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Power Generation from Utilizing Thermal Energy of Hazardous Waste Incinerators

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ABSTRACT

A large amount of thermal energy is generated from burning hazardous chemical wastes, and the temperature of the flue gases in hazardous waste incinerators reaches up to (1200 °C). The flue gases are cooled to (40°C) and are treated before emission. This thermal energy can be utilized to produce electrical power by designing a system suitable for dangerous flue gases in the future depending on the results of much research about using a proto-type small steam power plant that uses safe fuel to study and develop the electricity generation process with water tube boiler which is manufactured experimentally with theoretical development for some of its parts which are inefficient in experimental work. The studied system generates theoretically (120 kg steam /h at 8 bars) with dry wood as fuel and preheating for the air of combustion and feed water and a diesel engine of (8 hp) four-stroke with single piston converted to steam engine coupled with the electrical generator of (3 kVA). The results are compared with practical values valid in the literature about small power plants of steam capacity (0.1-1) ton/h and operating pressure up to 10 bars. Experimentally, the generated electrical power is little and sufficient to operate a small fan and lump. The current converted steam engine is better than a conventional steam engine in auto lubrication with some operational problems. The boiler efficiency is 63.28%.

Keywords: Waste to energy, Hazardous flue gases, Water tube boiler, Converted steam engine, Electricity generation, Prototype system.

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توليد القدرة باستخدام الطاقة الحرارية لمحارق المخلفات الخطرة

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الخلاصة

كمية كبيرة من الطاقة الحرارية تتولد اثناء حرق المخلفات الكيمياوية الخطرة وتصل درجة حرارة غازات الاحتراق الناتجة من محارق المخلفات الخطرة الى (1200 درجة مئوية) ويتم تبريدها الى (40 درجة مئوية) ويتم معاملتها كيمياويا قبل اطلاقها الى الجو. هذه الطاقة الحرارية تستخدم لتوليد طاقة كهربائية بتصميم منظومة ملائمة لمحتوى غازات الاحتراق الخطرة مستقبلا اعتمادا على نتائج مجموعة بحوث ومنها العمل الحالي الذي يتعلق باستخدام منظومة ريادية صغيرة تعتمد وقود غير خطر لدراسة وتطوير عملية توليد الكهرباء والتي تتكون من مرجل نوع الماء داخل الانابيب تم تصنيعه عمليا وتطوير بعض اجزائه نظريا فقط لان بعض الاجزاء المصنعة لم تعطي الكفاءة المطلوبة. تولد المنظومة المدروسة نظريا (120 كغم بخار/ساعة لضغط 8 بار) باستخدام الخشب الجاف كوقود مع التسخين الاولي لهواء الاحتراق وماء التغذية وتم استخدام محرك ديزل بقدرة (8 قدرة حصانية) اربعة اشواط ذو مكبس احادي تم تحويره الى محرك بخاري مرتبط مع مولد كهربائي قدرته (3 كيلو فولت امبير). قورنت النتائج مع نتائج عملية منشورة تتعلق بمنظومات صغيرة تتراوح سعتها (0.1−1) طن بخار/ساعة ولضغط اشتغال 10 بار. تم الحصول عمليا على طاقة كهربائية قليلة تكفي لتشغيل مروحة ومصباح كهربائي صغير وكان المحرك البخاري المحور افضل من المحرك البخاري التقليدي من حيث التزييت الذاتي رغم وجود بعض مشاكل التشغيل وكانت كفاءة المرجل 63.28%.

الكلمات المفتاحية: المخلفات الى طاقة، غازات احتراق خطرة، مرجل أنبوب الماء، ماكنة بخارية محورة، توليد طاقة كهربائية، منظومة ريادية.

1. INTRODUCTION

Wastes are undeniably part of human society; accumulating these materials causes many environmental problems. The carbon sources in the wastes can be converted to energy like electricity, heat, chill, and fuels **(Taherzadeh, 2015)**. One of the major problems facing modern society is the provision of energy with the minimum generation of pollution and the environmentally friendly disposal of waste that is not practicable to recycle or reuse. Incineration is a renewable source of electricity supply and solves the problems of landfills. Waste to Energy (WTE) incineration helps in reducing greenhouse gases (GHGs) by avoiding dumping into landfills **(Luna et al., 2010)**.
(Abd Al-Razak, 2009) studied the effect of using different kinds of liquid fuel on boiler efficiency. Also **(Patel et al., 2013)** studied boiler efficiency improvement using many types of coal with different Gross Calorific Value (GCV). The boiler capacity was (40-ton steam/h) at 32 bar. On the other hand **(Ahmad et al., 2013)** studied the recovery of wasted heat from furnace flue gases using a wasted heat recovery boiler (WHRB) of a two-pass fire tube boiler. **(Luna et al., 2010)** gave a technical and economical assessment of power generation from the incineration of municipal solid wastes in Sao Paulo city-Brazil, which produce 10000 ton

of solid waste per day with an average low heating value of 10.6068 MJ/kg. **(Zaman, 2010)** analyzed using SimaPro software three different treatment technologies: sanitary landfill, incineration, and gasification-pyrolysis using the life assessment tool. **(Kapitler et al., 2011)** studied the characteristics of combustion of municipal solid waste as a fuel in energy plant using computational fluid dynamics. **(Yadav and Samadder, 2015)** explored the options of management for municipal solid wastes using life cycle assessment. **(Kim and Jeong, 2017)** studied and analyzed the incineration of flammable industrial wastes according to economic and environmental cost analysis in cement furnaces. **(Komarov et al., 2017)** studied numerically the improvements of the fire tube boiler by modeling numerically the incineration process in the combustion chamber and the corresponding heat transfer process.

(Moora et al., 2017) determined the biomass content in combusted municipal solid waste and associated annual average fissile CO_2 emissions, which was 429 kg/ton of combusted municipal waste in Estonia. They summarized the research results conducted in Estonias first waste incineration plant. **(Sharma and Tiwari, 2017)** design a horizontal fire tube two-pass boiler of 300 kg steam/h at 5 bars and 150˚C capacity for commercial cooking of Indian food in restaurants with a required heat output of 100 MCal/h. **(Tanczuk et al., 2018)** analyzed theoretically the technical possibilities of heat recovery from grate-fired district heating boiler of 45 MW thermal capacity. **(Khudair et al., 2018)** illustrated that Baghdads average annual municipal solid waste generation was (433.083 kg/(Capita. year)). **(Al-Amen and Al-Hamdany, 2018)** presented the average daily municipal solid waste generation in Babylon governorate in Iraq was (0.802 kg/(Capita.Day)). **(Kingori, 2022)** studied theoretically for boilers of small steam capacity (less than 6800 kg/h) with limited modifications on boiler stack to get a significant amount of recovered wasted energy.

(Behrendt and Szczepanek, 2022) studied theoretically the utilization of wasted heat from marine exhausted flue gases using feed water preheating and air of combustion preheating, the efficiency of the marines main boilers was increased.

The previous works dealt with burning hundreds of tons of solid wastes per day that were needed to steam power plant with steam turbines, which are high costs and high working pressure of 40 bars **(Raja et al., 2006)**. However, when dealing with (0.1-1) ton of solid waste per day like farms solid wastes, it is useful to use a small power plant (or tiny power plant) as V.K. Desais (an Indian mechanical engineer) works using steam engines of different sizes (8-100) hp that gives electricity (5-70) kVA with working pressure 10 bars and (0.12-1) ton of steam/hr, (for simple steam engine 16 kg steam/hp h). The problems of Desais tiny power plants (which can be found on www.tinytechindia.com) are the need for a person to supply wood to the incinerator continuously (no automatic feeding), another person to lubricate the steam engine continually and the calibration of the steam engine to work at steady speed with variation of load from no load to full load or from full load to no load. Another problem (observed in this work) is that the output steam from the steam engine is rejected to the ambient, i.e., it was not condensed and cycled. It is not used to preheat the feed water and air of combustion to increase boiler efficiency.

The present work aims to:

1- Determine the quantity of hazardous wastes required to operate an electrical power plant continuously for 24 hours daily.

2- Specify the stages of treatment for hazardous flow gases from the burning step until they are exhausted from the chimney without any hazardous content theoretically.

3- The constituents of flue gases of two hazardous wastes, the contaminated soil with crude oil and the biomedical solid wastes of many local hospitals in Baghdad, theoretically determined the equivalent thermal energy.
4- Using Desais results to manufacture a prototype small power plant to produce electricity. This plant uses dry wood to fuel the theoretical analysis with experimental work in some parts of the studied system. The specific modification in the current research is using a converted steam engine instead of the conventional steam engine in Desais system and condensing the exhausted steam by bubbling method.

2. THEORETICAL ANALYSIS

The hazardous solid wastes are burned in an incinerator at (1200˚C), the resulting flue gases are cooled to (40 ˚C) using heat exchangers, then the treatment method of flue gases begins inside an off-gas system (including the process of neutralization, wet and dry scrubber and adsorption using active Carbon) to treat the acidic gases (SO_x and NO_x) then the residual gases (N_2, O_2, CO_2 and H_2O) is emitted through the chimney **(Visvanathan, 1996)**. The production of electrical energy from hazardous waste incinerators consists of many steps as follows:
1- Design an incinerator to burn specific hazardous solid wastes like biomedical solid wastes or contaminated soil with crude oil.
2- The design of heat exchangers and an off-gas system are under research (not completed).
3- Design a suitable boiler working on wasted heat to use the resulting thermal energy to evaporate wasted industrial water (under research) to produce electricity by producing low-pressure steam (less than 10 bars). The power is generated using a converted steam engine (less than 100 hp), consuming a low quantity of hazardous solid wastes (3 tons /h for non-continuous operation). Or using a steam turbine for large amounts (10 tons /h for 24 hours of continuous operation).
4- Studying a suitable converted steam engine and its performance and operational problems is safe if non-hazardous solid wastes are used as fuel of the boiler (like dry wood) before dealing with hazardous flue gases (the current presented research) and the following theoretical analysis is dealt with this step.

2.1 Wood Combustion Basics

Good details about wood combustion basics are given in **(Curkeet, 2011)**; the ideal and real equations of wood combustion are given as:

$$\alpha\, C_A H_B O_C + u\, O_2 + h\, N_2 \longrightarrow d\, CO_2 + h\, N_2 + j\, H_2O \tag{1}$$

$$\alpha\, C_A H_B O_C + u\, O_2 + h\, N_2 \longrightarrow d\, CO_2 + e\, CO + g\, O_2 + h\, N_2 + j\, H_2O + k\, C_x H_y \tag{2}$$

The stoichiometric (ideal) quantities are estimated as:

$$1 \text{ kg dry wood} + 6.4 \text{ kg air} \longrightarrow 1.83 \text{ kg } CO_2 + 0.52 \text{ kg } H_2O + 5.05 \text{ kg } N_2 \tag{3}$$

According to **(Curkeet, 2011)**, for good wood combustion, the recommended conditions are a range of combustion temperature ($T_{combustion}$) of (1100 to 1500) F or (593.33-815.55) ˚C. While the air-fuel ratio (Mass of air/Mass of fuel) is (10 to 12) kg_{air}/kg_{fuel} with excess air (50 to 100) %. Wood is a clean fuel. It does not have Sulphur content that produces SO_x in the flue gases, which can be converted to acidic materials and then cause corrosion to the metallic elements of the system **(Ganapathy, 1989)**. According to Eq. (3), for each 1 kg of wood completely burned, there is 1.83 kg of CO_2 (greenhouse gas) is emitted, which is less than Methane by 21 **(Luna et al., 2010)**.

2.1. Excess air and moisture calculations for wood incineration

The excess air used to burn wood in the current system is 100% **(Ganapathy, 2003; Curkeet, 2011)**. As a result, the excess O_2 is calculated as follows:

$$O_2\ (100\%\ excess) = 2\ O_2\ (stoichiometric) = 2.944\ \frac{kg_{air}}{kg_{fuel}} \quad (4)$$

$$Air\ required = \frac{O_2}{0.23} = 12.8\ \frac{kg_{air}}{kg_{fuel}} \quad (5)$$

$$N_2 = air\ required - O_2 = 9.856\ \frac{kg}{kg_{fuel}} \quad (6)$$

The moisture in the combustion air can also be determined from the following equations **(Ganapathy, 2015),** considering the average annual ambient temperature and relative humidity in Baghdad is approximately 30.8°C and 44.8 %, respectively **(Al-Jubouri and Hadi, 2019; Al-Musawi and Muhsin 2014)**:

$$Moisture\ (air) = \frac{0.622\ Pw\left(\frac{\mathrm{kg}}{\mathrm{cm}^2}.\mathrm{a}\right)}{(1.033 - Pw)} \quad (7)$$

where $1\left(\frac{\mathrm{kg}}{\mathrm{cm}^2}.\mathrm{a}\right) = 1\ \left(\frac{\mathrm{kPa}}{98.0665}\right)$

$$Pw = Relative\ humidity \times P\left(\frac{\mathrm{kg}}{\mathrm{cm}^2}\right) \quad (8)$$

From thermodynamics tables, the saturation pressure Psat at 30.8°C is 4.25 kPa or $(0.043338\ \frac{\mathrm{kg}}{\mathrm{cm}^2})$, the Pw is 0.0194154, the moisture (air) is 0.0119145 kg H_2O/kg air, and the quantity of moisture in air combustion is (0.0119145 × 12.8 kg/kg fuel, or 0.1525056 kg moisture/kg fuel). The final wood combustion with 100% excess air is given as:

1 kg dry wood + 2.944 kg O_2 + 9.856 kg N_2 + 0.1525056 kg H_2O $\longrightarrow$ 9.856 kg N_2 + 1.472 kg O_2 + 1.83 kg CO_2 + 0.6725056 kg H_2O + ash (9)

The mass of ash is calculated as:

$$Ash = reactants - products \quad (10)$$

= 0.122 kg/kg fuel, m_{dp} = 13.158 kg dry products /kg fuel.
$m_{moisture}$ = 0.67251 kg/kg fuel, $m_{flue\ gases}$ = 13.831 kg/kg fuel.

2.2 Boiler Efficiency

2.2.1 Direct Method

The efficiency of the boiler (η) can be obtained using two methods: direct and indirect. They can be determined **(Patel et al., 2013; Ganapathy, 2015)**:

$$\eta_{boiler}\,(direct) = \frac{Output\ thermal\ energy}{Input\ thermal\ energy} = \frac{m\ steam(hg\ steam - hf\ feed\ water)100\%}{m\ fuel * HHV} \tag{11}$$

$$\eta_{boiler}\,(indirect) = 100 - losses \tag{12}$$

The used fuel in the present system boiler is dry wood with a Higher Heating Value HHV of (21.7 MJ/kg). This work uses nearly 25 kg/hr of dry wood fuel, and the generated steam is 120 kg/h (according to Desai's results for an eight-hp steam engine) at 8 bars and a saturated temperature of 172˚C. The fuel is clean (no Sulphur content where SO_x condensed below 200˚C), so the flue gases can be cooled under 200˚C substitute for calculating the boiler efficiency by a direct method as follows:

$$\eta_{boiler}\,(direct) = \frac{qo\ steam \times 100}{q_i\ fuel} \tag{13}$$

In which the heat required to generate steam is:

$$qo\ steam = msteam\ \ (hg(172^{\circ}C) - hf\ (30.8^{\circ}C)) \tag{14}$$

$$= 120\ kg/h \times (2768.5 - 125.7)\ kJ/kg = 317.136\ MJ$$

The heat emitted by burned fuel is:

$$q_i\,fuel = HHV * fuel\ mass \tag{15}$$

$$= 21.7\ MJ/kg * 25\ kg = 542.5\ MJ$$

Then, the direct boiler efficiency equals (58.45 % without a preheating process for feed water and air of combustion).

2.2.2 Indirect Method

Thermal losses percentages are as follows **(Patel et al., 2013; Ganapathy, 2015)**:
Let L1 be the loss due to dry flue gas, L2 be the loss due to hydrogen in fuel, L3 is the loss due to moisture in fuel, L4 is the loss due to moisture in air, L5 is the loss due to CO formation, L6 is the loss due to un-burnt fuel in fly ash, L7 is the loss due to un-burnt fuel in bottom ash, L8 is the loss due to radiation and convection (surface loss). These losses are expressed as:

$$L1 = \frac{mdp\ cpdp\ (Tfg - Tambient)\ 100\%}{GCV} \tag{16}$$

$$= \frac{13.158 \times 1.086\ (300 - 30.8) \times 100\%}{21700} = 17.727\%.$$

For dry wood fuel, L3 is evaluated as:

L3 = 0

$$L2 + L4 = \frac{mmoisture\ (cpdp\ (Tfg - Tambient) + hfg) \times 100\%}{GCV} \tag{17}$$

$$= \frac{0.6725056\ (4.183\ (300-30.8)+2429.6)^{\times}100\%}{21700} = 11.02\ \%.$$

$$L5 = \frac{mash*\ GCV\ ash^{\times}100\%}{GCV} \tag{18}$$

$$= \frac{0.122^{\times}150^{\times}4.18^{\times}100\%}{21700} = 0.3525\%.$$

$$L6 = \frac{mash\ GCV\ ash^{\times}100\%}{GCV} \tag{19}$$

$$= \frac{0.122^{\times}700^{\times}4.18^{\times}100\%}{21700} = 1.645\%.$$

$$L7 = \frac{mblow\ down\ (hfg\ (172^{\circ}C)-hl(ambient))^{\times}100\%}{GCV*mfuel} \tag{20}$$

$$= \frac{30\ (2769-125.7)^{\times}100\%}{21700^{\times}25}$$

L7 = 14.617%.

L8= (1-2) % for small boilers = 2%. (21)

So, all losses are 47.36 %, and the indirect boiler efficiency η_{boiler} (indirect) is 52.64 % without the preheating process for feed water and air of combustion.

2.3 Feed Water and Combustion Air Pre-Heating

Boiler efficiency increases if wasted heat is recovered from flue gases (at 300˚C) to feed water and air of combustion (at ambient temperature 30.8 ˚C) using suitable pre-heating devices of helical shapes which are put inside the chimney of the boiler **(Behrendt and Szczepanek, 2022)**. The adopted helical shape of the preheater is to enhance the turbulence of the flow **(Kingori, 2022)**. The detailed design, performance, and manufacture of the preheating devices are out of current research aims, so a theoretical analysis is considered to compute the input and output temperature of flue gases and feed water in the preheater device. Then, the outer flue gases enter the air of the combustion preheater device zone inside the boilers chimney at a new temperature. The new input and outer temperatures of flue gases and air inside the preheater device assume that all heat recovered from flue gases will be gained from feed water and air of combustion. Assume flue gases enter the boilers chimney from the bottom at (300˚C) and the feed water exits the preheater at (T_{g2}). The feed water enters the preheater from the top at ambient temperature (30.8˚C) and leaves from the bottom at (T_{w2}) towards the check valve with a pressure greater than boilers pressure (8 bars). A counter-current gas-water exchange heat such as:

$$m_w Cp_w\ (T_{w2} - 30.8^{\circ}C) = m_{fg}\ Cp_g\ \left(300 - T_{g2}\right) \tag{22}$$

The feed water mass flow rate (m_w) is 120 kg/h (0.0333 kg/s) to produce steam of (120 kg/h). The blowdown water is (30 kg) left in the boilers cylindrical tank for the safety of boiler operation. The specific heat of feed water ($cp_w = 4.183 \frac{kJ}{kg.C}$), the flue gases total mass flow rate is calculated as follows:

m_{fg} = 13.8305 $\frac{\text{kg flue gases}}{\text{kg fuel}}$ × 25 kg of fuel

= 345.76264 $\frac{\text{kg flue gases}}{\text{h}}$ = 0.096045 $\frac{\text{kg flue gases}}{\text{s}}$,

c_{pg} = 1.086 $\frac{\text{kJ}}{\text{kg.C}}$, substitute the previous values in Eq. (22) gives:

0.13929 T_{w2} + 0.1043 T_{g2} = 35.581461, using try and error method to get

T_{w2} = 90.713˚C, T_{g2} = 220˚C. By following the same procedure, the heat balance is applied to the air preheater such that :

$$ma\ Cp_a(T_{a2} - 30.8) = m_{fg}c_{fg}(220 - T_{g3}) \tag{23}$$

ma = 12.8 $\frac{\text{kg air}}{\text{kg fuel}}$ × 25 kg fuel

= 320 $\frac{\text{kg air}}{\text{h}}$ = 0.0888 $\frac{\text{kg air}}{\text{s}}$,

Cp_a is approximately equal to Cp_g, substitute these values in Eq. (23) gives:

0.0888T_{a2} + 0.096045 T_{g2} = 23.8676, which is solved by trial and error method to get

T_{a2} = 90.318˚C, T_{g3} = 165˚C.

2.4 Boiler Efficiency after Preheating Process

The wasted heat recovered from flue gases into feed water and air of combustion decreases the consumption of wood fuel. It can be evaluated as:

$$qrecovered\ = m_g\ Cp_g\ (300 - 165) \tag{24}$$

= 50.692 $\frac{MJ}{h}$ = 14.08 kW.

q_{fuel} = 21.7$\frac{MJ}{kg}$ × 25 $\frac{kg\ fuel}{h}$ = 542.5$\frac{MJ}{h}$, q_{fuel2} = 491.81$\frac{MJ}{h}$, the saved fuel by recovered heat is nearly 10%. The boiler efficiency using the direct method can be computed as follows:

$\eta_{direct} = \frac{120kg\ (6769-376.9)kJ/kg \times 100\%}{491.81\ MJ/h}$ = 58.36%.

The boiler efficiency using the indirect method, the values of (L3, L5, L6, L7, and L8) are the same as before the preheating process because they didn't depend on the temperature of flue gases. The other thermal losses can be computed as follows with (T_g–T_{amb}=165–30.8= 134.5˚C):

L1 = 8.837%, L2 + L4 = 9.27%, and the boiler efficiency is:

$\eta_{indirect}$ = 63.27%.

2.5 Weight and Volume Fractions of Flue Gases

The mass of total flue gases for (1 kg of fuel) is ($13.8305 \frac{kg\ flue\ gases}{kg\ fuel}$) and the weight fraction of flue gases can be given as follows **(John and Swamy, 2011)**:

$$\%W = \frac{9.856}{13.8305} N_2 + \frac{1.472}{13.8305} O_2 + \frac{1.83}{13.8305} CO_2 + \frac{0.6725056}{13.8305} H_2O$$

$$\%W = 0.712627\ N_2 + 0.1064314\ O_2 + 0.132316\ CO_2 + 0.0486\ H_2O \tag{25}$$

The volume of gas (assumed as ideal gas) can be computed from the following equation **(Ganguly et al., 2017)**:

$$V_{gas} = \frac{mg*22.4*(Tg+273)}{Molecular\ weight\ of\ gas*273*3600} \tag{26}$$

The molecular weight of gases (N_2, O_2, CO_2, and H_2O) are (28, 32, 44, and 18) respectively. Substituting the volume of these gases (0.0035139, 0.0004592, 0.0004151, and 0.0003729)$\frac{m3}{s.\ kg\ fuel}$ respectively in Eq. (26), the total volume of the flue gases for (1 kg fuel) is ($0.0047611\frac{m3}{s.\ kg\ fuel}$), and the volume fraction of flue gases can be given as follows:

$$\%V = 0.7380437\ N_2 + 0.09644\ O_2 + 0.087185\ CO_2 + 0.0783222\ H_2O \tag{27}$$

2.6 Performance of Converted Steam Engine

The current steam engine is converted from a diesel engine of (8 hp) four-stroke single piston (more experimental details are given in section 3.2 later); the external combustion performance **(Sabah, 1984)** of the current steam engine can be given as follows:

$$25\frac{kg\ dry\ wood\ fuel}{h} \longrightarrow 120\frac{kg\ steam\ at\ 8\ bars}{h} + 345.76264\frac{kg\ flue\ gases}{h}\ [45.75\frac{kg\ CO2}{h}] + [3\ kVA\ (nearly\ 10\ amperes) - P_{pump} - P_{blower}] \tag{28}$$

The internal combustion performance for the same engine before its converting process to a steam engine can be given as following procedure (where a five hp diesel engine consumes diesel in internal combustion at a rate of ($2.2\frac{liter\ \text{diesel}}{h}$)) as observed from the experiments. The equation of combustion of diesel ($C_{12}H_{23}$ with $\rho = 0.845\frac{kg}{liter}$ and HHV = $44.8\frac{MJ}{kg}$) is given as:

$$C_{12}H_{23} + 17.75\ O_2 \longrightarrow 12\ CO_2 + 11.5\ H_2O \tag{29}$$

For 20% excess air, the combustion of diesel can be given as follows:

$$1\ kg\ (1.1833\ liter)\ C_{12}H_{23} + 4.08\ kg\ O_2 + 13.65913\ kg\ N_2 + 0.2113\ kg\ air\ moisture \longrightarrow 13.65913\ kg\ N_2 + 0.68\ O_2 + 3.16\ CO_2 + 1.45084\ kg\ H_2O$$

For $2.2\frac{liter\ \text{diesel}}{h}$, the equation of internal combustion is given as:

$$1.859\ kg\ (2.2\ liter)\ C_{12}H_{23} + 7.58472\ kg\ O_2 + 25.3923\ kg\ N_2 + 0.3928\ kg\ air\ moisture \longrightarrow 25.3923\ kg\ N_2 + 1.26412\ O_2 + 5.87444\ CO_2 + 2.697111\ kg\ H_2O$$

The total mass of flue gases is (35.2279 kg), and the performance of an internal combustion engine can be given as:

$$1.859\,\frac{kg}{h}\ (2.2\frac{liter\ diesel}{h})\text{diesel fuel} \longrightarrow 35.2279\frac{kg}{h}\ [5.87444\frac{kg\ CO2}{h}]+3\ kVA\ \text{of steady electrical power} \quad (30)$$

2.7 Steam Exhausts Condensation and Recycling

For best recovery of wasted heat, it is recommended to condense the exhausts of the steam engine **(Raja et al., 2006)**, assuming that the steam is at (4 bars and a corresponding saturated temperature of 144°C) with a mass flow rate of (120kg/h or 0.033kg/s). It is condensed by bubbling method inside a closed feed water tank that contains (600 liters of distilled water at ambient conditions). During one hour, all steam is condensed and mixed with the water in the feed tank to reach the thermal equilibrium at T_2 as in the following equation:

$$m_{steam}\ [c_{p\ steam}\ (T_s - T_2) + h_{fg}] = m_{feed\ water}\ c_p\ (T_2\text{-}30.8) \quad (31)$$

$$120\ [4.3\ (144\text{-}T_2) + 2131.8] = 600 \times 4.183 \times (T_2\text{-}30.8)$$

Solving for T_2 = 134.649°C, it is the corresponding saturated temperature at (3 bars).

2.8 Boiling Limitation

The nucleate and bubble boiling regions are presented in the economizer in the boiler tank due to the high subjected heat flux. To prevent an unstable film boiling region, one should not exceed a critical point, which is called burn-out heat flux (q_{cb}'') or critical heat flux (CHF), which is given by the equation below **(Ashrae, 2017)**:

$$q_{cb}'' = K_D\ \rho_g\ \ h_{fg}\ [\frac{g\ \sigma l\ (\rho l - \rho g\ )}{\rho g 2}\ ]^{0.25} \quad (32)$$

K_D is a constant depending on the heating surface-liquid combination, and it is equal to (0.006), σ_l is the liquid surface tension in (N/m), substitute the properties of Eq. (32) at (8 bars), then it becomes:

$$q_{cb}'' = 0.006 \times 4.1181 \times 2041.1\ [\frac{9.8 * 44.1\ (897 - 4.1181\ )}{(4.1181)2}\ ]^{0.25} = 619.41\frac{kW}{m^2}$$

More details about boiling limitations and applications can be found in **(Hadi, 2006)**.
The incineration of solid wastes inside the boiler produces steam; when the steam reaches a pressure of 10 bars, it enters the steam engine to have at least 1500 rpm to give electrical energy of 50 Hz and 220V. The output steam exhaust can be condensed inside a tank filled with water, and then the water can be pumped to the boiler.

3. EXPERIMENTAL WORK

The steps followed to produce electricity in this system are:
1- The dry wood is burned to produce the thermal energy required to heat the water in the boiler tank from ambient temperature to the saturated temperature corresponding to a

pressure of 8 bars (172˚C), and the superheated steam is generated by the superheater zone in the boiler.
2- Open the converted steam engine inlet valve manually to permit the engine to rotate at 1500 rpm to produce electrical power. This power is measured through an electrical control panel using a voltmeter and frequency meter.
3- Operate the feed water pump to supply the preheater with feed water, then to the economizer to be heated to 172˚C (8 bars), and the above procedure is repeated.
The details about the current systems parts manufacturing are given in the following sections.

3.1 Boiler Design

A copy of Desai's boiler is designed and manufactured to produce 120 Kg of steam/hr to operate an eight hp (5 kVA) four-stroke single piston converted diesel engine into a steam engine. The boiler shown in **Fig. 1** consists of the following parts **(Buecker, 2002):**

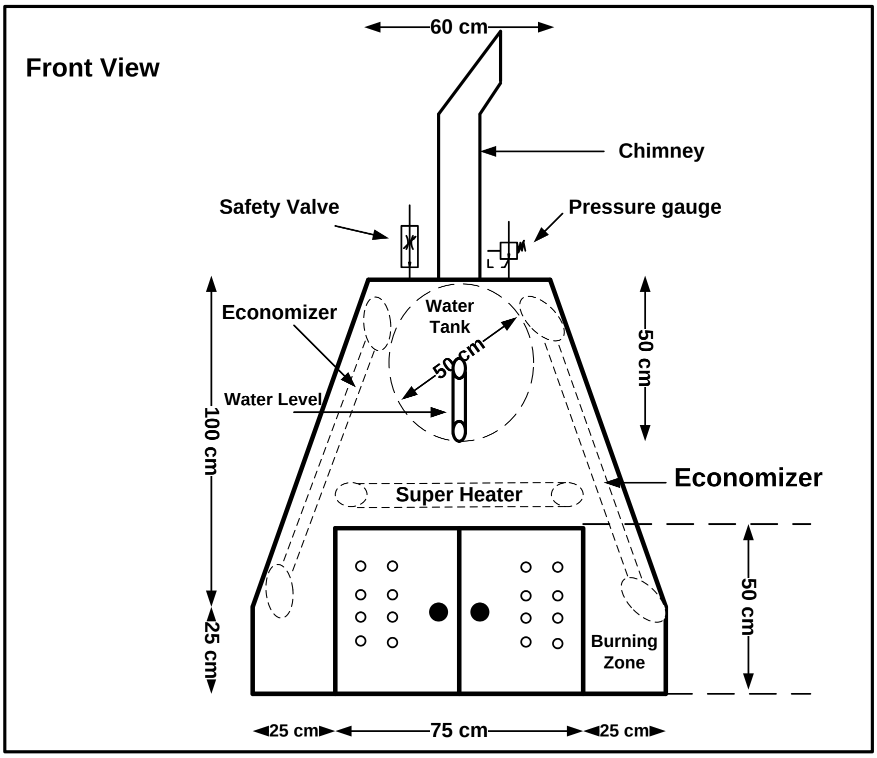


Figure 1. Schematic diagram of the boiler

1- The furnace zone works with burning wood or solid wastes (except hazardous wastes that need special treatment before emissions its flue gases to the air) to liberate the required thermal energy for steam generation. The lower side of the burning zone is covered with limestones.
2- Waters drum: It is a cylindrical tank with closed ends made from Carbon Steel with a diameter of (50 cm), 75 cm long, and 1 cm thick. The tank is filled with water to one-third of its size (50 liters). This tank is fixed horizontally at the top of the boiler. A liquid glass level is set at the end of the drum, as shown in **Fig. 1**.

3- The economizers' design has a feed water passage forty times the old design because there are 20 pipes in each economizer, connected by series in the modified design instead of parallel connection in the old manufactured design. The two economizers are connected in series in the modified design. A small quantity of feed water travels in a long heating path, which increases the heat transfer rate between the feed water and flue gases, which causes the efficiency of the system boiler to increase. Economizers are bands of pipes welded using Argon welding type and arranged as shown in **Fig. 2**.

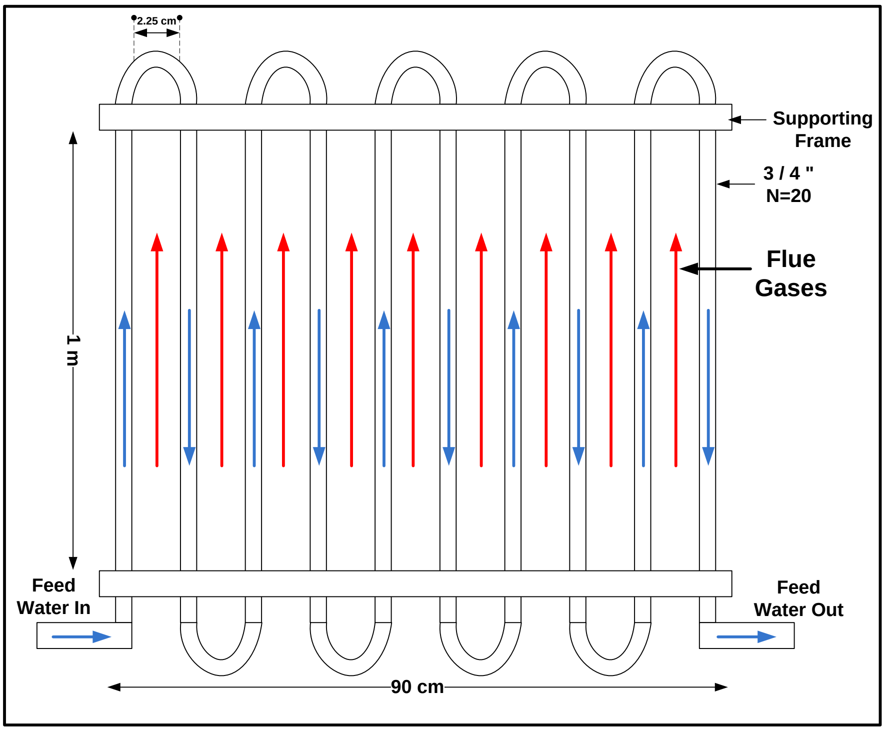


Figure 2. Schematic diagram of economizers design

There are two economizers where the water flows inside and changes phase from liquid to vapor then it enters the waters drum where the steam exists from top to the superheater.
4- The superheater is under the water's drum, where the steam is superheated at a pressure gauge of (8-10) bars. The valve will be opened manually to enter the steam into the steam engine.
5- The boiler shown in **Fig. 3** is thermally insulated with Rockwool of 5 cm thickness to decrease heat loss from the boiler. A check valve is set at the boiler inlet to control the feeding water pressure. The quantity of the obtained steam depends on the input heat flux that must be continuous to generate steam.

Figure 3. . Pictorial view of the manufactured Boiler

3.2 Steam Engine

A diesel engine (8 hp) four-stroke with a single piston is converted to a steam engine by getting out of the part (the camshaft) that is responsible for opening the air valve in the diesel engine, which assists the ignition of diesel inside the engine, for more details about diesel engines see **(Sabah, 1984)**. The camshafts steam engine and the conversion part are shown in **Figs. 4 and 5,** respectively.

Figure 4. Pictorial view of the steam engine

Figure 5. Pictorial view of the conversion part in camshaft.

3.3 Electrical Generator

An electrical generator of 3 kVA is used, and it is conducted with the steam engine by pulleys of ratios (1:2, 1:3, and 1:4), as shown in **Fig. 6.**

Testing the operation of the system shows that the produced electrical power is small compared with the input thermal heat energy. For best operation, a flywheel is added to the engine to increase the moment of inertia for the engine. The old design of the systems engine and electrical generator are shown in plates (2 and 4), respectively. Four pulleys of diameters (3, 6, 9, and 12) inch are used with ratios (1:2, 1:3, and 1:4) to get (750, 500, and 375) rpm, respectively. Where the small pulley is put at the electrical generator and the big pulley is put at the steam engine, for example, the (1:2) pulleys ratio when the big pulley rotates at 750 rpm, the small pulley rotates at 1500 rpm. The suggested flywheel of 10 kg mass is suitable to be fixed with the engine to get the best produced electrical power.

Figure 6. Pictorial view of the electrical generator of 3 kVA

3.4 Feed Water Tank

A tank of size 1000 liters is used to feed the boiler with water. The exhaust steam from the steam engine is entered into the feeding tank through a hydraulic thermal hose to condensate the steam inside the water tank by bubbling method then the water is pumped (a washing pump of cars is used to feed water at 130 bar and 7 liter/min) to the boiler through the check valve. The cycle of the system is complete.
The spiral shape of the feed water preheater is important to decrease pressure loss before the check valve unit because the hot water pump is expensive, cold feed water (at ambient temperature between zero to 50 ˚C between Winter and Summer) is pumped through the feed water preheater before entering check valve unit the feed water temperature becomes 90.713˚C the feed water after the check valve unit enters 40 of economizers pipes which are connected in series (nearly 40m heating passage of the feed water) this is sufficient to reach 172˚C the saturation temperature corresponding to 8 bars.
The air preheater is necessary to feed the combustion zone with hot air at a temperature of 90.32˚C to enhance the boilers' efficiency. Due to the system's open design to supply wood fuel manually, a quantity of fresh air enters from the system door. At the same time wood fuel boiler, for the best combustion conditions, needs (50-100) % excess air **(Curkeet, 2011),** which means there a thermal energy losses in this type of boiler.

3.5 Instrumentations

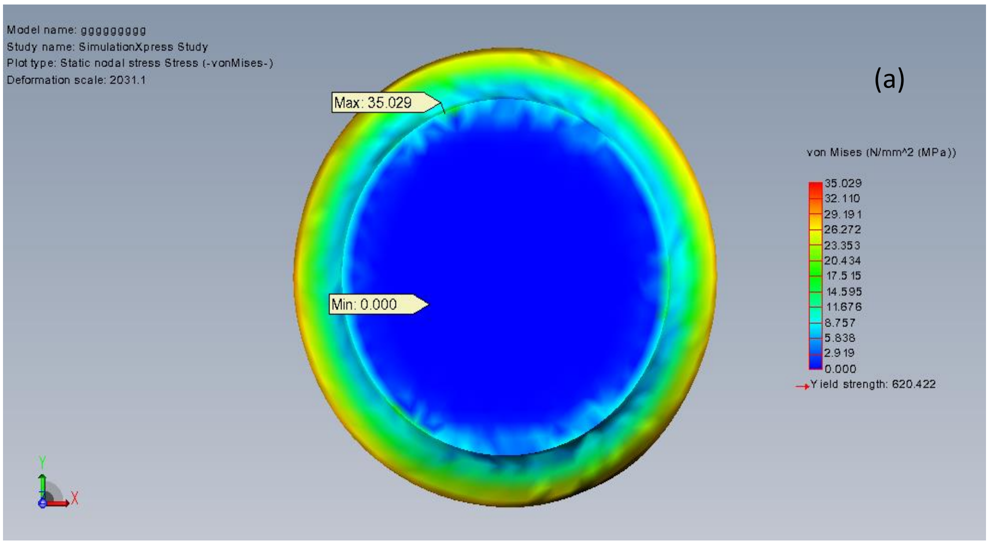
The instrument devices used in the current research are the pressure gauge on the outer surface of the boilers tank to indicate the steams pressure in (bar). A Liquid-level sight glass in the boiler tanks front side measures the interior water height. The control electrical panel is connected to the electrical generator and feeds electricity to the electrical load (small lump and fan). It contains three instrument electrical devices: a voltmeter, an ammeter, and a frequency meter.

4. RESULTS AND DISCUSSIONS

The results are presented in two stages because the current system was manufactured and operated in the first stage in 2018 and 2019, where the experiments showed many recorded operation problems in the boiler and the converted steam of the current studied system in 2020. The experimental operation stopped because of the COVID-19 pandemic. The second stage is reevaluation and reviewing the previous experimental work theoretically. A detailed analysis in 2020 and 2021 led to modifications in the design. The performance of the water tube boiler in converting water to steam is evaluated to feed the steam engine with the required quantity and quality of steam. The experimental operational problems are solved without further modifications.

4.1 Primary Experimental Results in 2018 and 2019

The experiments were done on the system from (May to November 2018) and (January to July 2019); the operation of the system started at 4 bars at the first experiments and gradually rose to 8 bars, the initial water quantity in the tank of the boiler ranged from (40-60) liters (nearly (25-40) % of the tanks capacity of 150 liters) with (30-50) minutes to heat water and generate steam at 6 bars with nearly 25 kg biomass/hr. Dry wood and paper wastes are used as a fuel source. The engine rpm is maintained at least 1500 rpm to generate electrical current from single phase electrical generator at 8 bars; 1350 rpm is reached at the first experiments (a tachometer UT371 is used to measure the engine rpm) at the first minutes from the operation time (10-25) minutes, the pressure gauge read 8 bars that then suddenly decreased to 5 bars (at the same time rpm decreases) because there is no feeding water at the first experiments of operation, but when the feeding water is supplied the pressure gauge read (6-7) bars with a sudden decrease in the temperature occurs that affects the quantity of steam generation because feed water must be passed through a long passage to gain more heat, i.e. the feed water after entering from the check valve must flow inside 40 total pipes of two economizers in which the two economizers pipes must be connected in series instead of parallel connections in the old design. The water drum is designed using a solid work program, as shown in **Fig. 7 a and b.** The tank can withstand a maximum stress of (35.03 MPa) at the welding zone.
The range of the obtained electrical power is (190 to 240 V, 50 to 60 Hz) feeding a lamp and a fan, as shown in **Fig. 8.**
The quantity of steam and its pressure are very important for the good and stable operation of the current steam engine. Refering to Eq. (32), there is a boiling limitation where the temperature difference between the inner wall of the economizer (T_{wi}) and the temperature of steam (T_{steam} is equal to 172˚C saturated temperature at a pressure of 8 bars) must not exceed nearly 100˚C to prevent unstable film boiling.



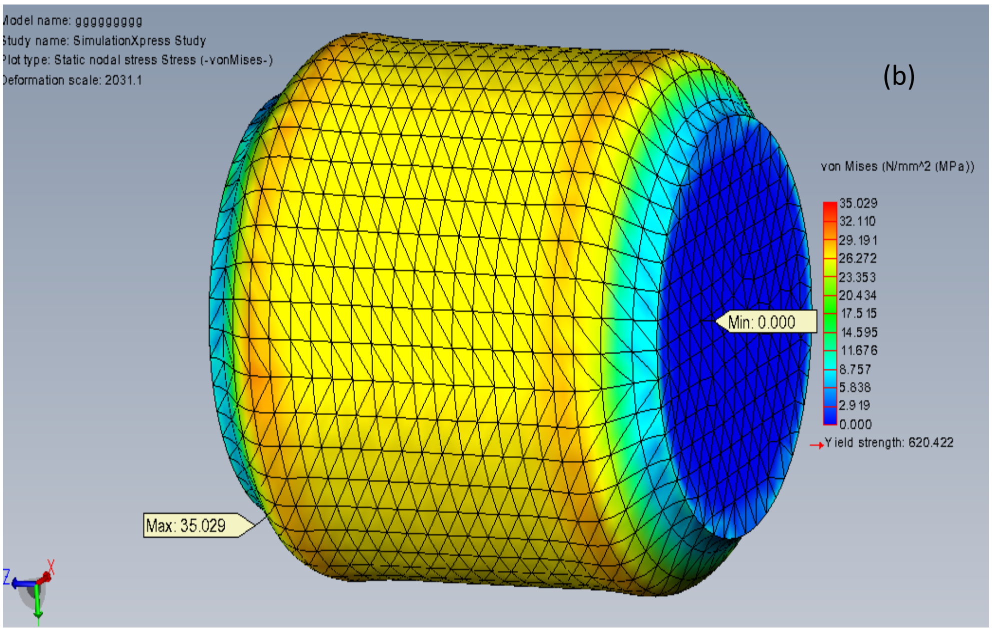


Figure 7. a) Solid work design of the water drum side view, **b)** Solid work design of the water drum

Another important cause for low electrical power generated by the current steam engine is removing a certain mass from the camshaft for the conversion process that causes loss of rotational dynamic equilibrium of the camshaft (or balance) so it could not withstand output electrical load, to solve this problem two suggested solutions. First, add an external mass of 10 kg and fix it on the camshaft like Desai steam engines. It was second, reviewing the conversion process and leaving the conversion part in the camshaft because this part is responsible for opening the air nozzle to enter the air of combustion of diesel fuel and closing the air hole only. So the camshaft can rotate in a balanced and steady method and withstand electrical load operation. Note that the converted steam engine rotates at 1500 rpm for no-load operation. The comparison between the current converted steam engine and Desai's steam engine is given in **Table 1**.

Figure 8. Pictorial view of the operated lamp and fan

Table 1. Current system Vs. Desais system.

Engine type	Current system	Methodology	Desai system
	Four-stroke single, piston diesel engine with 8 hp internal combustion converted to steam engine with external combustion	Experimental	Double cylinder, double acting steam engine 8 hp, cylinder diameter 76.2 mm, stroke 80mm, external combustion
Fuel feeding	Manual	Experimental	Manual
Lubrication	Automatic	Experimental	Manual
Pre-heating of feeding water	Valid	Theoretical	Invalid
Pre-heating of air of combustion	Valid	Theoretical	Invalid
Condensation of exhausted steam	Valid	Theoretical	Invalid
Obtained electricity	3kVA	Experimental	3kVA
Stability of engine in no electrical load	Stable 1500 rpm	Experimental	Stable 1500 rpm
Stability of engine in electrical load	Unstable	Experimental	Stable 1500 rpm in a certain calibration only

4.2 Theoretical Results at 2021

The theoretical modifications in the water tube boiler are done first by adding preheaters for feed water and air of combustion and second by modifications in economizers. The feed water and combustion air preheaters give feed water at 90.713 ˚C and air combustion at 90.318 ˚C instead of ambient temperature (0-50) ˚C and that increases boiler efficiency from (58.45%, 52.63%) to (58.35, 63.27%), for direct and indirect methods respectively with saving 10% of fuel consumption. The boiler efficiency before and after the pre-heating process and a comparison with previous works are given in **Table 2**.
The corresponding composition of the flue gases resulting from burning the dry wood (used as a solid fuel) by weight fraction and volume fraction are given in **Table 3**. N_2 is more than 70% of flue gases in weight and volume fractions. N2 passes the largest part of the heat carried out by the flue gases. So, oxy-combustion (using Oxygen only in combustion) reduces the required fuel and the corresponding CO_2 emissions. This means that a closed system must replace the present system. In **Table 4**, the weight and volume fractions of some dangerous flue gases are calculated and compared with other researchers results.

Table 2. Boiler efficiency before and after the pre-heating process.

Algorithm type	Reference	Before pre-heating process	After pre-heating process
Direct method	Current work	58.45 %	58.36 %
	(Sharma and Tiwari, 2017)	-	71.42 %
	(Patel et al., 2013)	-	79.05 %
	(Wadah, 2008)	-	-
Indirect method	Current work	52.63 %	63.27 %
	(Sharma and Tiwari, 2017)	-	75.96 %
	(Patel et al., 2013)	-	77.51 %
	(Wadah, 2008)	-	58 %

Table 3. Weight and volume fractions of flue gases.

	N_2	O_2	CO_2	H_2O
% W	0.712627	0.1064314	0.132316	0.0486
% V	0.7380437	0.09644	0.087185	0.0783222

The maximum boiling limitation heat flux is given in Eq. (32). The excess air (100%) is responsible for the low efficiency of burning solid fuel compared with (20% excess air for liquid fuel). The performance of the used engine before (Internal Combustion) and after (Outer Combustion or steam engine) the conversion process is given in Eq.s (30 and 28), respectively, and they are given in **Table 5**.

The performance of the used engine shows that for small systems of steam capacity between (0.1-1) ton/h and maximum operating pressure of 10 bars, it is better to use resulted steam to produce mechanical energy or thermal energy instead of electrical energy because of first of large emissions of CO_2 and second of low overall safety because the boiler is a dangerous equipment that must be operated carefully to prevent leaking of steam towards workers.

Table 4. Weight and volume fractions of some dangerous flue gases.

Dangerous wastes		N_2 ($*10^{-1}$)	O_2 $*10^{-2}$	CO_2 $*10^{-2}$	H_2O $*10^{-2}$	SO_2 ($*10^{-4}$)	H_2SO_4 ($*10^{-5}$)	HCl ($*10^{-4}$)
One ton/h of contaminated soil with crude oil	% W	7.25358	10.6852	10.16538	6.53198	7.78398	3.68636	-
	% V	7.36028	9.4871	6.564	10.3103	3.45559	1.06873	-
100 kg/h of solid bio-medical wastes from many hospitals in Baghdad	% W	7.1913	11.7016	10.1913	6.1077	-	-	8.625
	% V	7.323	10.426	6.604	9.675	-	-	6.737
(Wadah, 2008)	% V	7.53	3.2	11.85	9.3	33.0	-	-

Table 5. Performance of current steam engine before and after conversion.

	Type of combustion	Fuel name	Fuel consumption rate (kg/h)	Total emitted flue gases rate (kg/h)	Emitted CO_2 rate (kg/h)
Before conversion	Internal combustion	Diesel $C_{12}H_{23}$	1.859 (2.2 liter diesel/h)	35.23	5.875
After conversion	External combustion	Dry wood	25	345.76	45.75

5. CONCLUSIONS

The current research is one of many works toward utilizing the wasted heat from the incinerators of hazardous wastes. Experimentally, the generated electrical power is little and sufficient to operate a small fan and lamp. The conclusions extracted are as below:

1- For small systems of steam capacity between (0.1-1) ton/h and a maximum operating pressure of 10 bars. It is better to produce mechanical or thermal energy than electrical energy by the steam generated.
2- The feed water heater provides the boiler with feed water at 90.7 ˚C, and the air preheater feeds the combustion zone with air at 90.3 ˚C, increasing the boiler efficiency from (58.45%, 52.63%) to (58.354, 63.27%) for direct and indirect methods respectively and save nearly 10% from fuel consumption.
3- The performance of the steam engine of the current study is better than the Desais steam engine by auto lubrication. However, the conversion process by removing a certain part from the camshaft of the current engine changes the moment of inertia, which gives low-produced electrical power in loading operation, so the converted engine needs to outer flywheel to increase produced electrical power. An output electrical current of (190-240) V and a frequency of (50-60) Hz, and low electrical current are gained from the current study.
4- Adopting the condensation process of steam exits from the engine will have better and higher heat recovery if the feed water tank is insulated and closed,

Acknowledgment

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NOMENCLATURE

Symbol	Description	Symbol	Description
c_p	Specific heat, kJ/(kg.°C)	q_{cb}''	Critical boiling heat flux, W/m^2
GCV	Gross calorific value of fuel, kJ/kg	T_a	Ambient temperature, °C
h_f	Enthalpy of liquid, kJ/kg	T_{a2}	Temperature of air of combustion after pre-heating process, ˚C.
h_{fg}	Latent heat of vaporization, kJ/kg	T_2	Final temperature of feed water after mixing with exhausted steam, ˚C.
h_g	Enthalpy of vapor, kJ/kg	T_{g2}	Exit temperature of flue gases after pre-heating process, ˚C
HHV	Higher heating value of fuel, kJ/kg	T_s	Temperature of exhausted steam from steam engine, ˚C.

K_D	Constant in Eq.(17)	V	Volume of gas per time for 1 kg fuel,. $m^3/(s.kg_{fuel})$
L	Thermal loss in boiler, %	%V	Volume fraction of flue gases, unitless.
m	Mass, kg	%W	Weight fraction of flue gases, unitless.
P_w	Pressure of waters vapor in air, kg/cm^2	**Greek Symbols**	
p	Pressure of boiler, bar.	ρ	Density, $\frac{kg}{m3}$.
P	Power, W	η	Boiler efficiency, unitless.
Q	Thermal energy, W	σ	Surface tension of liquid, $\frac{N}{m}$.

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