Feasibility of Recovering Energy from Municipal Solid Waste to Generate Electricity

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Abstract. Population growth and economic development in Indonesia have increased the production of municipal solid waste (MSW) in many big cities, causing sanitary problems. The (MSW) disposal problem can be solved by applying an appropriate technology that can reduce the volume of the waste effectively and efficiently. Waste-to-Energy (WTE), or Energy-from-Waste (EFW), is one of the most effective and efficient technologies for reducing the waste volume. Energy recovered from the waste can be used for thermal or electricity generation. This paper deals with a feasibility study of utilizing MSW for generating electricity. A survey and investigation of waste characteristics, including waste composition, chemical and physical composition, and heating value, were carried out for typical Bandung MSW. An average heating value of 1500 kcal/kg can be expected from pre-treated MSW to be used as a fuel for direct combustion in a WTE plant. A typical design for a small-scale WTE plant is shown in this paper and also an energy analysis is provided. Approximately 800 kW of electric power can be generated from 50 tonnes of MSW per day.

1   Introduction

The amount of municipal solid waste (MSW) in many cities in Indonesia has increased significantly due to the population growth and economic development. Open dumping, the only method currently used for the final disposal of MSW, faces many difficulties due to the limited area available and resistance from surrounding communities. The MSW disposal problem can be solved by applying an appropriate technology that can reduce the waste volume effectively and efficiently. Moreover, the technology must be economically sustainable, and use a relatively small area over a long period of time. Waste-to-Energy (WTE), or Energy-from-Waste, is one of the most effective and efficient technologies for reducing the waste volume. Energy recovered from the waste can be used for thermal or electricity generation. Furthermore, open dumping of MSW generates green house gases such as methane and other poisonous gases when it is unintentionally burned. Hence, the utilization of a WTE plant could

also reduce the green house gases emitted by dumped MSW. The application of WTE for removing green house gases is approved by UNFCCC's document AM0025 and is eligible for the Clean Development Mechanism (CDM) scheme [1].

This paper deals with a feasibility study of utilizing MSW for generating electricity. The study covers only the technical aspect of the thermal analysis. A series of surveys were carried out to find out the composition of MSW in the Bandung area, followed by proximate, ultimate and heating value tests of the most important waste components. Since some of the components are taken for recycling and reuse, only the remaining components can be used as fuel for a WTE plant. The chemical and physical as well as the heating value of these remaining wastes were evaluated for their use as a fuel in the furnace and boiler of a small-scale WTE plant. The objectives of this study were to investigate the characteristics of typical tropical MSW and the possibility of applying this tropical MSW in a WTE plant. This paper provides information about the typical characteristics of MSW from tropical cities and a basic design for a small-scale WTE plant using tropical MSW.

2   Methodologies

The study started with a survey of MSW components. Municipal solid waste in many cities in Indonesia mainly comes from homes, public facilities, streets, offices, malls, and markets/supermarkets. Citizens are responsible for disposal of domestic waste to temporary collection/disposal areas (TPS), and the municipal authorities are responsible for its transfer from the temporary disposal area to the final disposal area (TPA). The MSW survey was carried out at 23 TPSs and TPAs in the Bandung area. From each TPS and TPA 3 m^3 MSW sample was separated into several component categories such as organic materials, food, glass, metal, recyclable plastic, non recyclable plastic, rubber, paper, foam, textile, electronics and other wastes. The analyses were carried out on eight consecutive days. The heating value, ultimate and proximate analysis was then done for each waste component. The tests were done at TekMIRA (*Pusat Penelitian dan Pengembangan Teknologi Mineral dan Batu Bara, Kementerian Energi dan Sumber Daya Mineral,* Bandung, Indonesia). The testing methodology/codes are summarized in Table 1.

Some valuable waste components, such as recyclable plastic, paper, electronics, glass, and metal, are often selected and taken by informal collectors from TPS's and TPA's, hence only the remaining waste components can be incinerated in the WTE plant. The combined properties of these remaining waste components were calculated to predict their combined ultimate, proximate and heating value. These properties were then used for an energy analysis and the design of a

furnace and boiler. The energy analysis was done using the Cycle Tempo software application [2] in order to find the operating conditions for the main components of the WTE steam power plant. The operating conditions were calculated with known heat input in the boiler. The heat input was calculated from the amount of MSW utilized and the predicted heating value. Then, the dimensions of the furnace and boiler were calculated using the FireCad software application [3]. The calculations were iterated to find the operating conditions that give maximum power output.

Table 1   Standards used for testing at TekMIRA.

Component	Standard
Moisture	ISO 11722 ASTM D.3173
Ash	ISO 1171 ASTM D.3174
Volatile matter	ISO 562
Fixed carbon	100%-M-Ash-VM
Carbon	ISO 625 ASTM D.3178
Hydrogen	ISO 625 ASTM D.3178
Nitrogen	ISO 332 ASTM D.3179
Sulfur	ASTM D.4239
Oxygen	100%-C-H-N-S-Ash
Calorific value	ASTM D.5865

3   Waste Characteristics

The results of the survey of the composition of the waste from the TPSs are shown in Table 2. The table shows the MSW composition in mass and volume fraction respectively.

Table 2   MSW Composition.

Component	Mass Fraction (%)	Volume Fraction (%)
Organic matter	35.58	44.51
Food waste	22.58	11.75
Paper	13.67	14.24
Recyclable plastic	7.06	15.30
Non recyclable Plastic	5.69	4.91
Glass	3.19	2.58
Metal	3.31	1.61
Textile	1.94	0.92
Rubber	0.68	0.36
Styrofoam	0.25	0.83
Electronic waste	0.56	0.4
Others	5.49	2.59

The results of the proximate, ultimate, and heating value tests of several waste components are shown in Tables 3 and 4. The tested samples were air-dried based (adb) samples. From these figures it can be seen that the MSW components were dominated by the element carbon. However, most of the carbon was in volatile matter, as the amount of fixed carbon was less than 20%. The higher heating value (HHV) of several of the components is significantly higher under adb conditions, which indicates a high possibility of being utilized as fuel.

Table 3   Proximate analysis result of the MSW components.

Sample Mark	Moisture %, adb	Ash %, adb	Volatile Matter %, adb	Fixed Carbon %, adb
Leaf	10.78	7.28	62.27	19.67
Food waste	8.48	4.51	72.52	14.49
Wood	8.82	7.15	66.64	17.39
Thick Paper	7.56	5.40	75.01	12.03
Writing paper	6.42	11.77	75.13	6.68
Duplex paper	20.64	9.54	61.02	8.80
Box paper	6.81	8.44	75.34	9.41
PVC	0.28	4.96	79.83	14.93
Bottle plastic	0.63	0.62	89.32	9.43
Hard plastic	0.52	0.41	89.90	9.17
Wrapping plastic	0.31	3.54	89.76	6.39
Toy plastic	0.20	1.70	98.09	0.01
PP plastic	0.07	0.66	99.23	0.04
OPP plastic	0.76	0.18	99.06	0.00
Container plastic	0.20	1.49	98.05	0.26
HD plastic	0.06	0.41	99.53	0.00
Syringe	0.36	0.69	98.48	0.47
PE plastic	0.03	0.41	99.56	0.00
Plastic bag	0.12	1.85	98.03	0.00
Medical plastic	0.21	0.46	94.33	0.00
Plastic cup	0.18	0.79	99.03	0.00
Styrofoam	1.45	0.84	96.75	0.96
Synthetic	1.54	14.97	70.27	13.22
Waste sample I	5.80	26.77	54.98	12.45
Waste sample II	33.08	8.98	48.66	9.28
Textile	1.23	0.42	89.07	9.28
Rubber	0.01	22.91	74.84	2.23
Others	5.72	0.28	79.08	14.89

Although the amount of volatile matter was significant, as the waste contains a high moisture content in as received (ar) condition, direct combustion was chosen as the process for energy recovery in the WTE plant instead of gasification. The chlorine contained in the samples was also tested, because chlorine is a source of dioxin, a carcinogen that may be generated in low-temperature combustion.

Valuable components such as recyclable plastic, paper, electronics, glass, and metal are often selected and taken by informal collectors from TPSs and TPAs, hence the remaining waste consisted only of organic matter, non-recyclable plastic and other wastes, as shown in Table 5. The ultimate, proximate composition and heating value of this remaining waste are shown in Tables 6 and 7. Based on these figures, the combined properties of the remaining waste components (organic matter, food waste, non recyclable plastic, textile, rubber, and miscellaneous) was calculated as follows:

$$\phi_{comb} = \sum \varphi_i \phi_i \tag{1}$$

where φ_{comp} = any combined element, ϕ_i = mass fraction of waste component, φ_i = element i of the component. The related elements are: ash, moisture, fixed carbon, volatile matter, total carbon, hydrogen, oxygen, nitrogen, and sulfur of the combined remaining waste. The heating value (HHV) was calculated in a similar way. The proximate and ultimate elements of the combined remaining waste components can be seen in Table 8.

The following equations are used to convert the *air-dried based* composition to *as receive based* composition [4]:

$$z_{ar} = z_{MAF} \times \left(1 - \varphi_{ash,ar} - \varphi_{M,ar}\right) \tag{2}$$

$$z_{MAF} = \frac{z_{adb}}{1 - \varphi_{ash,adb} - \varphi_{M,adb}} \tag{3}$$

where z_{ar} = any properties *as received basis*, z_{MAF} = any properties *moisture and ash free basis*, z_{adb} = any properties *air dried basis*, ϕ_{ash} = ash mass fraction, ϕ_M = moisture mass fraction, the subscript *adb* indicates *air dried basis*, while *ar* indicates *as received basis*. The proximate and ultimate elements on *as received basis* can be calculated at various moisture contents by assuming that the ash mass fraction is fixed at 20%, the value that is usually encountered in WTE plants. The fraction of elements with 40 to 60% moisture content can be seen in Table 9.

Table 4 Caloric value and ultimate analysis result of the MSW components.

Sample Mark	HHV kJ/kg, adb	C %, adb	H$_2$ %, adb	N %, adb	S %, adb	O$_2$ %, adb	Cl %, adb
Leaf	17258	42.50	5.86	0.98	0.39	42.99	0.40
Food waste	20009	45.06	6.98	2.90	0.27	40.28	2.70
Wood	15684	41.93	5.72	0.70	0.10	44.40	0.10
Thick Paper	15165	41.72	5.95	0.07	0.11	46.75	0.07
Writing paper	12548	34.96	4.60	0.08	0.08	48.51	0.02
Duplex paper	12297	32.68	6.20	0.12	0.12	51.34	0.12
Box paper	15474	39.00	5.70	0.45	0.16	46.25	0.08
PVC	19418	36.00	4.91	0.00	0.17	53.96	3.83
Bottle plastic	21876	62.50	4.76	0.03	0.09	32.00	0.04
Hard plastic	23375	70.50	6.52	0.45	0.08	22.04	0.06
Wrapping plastic	31041	60.55	7.53	0.11	0.23	28.04	3.82
Toy plastic	44966	87.23	7.71	0.01	0.08	3.27	0.04
PP plastic	45770	85.71	13.15	0.04	0.07	0.37	0.06
OPP plastic	45766	84.01	12.66	0.01	0.11	3.03	0.03
Container plastic	44795	83.81	10.05	0.06	0.01	4.49	0.08
HD plastic	45586	72.30	11.33	0.02	0.13	15.81	0.02
Syringe	45653	83.60	11.10	0.04	0.09	4.48	0.07
PE plastic	46084	83.75	13.08	0.05	0.08	2.63	0.06
Plastic bag	45008	89.95	5.68	0.07	0.10	2.45	0.04
Medical plastic	45644	83.93	13.70	0.03	0.09	1.88	0.04
Plastic cup	46143	81.22	15.33	0.04	0.07	33.21	0.12
Styrofoam	38359	91.35	6.49	0.07	0.14	1.11	0.02
Synthetic waste	21956	45.72	6.67	1.45	0.39	30.80	3.85
Waste sample I	14712	27.80	3.18	0.92	0.23	41.10	0.08
Waste sample II	11045	24.33	10.78	0.55	0.16	55.20	0.10
Textile	18774	52.54	5.69	0.44	0.21	40.71	0.03
Rubber	28948	45.72	6.67	1.45	0.39	30.80	3.85
Others	22588	42.25	5.79	0.84	0.25	43.69	0.10

Table 5 Composition of the remaining MSW.

Component	Mass Fraction	Volume Fraction
Organic matter	49.24	68.22
Food Waste	31.23	18.00
Non Recycled Plastic	8.21	7.85
Textile	2.83	1.42
Rubber	0.92	0.55
Others	7.57	3.96

Table 6   Proximate analysis result of the remaining MSW components.

Component	Moisture %, adb	Ash %, adb	Volatile Matter %, adb	Fixed Carbon %, adb
Organic matter	9.80	7.215	64.45	18.53
Food waste	8.48	4.51	72.52	14.49
Non-recycled plastic	0.88	2.19	93.25	3.67
Textile	1.23	0.42	89.07	9.28
Rubber	4.78	14.55	72.55	7.72
Others	0.71	5.70	79.10	14.49

Table 7   Caloric value and ultimate analysis result of the remaining MSW components.

Sample Mark	HHV kJ/kg, adb	C %, adb	H_2 %, adb	N %, adb	S %, adb	O_2 %, adb	Cl %, adb
Organic matter	16446	42.22	5.79	0.84	0.25	43.69	0.25
Food waste	20003	45.06	6.98	2.90	0.27	40.28	2.70
Non-recycled Plastic	34691	75.95	7.01	0.09	0.18	14.57	1.92
Textile	18769	52.54	5.69	0.44	0.21	40.70	0.03
Rubber	25445	45.72	6.67	1.45	0.39	30.80	3.85
Others	22582	54.41	6.59	1.28	0.23	32.85	0.21

Table 8   Proximate and ultimate analysis result of the remaining MSW components.

Proximate		Ultimate	
Component	%	Component	%
Volatile matter	71.19	Carbon	48.46
Fixed carbon	15.41	Oxygen	41.98
Moisture	8.04	Hydrogen	6.58
Ash	5.36	Nitrogen	1.49
		Chlorine	1.23
		Sulphur	0.26

From Table 9 it can be seen that the sulfur content is less than 0.1%, which is lower compared to the average sulfur content in coal (0.7%) [5]. The chlorine content of waste fuel is less than 0.5%; this value is higher compared to the chlorine content in coal (0.3%) [6] but still within the range of biomass fuels [7]. The sulfur and chlorine contents are harmless concentrations because they are smaller than 0.3% and 1.0% respectively [8].

Table 9 Prediction of element composition of remaining waste on *as receive basis* (*ar*).

Element	Mass Fraction (%)		
Moisture	40.0	50.0	60.0
Carbon (C)	19.38	14.54	9.69
Hydrogen (H$_2$)	2.63	1.97	1.32
Nitrogen (N)	0.59	0.45	0.30
Sulfur (S)	0.10	0.08	0.05
Oxygen (O)	16.80	12.60	8.40
Chlorine(Cl)	0.49	0.37	0.25
Ash	20.0	20.0	20.0

The heating values obtained from the tests were *air dried basis* (adb) values (*HHV$_{adb}$*). These values have to be changed to *as received basis* (ar) values (*HHV$_{ar}$*) and they can be calculated from:

$$HHV_{ar} = HHV_{MAF} \times (\varphi_{FC} + \varphi_{VM}) \tag{4}$$

$$HHV_{MAF} = \frac{HHV_{adb}}{1 - \varphi_{ash}} \tag{5}$$

where ϕ_{FC} = mass fraction of the fixed carbon and ϕ_{VM} = mass fraction of the volatile matter, HHV_{MAF} = heating value in moisture and ash free condition, ϕ_{ash} = mass fraction of the ash. The *as received basis* low heating value (*LHV$_{ar}$*) is then calculated from:

$$LHV_{ar} = HHV_{ar} - Q_{H_2O} \tag{6}$$

where:

$$Q_{H_2O} = Q_1 + Q_2 \tag{7}$$

Q_1 = heat to evaporate moisture within the fuel:

$$Q_1 = \varphi_M \times h_{fg} \tag{8}$$

Q_2 = heat to evaporate water that is formed from the combustion reaction of the hydrogen:

$$Q_2 = 9 \times \varphi_H \times h_{fg} \tag{9}$$

with ϕ_M = mass fraction of the moisture within the fuel, ϕ_H = mass fraction of the hydrogen within the fuel, and h_{fg} = latent heat of evaporation at 100°C,

2257 kJ/kg. The heating value LHV_{ar} for different values of moisture content can be seen in Figure 1.
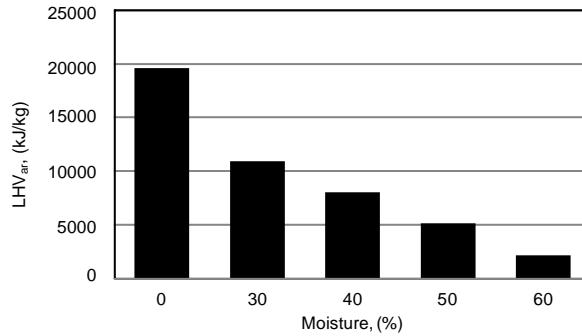

Figure 1   Variation of waste heating value with moisture content.

From Figure 1 it can be seen that the heating value is strongly influenced by the moisture content. For the waste to be burned without using additional fuel, the moisture content should be lower than 50%, the ash content lower than 60%, and the fixed carbon content larger than 25% [9]. This condition is shown by the shaded area in Figure 2. Since the actual moisture content in fresh tropical MSW can reach 60 to 70%, the waste has to be pre-treated before it can be burned in a furnace. For a moisture content of 40% the heating value (LHV) of the waste is around 1500 kcal/kg (6000 kJ/kg). This heating value and its related ultimate elements composition were used in the design of a WTE plant.
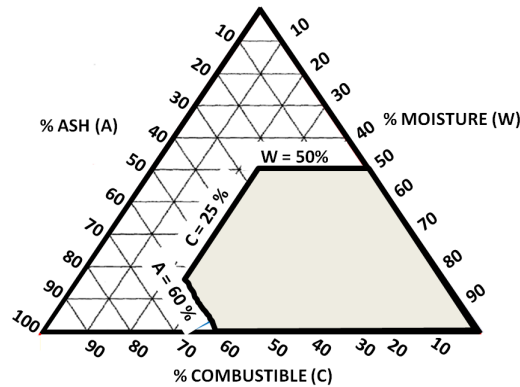

Figure 2   *Tanner* diagram for waste combustion [8].

4 Waste to Energy Plant

A small WTE plant concept is shown in Figure 3; the waste collected from the city is dumped into a ditch where informal collectors can select recycleable materials. Then the remaining waste is chopped in a chopping machine and distributed by a dozer on the drying floor. The WTE plant is planned to be located close to a TPA. The waste is air-dried for several days before it is sent to the furnace by a belt conveyor system, so that the moisture content drops below 40%. The waste is self-burned in the furnace at a temperature above 850 °C. The flue gas is used to generate steam in a boiler for electric power generation. The flue gas is treated and conditioned before it is released to the surrounding air through a stack.
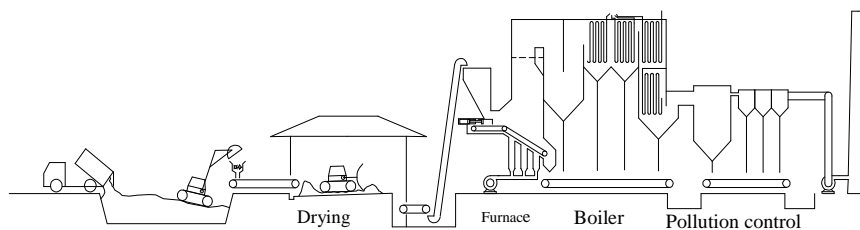

Drying   Furnace   Boiler   Pollution control

Figure 3 A small-scale Waste to Energy plant concept.

The operating conditions of the steam power plant were simulated using the Cycle Tempo software application. The input for the program was the technical specification of a commercial turbine, as shown in Table 10. Assumptions used in the simulation were: 85% of turbine isentropic efficiency, 75% of pump isentropic efficiency, 28°C ambient temperature, 76% of relative humidity of the surrounding air, and saturated vapor at the outlet of the turbine. The simulations were done for a water-cooled and an air-cooled condenser; the results are shown in Figure 4, and a summary of the results is shown in Table 11.

Table 10 Steam turbine specification.

Parameter	Value
Power	800 kW
Steam mass flow rate	1.149 kg/s
Inlet temperature	340 °C
Inlet pressure	13 bar
Extraction Pressure	1.71 bar
Extraction steam mass flow rate	0.134 kg/s
Outlet pressure	0.1 bar
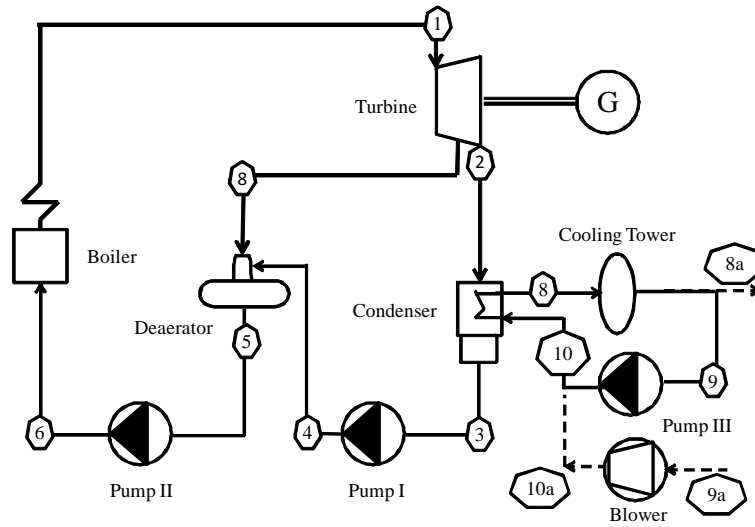
Station	Water-cooled condenser			Air-cooled condenser		
	P (kPa)	T (°C)	m (kg/s)	P (kPa)	T (°C)	m (kg/s)
1	1300.0	340	1.149	1300.0	340	1,149
2	10	45.81	1.019	10	45.81	1.019
3	10	45.81	1.019	10	45.81	1.019
4	171.0	45.83	1.019	171.0	45.83	1.019
5	171.0	115.3	1.149	171.0	115.3	1.149
6	1300.0	115.5	1.149	1300.0	115.5	1.149
7	171.0	146.84	0.13	171.0	146.84	0.130
8	151.3	38.01	53.71			
9	101.2	28.00	53.71			
10	201.3	28.01	53.71			
8a				102.3	40.00	225.08
9a				101.3	28.00	225.08
10a				103.3	30.24	225.08

Figure 4 Process diagram of WTE Plant.

Table 11 Summary of simulation.

Item	Water cooled	Air cooled
Heat in boiler, kW	3040	3040
Gross turbine power, kW	800	800
Pump I work, kW	0.37	0.38
Pump II work, kW	2.55	2.56
Pump III/Blower work, kW	8.93	547.3
Net power, kW	788	249
Thermal efficiency (%)	25.92	8.21

From the simulation results it can be seen that a small steam power plant can be fueled by the remaining waste from the MSW. Using a small steam turbine with extraction for an open type feed water heater (de-aerator), the plant produces 800 kW power. The system is a closed system using a low-pressure condenser. A water-cooled condenser system produces a much higher net power compared to an air-cooled system. An air blower consumes a high power and reduces the net power output and thermal efficiency of the system.

The Cycle Tempo simulation results were used as the input for a furnace and boiler simulation. The FireCad software application was used for the simulation. The input and assumptions were: 4136.4 kg/hour steam mass flow rate, 13 bar of water pressure entering the boiler, water entering the boiler with a temperature of 115 °C, and a steam temperature at the Super-heater outlet of 340°C, a flue-gas temperature leaving the stack of 180°C, 80% excess air in the furnace, 20% flue gas return (FGR), and waste-element composition used in the simulation as shown in Table 11. The FireCad simulation results were checked by re-inputting them into Cycle Tempo until convergence of steam mass flow rate and boiler heat load was reached. A summary of the results is shown in Table 12. The results show that the waste mass flow rate is 2040 kg/hour or around 2 ton/h if the WTE operates 24 hours a day, 4.2 ton/h of steam and 800 kW of electric power will be generated. The resulted main dimensions of the furnace and boiler are shown in Tables 13 to 16.

Table 12 Element composition of waste used in FireCad simulation (without chlorine).

Element	Mass Fraction (%)
Carbon	19.63
Hydrogen	2.66
Nitrogen	0.60
Sulphur	0.11
Oxygen	17.0
Ash	20.00
Moisture	40.00

The tables show that the furnace temperature reaches 900°C and the gas residence time is longer than 2 seconds, which fulfills the requirement for dioxin destruction [10-12]. The resulted dimensions have been checked manually and can be used for further designing of the plant.

Table 13 Summary results of FireCad simulation.

Parameter	Value
Steam generated, kg/hour	4136.4
Steam pressure, bar	13
Excess air, %	80.0
FGR, %	20.0
Boiler efficiency	79.27
Waste mass flow rate, kg/hour	2040.62
LHV waste, kJ/kg	6521.094
Boiler heat load, kW	3051 kW

Table 14 Furnace main dimensions.

Parameter	Value	Unit
Flue gas mass flowrate	12843,2	kg/hour
Flue gas volumetric rate	45020.2	m3/hour
Flue gas velocity	7.0	m/s
Furnace width	1.446	m
Furnace depth	1.221	m
Furnace height	19.0	m
Gas residence time	2.67	s
Gas temperature	915.5	°C

Table 15 Superheater main dimensions.

Parameter	Value	Unit
Pipe diameter	50.8	mm
Pipe thickness	4.0	mm
Pipe length	5.36	m
Transversal pitch	154.0	mm
Longitudinal pitch	154.0	mm
Umber of pipe pass	3	-
Number of pipe each row	4	-
Heat load	507	kW
Heat transfer area	10.26	m^2
Steam outlet temperature	386.28	°C
Gas temperature outlet	864.9	°C
Overall heat transfer coefficient (U)	39.0	W/m^{2}K

Table 16 Boiler bank main dimensions.

Parameter	Value	Unit
Pipe diameter	50.8	mm
Pipe thickness	3.66	mm
Pipe length	461	m
Transversal pitch	105	mm
Longitudinal pitch	100	mm
Number of pipe pass	22	-
Number of pipe each row	13	-
Heat transfer area	210.23	m2
Steam outlet temperature	199.18	$^{\circ}$C
Gas temperature outlet	326.42	$^{\circ}$C
Overall heat transfer coefficient (U)	35.26	W/m^{2}K

5   Conclusion

Based on the analysis results discussed above, it can be concluded that tropical municipal solid waste (MSW) can be used as a steam power plant fuel without using additional oil or solid fuel, even if recyclable components have been removed. The existing moisture content of the MSW is larger than 60%, so a pre-treatment process has to be applied to reduce the moisture content to 40-50%. The waste with a moisture content of 40% will have a heating value of 6500 kJ/kg or 1500 kcal/kg (LHV) on *as received* basis. Using the waste with a moisture content of 40%, a small WTE plant can be designed that can deliver 800 kW electric power from 50 tonnes/day or 2.04 kg/hr of waste. A WTE with an air-cooled condenser produces less power output and has lower thermal efficiency. The cycle simulation result data can be used for the design of a furnace and boiler. The results show that the waste may generate enough heat to maintain the furnace temperature at around 900°C and the gas residence time is longer than 2 seconds, as required for dioxin destruction.

Nomenclature

h_{fg} = latent heat of evaporation
HHV   = higher heating value
LHV   = lower heating value
M   = mass flow rate kg/s
MSW   = municipal solid waste
P   = pressure, kPa
T   = temperature in °C
WTE   = Waste-to-Energy
z_{ar} = any properties on as receive basis

z_{MAF}	= any properties on moisture and ash free basis
z_{adb}	= any properties on air-dried basis
ϕ_{ash}	= ash mass fraction
φ_{comp}	= any combined element
ϕ_H	= mass fraction of hydrogen within the fuel
ϕ_i	= mass fraction of waste component
φ_i	= element i of the component
ϕ_M	= mass fraction of moisture within the fuel

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