piston = 4.9 in.^{2}
N = Number of revolutions per min = 210
M = Number of power stroke per revolution = 2
F = 0.8

For two cylinders, the power is given by

$$BHP = 2 \times 80 \times 0.417 \times 4.9 \times 210 \times 2 \times 0.8$$

$$= 3.35 \text{ hp}$$

$$= 2.50 \text{ kW}$$

The electrical output is given by

$$P_{o,e} = \frac{205 \times 3.3}{1000} = 0.68 \text{ kW}$$

The overall engine efficiency is given by

$$\eta_o = \frac{BHP}{Q_f} = \frac{2.5}{94.44} = 2.65 \text{ \%}$$

The overall electrical efficiency is given by

$$\eta_{o,e} = \frac{P_{o,e}}{Q_f} = \frac{0.68}{94.44} = 0.72 \text{ \%}$$

The specific fuel consumption is given by

$$sfc = \frac{m_f}{3.35} = 7.46 \text{ kg/hr hp}$$

The specific steam consumption is given by

$$ssc = \frac{1.28 \times 60}{3.35} = 22.91 \text{ kg/hr hp}$$