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A Process Concept of Waste-Fired Zero Emission Integrated Gasification Magnetohydrodynamic Cycle Power Plant

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Abstract: A layout of urban waste fired zero emission power plant is described in this paper. The principle of layout, which comes from similar coal-fired plants retrieved from the literature, integrates gasification with a power generation section, and implements two parallel conversion processes, one supplied by the heat of the gasifier consisting of a thermoacoustic-magnetohydrodynamic (TA-MHD) generator, while in the second one the syngas is treated in order to obtain almost pure hydrogen, which is fed to fuel cells. The CO_2 deriving from the oxidation of Carbon base is stocked in liquid form. The novelty of the proposed layout lies in the fact that the entire conversion is performed without solid moving parts. The resulting plant avoids any type of emissions in the atmosphere, increases mechanical efficiency as compared to traditional plants, thanks to the absence of moving parts, nonetheless, resolving at its root the ever-increasing waste-related pollution problems.

Keywords: magnetohydrodynamic; thermoacoustic; fuel cells; waste-fired power plant; zero emission power plant

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1. Introduction

By the year 2050, it is projected that a significant majority of the global population, estimated at 66%, will be concentrated in urban areas, marking a substantial rise from the current approximate proportion of 54% [1]. This demographic shift indicates the potential addition of approximately 2.4 billion individuals to the global urban populace. Consequently, such urbanization trends will inevitably instigate a substantial expansion of existing urban landscapes and necessitate the establishment of novel urban environments. Notably, despite occupying less than 2% of the Earth's surface, cities disproportionately consume more than 75% of the world's available natural resources. The United Nations Environment Programme anticipates that the material consumption attributed to urban areas will soar to approximately 90 billion tons by 2050, a notable escalation from the 40 billion tons recorded in 2010. These resources encompass critical components such as primary energy, raw materials, fossil fuels, water, and food [2].

As a consequence, urban areas are poised to confront formidable challenges concerning growth, performance, competitiveness, and the overall quality of residents' lives [1]. The deterioration of livability standards arising from issues such as waste management, resource scarcity, air pollution, and traffic congestion, which not only give rise to concerns about human health but also contribute to the degradation of aging public infrastructure, exemplify the complexities generated by rapid urbanization [3]. In order to effectively tackle these multifaceted problems, the concept of smart cities has emerged as a promising avenue for exploration and potential resolution.

The central emphasis of this paper revolves around the reduction of waste pollution, specifically targeting those waste materials that are not amenable to recycling or deemed economically unfeasible for recycling purposes.

In countries where landfills is an environmental and public health issue, municipal waste is often incinerated to reduce volume, and increasingly this is done with energy recovery, generating electricity and heat (e.g., for a regional domestic hot water system) [4]. These activities in turns cause major problem in environment which produces all kinds of pollutions and disturb ecosystem.

Problem of emission and greenhouse gases and pollutants related to waste including landfills etc. The thermal treatment of waste can be employed but the issues due to harmful gases and solid ashes must be handled properly. From this point of view, some techniques developed in the past century to prevent the emissions caused by the use of coal [5] can be borrowed in this context.

In this paper, an innovative layout of waste treatment plant is proposed, which integrates gasification with a power generation section. The entire plant is devoid of moving parts and emission of any gases in the atmosphere is avoided. To this end, energy conversion is performed by a series of static devices, such as the gasifier, thermoacoustic resonators [6] and magnetohydrodynamic (MHD) electrical generators. The resultant CO_2 is stored in a tank as a marketable byproduct of the whole process [7,8].

Table 1. Technologies of thermoacoustic and magnetohydrodynamic power generation / Overview of renewable energy generation technologies.

Technology/Process	Power	Advantages	Disadvantages	Refs
Thermoacoustic generator				
Standing wave (wf: air)	0.21 W 0.084%	Novel cold heat exchanger design for thermoacoustic engine (TAE) is introduced.	Helium gas can be used to improve efficiency.	[9]
Travelling wave (wf: He-Ar mixture)	10.6 W 1.51%	Three-stage looped thermoacoustic electric generator	The thermal-to-electric efficiency stabilizes at around 1.5% when hot temperature is in the range of 120 °C – 170 °C.	[10]
Travelling wave (wf: helium)	3.46 kW 18.4%	Three-stage traveling-wave thermoacoustic electric generator (heat engine and linear alternators)	The acoustic impedance of the linear alternator can be greatly affected by the electric capacitance and resistance, thereby the system performance can be greatly changed.	[11]

wf: working fluid.

The paper is organized in four sections. In section 2, the processes implemented in the layout of the power plant are described in detail separately. In section 3, the layout of the power plant is described along with the working. Sections 4 and 5 provide the results, and discussion and conclusion respectively.

2. Materials and Methods

2.1. Gasification

The main two types of synthetic reactions for reforming of carbonaceous fuel are steam reforming and water-gas shift reaction (WGSR). The steam reforming reaction can be expressed as:

$$\mathrm{C}_{(s)} + 2\mathrm{H_2O}_{(g)} \longrightarrow 2\mathrm{H}_{2\,(g)} + \mathrm{CO}_{2\,(g)} + \Delta H^{\ominus}_{f\,\mathrm{CO_2}} - 2\Delta H^{\ominus}_{f\,\mathrm{H_2O}} \quad (1)$$

where $\Delta H^{\ominus}_{f\,\mathrm{CO_2}} - 2\Delta H^{\ominus}_{f\,\mathrm{H_2O}}$ ([–393.52 kJ/mol] – 2×[–241.83 kJ/mol] = 90.14 kJ/mol C) is an estimated heat absorbed by the standard molar formation enthalpies of CO_2 and H_2O [12,13]. The reaction proceeds

$$\mathrm{C}_{(s)} + \mathrm{CO}_{2\,(g)} \longrightarrow 2\mathrm{CO}_{(g)} + 2\Delta H^{\ominus}_{f\,\mathrm{CO}} - \Delta H^{\ominus}_{f\,\mathrm{CO_2}} \quad (2)$$

$$\mathrm{C}_{(s)} + \mathrm{H_2O}_{(g)} \longrightarrow \mathrm{CO}_{(g)} + \mathrm{H}_{2\,(g)} + \Delta H^{\ominus}_{f\,\mathrm{CO}} - \Delta H^{\ominus}_{f\,\mathrm{H_2O}} \quad (3)$$

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above a temperature of about 873 K. The reactions in which carbon dioxide is converted to carbon monoxide due to excess of carbon and the conversion of carbon to syngas is as follow:

The reactions (2) and (3) proceed at higher than 1473 K temperature and according to chemical equilibrium of both reactions, the volume ratio of H_2 to CO, as obtained from these reactions, is 1:2 which almost does not depend upon the pressure [14]. If 1 mol of carbon is gasified, ⅓ mol of carbon reforms into ⅔ mol of carbon monoxide in reaction (2) while ⅔ mol of the remaining carbon is converted into ⅔ mol of carbon monoxide and ⅔ mol of hydrogen gas in reaction (3) resulting in $3\Delta H^{\ominus}_{f\,\mathrm{CO}} - \Delta H^{\ominus}_{f\,\mathrm{CO_2}} - \Delta H^{\ominus}_{f\,\mathrm{H_2O}}$ (3×[–110.53] – [–393.52 – 241.83] = 303.76 kJ/mol) absorption of heat [12,13,15].

In the conventional process of carbonaceous fuel reforming, the heat of reaction is supplied partially by the combustion of the fuel. Here, the maximum heat of combustion is obtained by the synthetic fuel which is equivalent to the same heat produced by direct combustion of the main fuel. In the case of reaction (1), it is assumed that total consumption of carbon in the combustion reaction (4) and in the gasification reaction (1) is given by $x + y \longrightarrow 1$.

$$2\mathrm{C}_{(s)} + \mathrm{O}_{2\,(g)} \longrightarrow 2\mathrm{CO}_{(g)} + 2\Delta H^{\ominus}_{f\,\mathrm{CO}} \tag{4}$$

The gasification heat is $y\left(\Delta H^{\ominus}_{f\,\mathrm{CO_2}} - 2\Delta H^{\ominus}_{f\,\mathrm{H_2O}}\right)$ which must be equal to the heat of combustion represented by $-x\Delta H^{\ominus}_{f\,\mathrm{CO_2}}$ then, we get $y = \Delta H^{\ominus}_{f\,\mathrm{CO_2}} / \left(2\Delta H^{\ominus}_{f\,\mathrm{H_2O}}\right)$ mol. The moles of H_2 produced by the reaction (1) is 2y, out of which, heat of combustion is $-2y\Delta H^{\ominus}_{f\,\mathrm{H_2O}} = \Delta H^{\ominus}_{f\,\mathrm{CO_2}}$, that is, the combustion heat of 1 mol C. Following the same calculations to reactions (2) and (3), the mole numbers of synthetic fuel are approximately 974.3 and 487.1 mol for CO and H_2, respectively. Again, the total heat of combustion of CO and H_2 is equivalent to that of 1 mol C.

The preceding calculations show that the thermal energy through the combustion reaction is provided by the absorption of heat by the chemical energy of the synthetic fuel. Therefore, if heat of reforming is provided from exhaust gases at a suitable high temperature unit and the unit is powered by syngas, the heat of combustion supplied will increase the primary combustion temperature, depending on the amount of heat absorbed by the syngas. This thermochemical process is fundamental for the design of an efficient CO_2-free energy systems.

2.2. Water-gas Shift Reactions

The water–gas shift reaction (WGSR) process is an intrinsic inclusion into the reforming process; WGS is seen to increase the H_2:CO ratio. In the process of steam reforming of ethanol, the catalysts usually yield carbon monoxide (CO). The WGSR is has equal moles of carbon monoxide (CO) and steam ($H_2O_{(g)}$) in the mixture, also the reaction releases heat so is relatively exothermic [16].

One way to perceive the process of WGSR is given here: [17]:

$$2\mathrm{H_2O}_{(g)} \xrightarrow{\Delta} 2\mathrm{H}_{2(g)} + \mathrm{O}_{2\,(g)} - 2\Delta H^{\ominus}_{f\,\mathrm{H_2O}} \tag{5}$$

Combining the reactions (4) and (5) gives WGSR.

$$\mathrm{CO}_{(g)} + \mathrm{H_2O}_{(g)} \longrightarrow \mathrm{H}_{2(g)} + \mathrm{CO}_{2\,(g)} + \Delta H^{\ominus}_{f\,\mathrm{CO_2}} - \Delta H^{\ominus}_{f\,\mathrm{CO}} - \Delta H^{\ominus}_{f\,\mathrm{H_2O}} \tag{6}$$

Because WGSR is moderately exothermic, that is, $\Delta H^{\ominus}_{f\,\mathrm{CO_2}} - \Delta H^{\ominus}_{f\,\mathrm{CO}} - \Delta H^{\ominus}_{f\,\mathrm{H_2O}}$ $(-393.52 - (-110.53 - 241.83) = -41.16\,\mathrm{kJ/mol})$ [12,13,15], the equilibrium constant of the reaction decreases as temperature rises, but high yield is achieved with low temperatures. If the quantity of steam is increased as compared to the stochiometric equilibrium, the conversion is advanced. Nonetheless, at low temperatures, the stochiometric and dynamic equilibrium helps in the growth of products with the domination of reaction kinetics [16,18].

The WGSR works perfectly between 477 K and 755K in the presence of several catalysts. The total number of moles of reactants and products involved in the reaction does not change, resulting in very minimal effect of pressure on the reaction. Typically, very large amount of moisture is available in the scrubber syngas, due to slurry-fed gasifier, which is adequate to push the WGSR in order to attain the essential ratio of H_2:CO. Although, in some of such cases, some part of the syngas feed

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is detoured, to prevent excess of product. If the gasifier is dry-fed, supplementary steam ($H_2O_{(g)}$) is added before the WGSR begins for appropriate syngas output [18].

2.3. Integrated Gasification Combined Cycle

As the rise of climate-related concerns and keeping in view the energy requirements of the current state of the world, the heads have turned to develop more advanced technologies of near-zero emissions and clean energy systems of high efficiency. Typically, integrated gasification combined cycle (IGCC) technology adds less emissions to atmosphere and have more flexibility in terms of selection of fuel as compared to traditional technologies of coal-based power generation [5]. IGCC is a next-generation thermal power technology which partially oxidize solid feedstock (biomass, coal, lignite, etc.) with oxygen (O_2) and steam ($H_2O_{(g)}$) to produce syngas or synthesis gas [19–21] (fuel gas or synthesis gas or syngas is mixture of mainly three gasses which are hydrogen (H_2), carbon monoxide (CO), and very often some carbon dioxide (CO_2), that could be used as a potential intermediate in the conversion of biomass into fuel [22]). Conventionally, when power is generated without the collection of carbon with IGCC design, the synthesis gas is cleansed for hydrogen sulfide (H_2S) and dust, and then pushed to a Gas-Steam Combined Cycle system for power production. The technologies like carbon capture and storage (CCS) are anticipated to engage in a significant role in the near future for the reduction of harmful greenhouse gas emissions [21]. One of the very promising technology in power generation is IGCC, which is not only capable to capture CO_2 but also do not put much penalties on the efficiency of the power plant, CAPEX and OPEX [19]. One benefit of using IGCC is, it has the ability to effectively capture carbon dioxide before combustion without reducing the efficiency as compared to typical power plants fired with pulverized coal [5]. The estimated increase on efficiency with the deployment of large-type IGCC systems is about 15% along with the reduction of carbon dioxide emissions as compared to typical coal-fired thermal power systems [20,23].

2.4. Waste to Energy

Most of the developed as well as developing countries are irrefutably facing the dire problem of handling, treating, compacting waste due to mismanagement of which has resulted in dangers and threats to the biodiversity and ecosystem in general and atmosphere and environment in specific. A well-managed municipal solid waste (MSW) is one of the sources of waste to energy (WTE), which has the capacity to produce biogas that can combinedly generate heat and power with the application of WTE processes. Such techniques have to be conceptualized on the basis of the composition, assessment, and keeping the financial value of the waste as a criterion. Although, the selection of the appropriate technology for WTE is a difficult task as the generation of waste is constantly affected by the producer's season, region, and socioeconomic level [24].

2.5. Magnetohydrodynamic Generator

The main aim of an advanced energy power system is to enhance the efficiency of the overall conversion from source to power production as well as to minimize the adverse impact of such activities on the environment. The conversion efficiency for the performance of the steam has already achieved its upper limit of 40% and the only workable solution to enhance it further is to combine steam cycles with various conversion systems. The magnetohydrodynamic (MHD) generator intrinsically comes along into this application, because of its operation at the high temperatures [25]. The MHD generator is an atypical electric power generation technology which generates electricity when a conducting fluid (plasma) flows under a magnetic field. When the plasma moves in the presence of magnetic field, it behaves as a mobile electrical conductor and it becomes seat of an electromotive force [26].

If the plasma in a gas, the kinetic energy is converted directly into electrical energy during the expansion.

The generic charge q in the plasma flowing in the induction field **B** is subject to the Lorentz force **F** (**Figure 1**) according to the equation:

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \tag{7}$$

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Two electrodes at direct contact with the plasma, arranged perpendicularly with respect to both the flow and the induction field and positioned on opposite walls of the duct, intercept the charged particles providing an interface with the external circuit, obtaining a source of direct current, with density **J** (equation (8)).

$$\mathbf{J} = \sigma\left(\mathbf{v} \times \mathbf{B}\right) \tag{8}$$

where σ is the electric conductivity. The produced electric energy, net of losses, is equal to the reduction of enthalpy of the fluid stream.

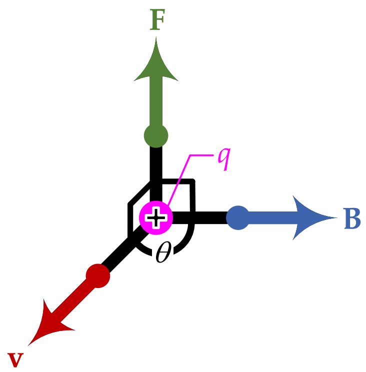

Figure 1. Charge q moving at velocity **v** in magnetic field **B**, experiences a Lorentz force **F** normal to the plane containing **v** and **B**.

The power of an MHD generator for each cubic meter of the channel volume is given by equation (9):

$$P_{\mathrm{el}} = \mathbf{J} \cdot \mathbf{V}_0 = \sigma v^2 B^2 K\left(K-1\right) \tag{9}$$

where $K = V_0/E_{ind} = V_0/\left(\mathbf{v}\cdot\mathbf{B}\right)$ is the load factor (ratio between open-circuit voltage and induced voltage). It can be noted that, due to the fact that the current density **J** flowing through the load and the open circuit voltage are aligned, the dot product between **J** and $\mathbf{V}_0$ is electrical power P_{el} between modules (equation (9)). Therefore, the power P_{el} is proportional to the electrical conductivity σ, the square of the gas velocity **v**, and the square of the intensity of the magnetic field **B**. In order to reach a competitive operability with existing electric generators, the MHD system needs to have a high conductive gas, at high temperature, high speed, compatibly with the increase of the turbulence, and an extremely intense magnetic field (5-7 tesla), coherently with the costs for the necessary superconducting magnets [27–29].

Typically, an electrically conductive high-pressure gas is produced by combustion of fossil fuels. Unfortunately, the most common gases do not ionize significantly at temperatures obtainable through chemical reactions with fossil fuels. This requires doping the hot gases with small amounts of easily ionizable materials, such as the alkali metals. Materials such as potassium and cesium have so low ionization potentials that tend to ionize at temperatures achievable by combustion in air. Recovery and reuse of doping materials from the MHD channel exhaust system are fundamental both for economic issues and pollution prevention.

The application of MHD generators is especially for large-scale power production as these work as the volumetric expansion engines. Since the MHD generators only consists of ducted components, and no high-stressed moving parts are present, therefore, they reliability as a power generation system is pronounced at high temperatures [25].

2.5.1. Types of MHD Generators

There are three fundamental methods to MHD power generation: open cycle, closed cycle plasma and closed liquid-metal systems. In open cycle MHD systems, the working fluid is emitted in the atmosphere after the electricity generation [30–34], the closed cycle MHD system does an extra step, it recycles the working fluid in order to make use of the thermal energy present in the fluid as it exits the MHD chamber (after the electricity has generated by MHD system) [35] whereas closed liquid-metal MHD systems, the liquid metals is used as the electrically conducting fluids and that is why it is called *liquid-metal* MHD generators [36,37]. The liquid metals can be used as conducting fluids in MHD generators because the metals have extremely high electrical conductivity. Another benefit of generating electricity with liquid-metal MHD generator is its operation at low temperatures as compared to other MHD generators which require high temperature for production of plasma. The normal working principal is, the liquid metal is accelerated with a thermodynamic pump or fused with the driving gas and then detach it from the driving gas before the liquid metal passes through the MHD channel [26,36].

2.6. Gasifier – MHD Generator

The concept of thermochemical heat recovery is employed for the advanced energy system in which the heat produced by MHD generator regenerates the chemical energy of coal-based fuel through pyrolysis while making use of the exhaust gases of MHD generator as an oxidant agent [38]. The benefits of such type of open-cycle MHD generator are: (1) the coal is converted to gaseous fuel by heat of the MHD topping unit and by the exhaust—this method increases the heat of combustion of main fuel (coal) by the heat of reaction; (2) the synthetic fuel is re-circulated to the MHD combustor through a high-temperature fuel preheater; and (3) the availability of pure oxygen for combustion which results in efficient recovery and separation of syngas [39].

2.7. Thermoacoustic Generator

The main principle of thermoacoustic heat engine is to convert thermal power into acoustic power without any mechanical moving parts, while the acoustic power is converted to electricity employing linear alternators. The inexpensive electricity in the developing countries can be provided by using simple fabrication of such thermoacoustic electricity generators (TAG). The waste heat present in the flue gases can be recovered by thermoacoustic energy conversion processes to generate electricity as by-product [40]. When a temperature gradient is imposed in the direction of the acoustic wave propagation, interactions between gas undergoing acoustic excitation and porous medium give rise to the thermoacoustic effects [6].

The leading sustainable source of energy include low-grade thermal energy, such as solar thermal energy, geothermal energy, ocean thermal energy and waste heat. To recover the low-grade heat source, in recent years, several types of technologies for electric generation have been developed, such as organic Claude cycle, polymer thermoelectric generation, Rankine cycle and thermally regenerative batteries. Because of exceptional characteristics of extreme reliability and environment-friendliness, thermoacoustic generator is one of the appealing and promising energy conversion solution to recover low-grade thermal energy [10]. Additionally, helium and nitrogen are the working substance in TAG which are environmental friendly gases [11].

The hot temperature T_h plays an important part in the determination of the performance of the thermoacoustic engine, as well as the quality of available heat source. And as we know, greater the difference between the hot T_h and the cold T_c temperatures result in a higher Carnot efficiency. Therefore, it is more rational to assess the performance of the system by relative Carnot efficiency (defined as the ratio of the thermal efficiency to the Carnot efficiency equation (10)) [10].

$$\varepsilon = \left(1 - \frac{T_c}{T_h}\right) \times 100\% \tag{10}$$

2.8. Thermoacoustic – Magnetohydrodynamic Generator

Mechanical energy can be produced by thermoacoustic generator (TAG). The oscillations of the velocity in a compressible fluid produced by the pressure wave generate energy. The mechanical energy can be converted into electricity in various methods. Piezoelectricity, for example, is one of the possibilities. But, this effortless technique produces only a little power (few watts maximum) [33,35,41]. Some other solutions which produce more power could use a rotating machine. Obviously, in this case, moving parts must be present in the machine which limits the interest in it, because here the objective is the model of a generator without any moving parts. Another possibility could be the use of linear induction machines which employs solid pistons to generate alterations in the magnetic flux of a coil and resulting in the generation of electric power. Although this concept is much humbler than the previous one, this option also involves strong mechanical parts in motion [42].

The equations for fluid mechanics used in MHD are the mass and the momentum conservation equations (see equations (11) and (12)) with the addition of the electromagnetic force depending on the current density and on the magnetic field according to equation (7):

$$\frac{\partial \rho}{\partial t}+\nabla(\rho \mathbf{v})=0 \tag{11}$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v})=\mathbf{v}\cdot\nabla(\rho \mathbf{v})=-\nabla p+\nabla\cdot\boldsymbol{\tau}+\mathbf{J}\times\mathbf{B}+\mathbf{F}_{\mathrm{v}} \tag{12}$$

where ρ is the fluid mass density, p is the pressure, $\boldsymbol{\tau}$ is the stress tensor, and $(\rho\mathbf{g})$ is the specific gravity force, if $\mathbf{g}$ is the gravitational acceleration. The gravitational effects are neglected because the height differences between any pair of points within the systems studied in this thesis are negligible if compared to the weight of the gas. The stress tensor could be expressed by the linear constitutive equation.

$$\boldsymbol{\tau}=\zeta(\nabla\cdot\mathbf{v})\mathbf{I}_{\mathrm{d}}+\eta\left(\nabla\mathbf{v}+(\nabla\mathbf{v})^{\mathrm{T}}-\frac{2}{3}(\nabla\cdot\mathbf{v})\mathbf{I}_{\mathrm{d}}\right) \tag{13}$$

where $\mathbf{I}_{\mathrm{d}}$ is the identity tensor, ζ is the bulk viscosity and η is the fluid dynamic viscosity. The first left-hand side of equation (13) is usually neglected for incompressible fluids or monoatomic gases like noble gases at standard temperature and pressure or, in general, like all the gases at a sufficiently high temperature. Therefore, the most general form of the momentum equation for compressible fluids becomes:

$$\frac{\partial}{\partial t}(\rho \mathbf{v})+\mathbf{v}\cdot\nabla(\rho \mathbf{v})=-\nabla p+\eta\left(\Delta\mathbf{u}+\frac{1}{3}\nabla(\nabla\mathbf{u})\right)+\mathbf{J}\times\mathbf{B} \tag{14}$$

The plasma thermodynamic behavior could be described by the ideal gas state equation (15) due to the fact that the proposed study deals with noble gases or air at standard temperature and pressure conditions.

$$p=\rho\Re T \tag{15}$$

where $\Re$ is the specific gas constant and T its temperature.

The energy transfer could be modeled through a global energy balance:

$$\rho\frac{d(e)}{dt}=-\nabla\cdot(p\mathbf{u})+\nabla\cdot(k\nabla T)+\mathbf{u}\cdot(\nabla\cdot\boldsymbol{\tau})+\mathbf{J}\cdot\mathbf{E}+S_{\mathrm{int}}+Q_{\mathrm{wall}} \tag{16}$$

where e is the total energy per volume unit (sum of kinetic and internal specific energy), k is the thermal conductivity, S_{int} a generic internal power source and Q_{wall} is the wall heat transfer per volume unit and time unit. Equation (16) will be simplified considering the adiabatic flow assumption:

$$\frac{d}{dt}\left(\frac{p}{\rho^{\gamma}}\right)=0 \tag{17}$$

where $\gamma=c_{\mathrm{p}}/c_{\mathrm{v}}$ is the heat capacity ratio between specific heat at constant pressure and specific heat at constant volume. Equation (17) is the energy equation written for the simplest possible functioning conditions and could be used replacing the overall energy balance.

The prospect of linking the thermoacoustic effect with the magnetohydrodynamic effect is very appealing as it does not include any mobile mechanical parts. It is worth noting that MHD generator in which liquid metal is a working fluid, has been previously proposed in the articles and conference proceedings as well as tested successfully. The main principle is conceptualized as electromagnetic pumps working in generators. But here the pumps transform the electromagnetic energy into mechanical energy which is exactly opposite to the transfer that occurs in generators [41,43,44].

3. Layout of the Power Plant

The power plant presented in this paper consists of the following main components: boiler, thermoacoustic resonator and magnetohydrodynamic generator. Other components, like heat exchangers, WGSR, absorption column, condenser, and fuel cells are accessory parts, which help the power plant to run smoothly and to produce the electricity output. Each of these components are discussed below:

3.1. Boiler

The boiler in the present layout is a *waste-to-energy* (WtE) type boiler which converts the mixed municipal solid waste (MSW) into to thermal energy by taking feedwater as a working fluid. The MSW is crushed and fed in the WtE as the source of energy, while the feedwater and the atmospheric air enter the WtE boiler and is heated by the flue gases generated from the incineration of MSW. The mixture of CO, H_2 and CO_2 (syngas) exit the WtE boiler in the form of flue gases. At the end of the incineration process, unwanted slag is also produced which does not play any role in the production of electricity at the any stage, therefore, increasing the economic efficiency of the system along with reducing the carbon footprint, the slag can be used as a partial replacement of cement in mortar and concrete [45,46]. If the slag is left untreated, it will affect far more adversely than the original MSW [47,48].

3.2. Thermoacoustic Resonator

A thermoacoustic resonator (TAR) is an experimental device used to investigate and harness the interactions between heat and sound waves within a system. In a TAR, the primary objective is to achieve resonance between the acoustic waves and the geometry of the system. The resonator typically consists of several components, including a resonant cavity, a stack of porous materials, and a heat source [6].

The resonant cavity, also known as the resonator, is a carefully designed chamber that provides the necessary space for sound waves to propagate and interact with the surrounding materials. The geometry and dimensions of the resonator are crucial in determining the resonant frequencies and optimizing the efficiency of the device [9].

The stack of porous materials is a key element within the resonator. It is often composed of solid-state materials with interconnected pores, such as metal foams or ceramic structures. These porous materials serve two important purposes: they facilitate the propagation of sound waves, and they enable heat transfer through the stack. As sound waves pass through the stack, they induce pressure fluctuations and temperature oscillations due to the complex interactions between the fluid and the solid matrix [11].

In terms of operation, TARs can be utilized in two primary modes: the cooling mode and the power generation mode.

In the *cooling* mode, the TAR is designed to transfer heat from a heat source, such as a refrigeration system or a heat sink, to another location. This process involves the generation of high-amplitude sound waves, typically achieved using a loudspeaker. As the sound waves traverse the stack of porous materials, they undergo compression and expansion cycles, leading to the establishment of temperature gradients. These temperature gradients facilitate the transfer of heat from the heat source to the desired destination [6].

In the *power generation* mode, the TAR exploits temperature differences within the system to generate acoustic waves, which can then be converted into other forms of energy, such as electrical power. The thermal gradients present in the stack induce corresponding pressure oscillations, resulting in the generation of sound waves. These sound waves can be captured and transduced into useful energy through various techniques, including piezoelectric transducers or electromagnetic devices [44,49].

TARs offer a range of advantages for experimental investigations and practical applications. They provide a unique platform for studying the intricate relationship between heat and sound waves. Furthermore, they offer environmentally friendly alternatives by eliminating the need for traditional refrigerants or mechanical components, which can be beneficial for cooling systems and energy conversion processes.

3.3 Magnetohydrodynamic Generator

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A magnetohydrodynamic (MHD) generator is a device that converts the energy of a flowing conducting fluid, such as plasma or ionized gas, directly into electrical power using the principles of MHD. The operation of an MHD generator involves several key components and processes. Firstly, a conductive fluid, often in the form of a high-temperature plasma, is introduced into a channel or duct. This fluid can be produced through processes like combustion or ionization [36].

As the conductive fluid flows through the channel, it interacts with a strong magnetic field applied perpendicular to the flow direction. The interaction between the moving charges within the fluid and the magnetic field induces electric currents known as MHD currents. These MHD currents, in turn, generate an electric potential difference or voltage across the fluid, perpendicular to both the flow direction and the applied magnetic field. This electric potential difference drives the flow of electric current through an external load, such as a set of electrodes or conductors placed across the fluid channel [41].

By extracting electrical power from the MHD currents, the magnetohydrodynamic generator converts the kinetic energy of the flowing fluid directly into electricity. This eliminates the need for traditional mechanical components like turbines or rotating generators, which are common in conventional power generation systems [26].

MHD generators offer several advantages in terms of efficiency and simplicity. Since they directly convert the energy of the fluid into electricity, without intermediate mechanical conversion, they can achieve higher overall efficiency compared to traditional power generation methods. Additionally, MHD generators can operate at high temperatures, making them suitable for applications involving high-temperature plasma, such as in fusion reactors or certain types of power plants.

However, there are also challenges associated with magnetohydrodynamic generators. The generation of MHD currents can lead to the creation of electromagnetic forces that may introduce instabilities and turbulence within the fluid flow. These effects need to be carefully managed to ensure stable and efficient operation of the generator.

In the next section, the efficiency of the proposed layout is discussed in detail with a theoretical parameter.

4. Case Study

As a case study the Southern part of Lebanon has been used as reference. More specifically, forty-three villages in the three Union of Municipalities of Iqleem at-Tuffah, Jezzine and Jabal Al Rihan encompassing area of 139 km² have been considered. The motivation of such a selection is the numerous open landfill sites are distributed throughout the targeted area exerting immediate adverse effects on the well-being of local residents and the surrounding ecosystem. The persistent incineration of waste materials at these open landfill sites is also posited as a significant etiological factor for various diseases and disorders. Importantly, a subset of these landfills is situated in direct proximity to the banks of the Sainiq River. Consequently, the leachates emanating from these landfills directly contaminate the underlying aquifers, the Sainiq River itself, and ultimately find their way into the Mediterranean Sea. Addressing this central environmental concern stands as the primary objective of the undertaken power plant layout [50].

The net production of mixed solid waste generated at the target area is 65 tons/day according to a study conducted in 2022 [50]. Therefore, 65 tons/day of mixed solid waste can generate the energy content as follow [equation **Error! Reference source not found.**]:

$$\begin{aligned}\text{Energy content of 65 t/day} &= \text{Energy content} \times \text{Waste production}\\ &= 19.55\ \text{MJ/kg} \times 65\ \text{t/day} = 14.71\ \text{MW}\end{aligned} \quad (18)$$

The **Table 2 Error! Reference source not found.** reports the overall mass and energy balance and **Table 3 Error! Reference source not found.** reports the characteristics of ZE-IGMC power plant described in this paper.

Table 2. Mass and energy balance.

Quantity	Value
Ambient temperature (K)	298
Carbon dioxide mass flow (kg/s)	1.948

Carbon dioxide removal (%)	97.4
CO conversion (%)	97.5
CSC steam production (kg/s)	3.0
Efficiency of heat exchanger (HX1) (%)	59.7
Efficiency of heat exchanger (HX2) (%)	55.7
Gasifier cold gas efficiency (%)	82.1
Hydrogen mass flow (kg/s)	0.124
Oxygen mass flow (kg/s)	0.630
Raw gas mass flow (kg/s)	1.463
Shift conversion steam requirement (kg/s)	1.462
Steam (water for slurry) mass flow (kg/s)	0.063
Temperature of gases entering heat exchanger (K)	1673
Temperature of gases entering TA resonator (K)	1620
Temperature of gases entering/exiting WGSR (K)	673
Temperature of gasses exiting heat exchanger (K)	673
Temperature of gasses exiting WGSR (K)	298
Thermal input (MW) [eq. **Error! Reference source not found.**]	14.71
Waste energy content (MJ/kg) [eq. (20)]	19.55
Waste mass flow (kg/s)	0.75
Waste mass flow (t/day) [50]	65

Table 1. Characteristics of Thermoacoustic – Magnetohydrodynamic generator [43]

Quantity	Value
Current (A)	10
Efficiency of fuel cells (%)	70
Efficiency of TA-MHD generator (%)	31.3
Energizing electrical power (W)	500
Liquid metal	NaK
Mean pressure of the fluid (MPa)	3.0
Specific mass (W/kg)	10
Temperature of cold source (K)	298
Temperature of hot source (K)	1500
Thermodynamic fluid	air
Total mass (kg)	25
Voltage (V)	80

As described in the previous section, the main components of the power plant are the boiler, thermoacoustic resonator and the magnetohydrodynamic generator. The boiler is fed with crushed municipal solid indifferentiable waste that cannot be treated in other ways and is currently burnt in open atmosphere or used in landfills (mostly untreated). These both methods cause deterioration of environmental quality in terms of additions of CO_2 and other harmful substances in the atmosphere as well as making the land unlivable by polluting it. Hence, an emission free process is proposed in this paper to cater to these environmental issues at large.

4. Results

The layout of the power plant is shown in **Figure 2**. The waste is burnt in the presence of oxygen below the stoichiometric concentration, to produce syngas according to equations (4) and (5). This syngas at the outlet has temperature of about 1400 °C (1673 K). A heat exchanger is attached to utilize the thermal energy generated during the gasification of waste. The convective heat exchanger (HX1) releases this thermal energy to thermoacoustic resonator (TA resonator) which generates a vibration in the gas present in the TA resonator. The vibration power is carried to the magnetohydrodynamic generator (MHD generator) which contains liquid metal in the presence of radial like poles of permanent magnet, north poles in this case [34]. As the wave energy is transferred to the liquid metal, an alternating induced current is generated through the principle of magnetic induction.

The syngas passing through the HX1, reaches to temperature of about 400 °C (673 K) and it passes through water-gas shift reactor (WGSR) where the CO fraction is oxidized by reacting with steam, so that its chemical energy is transferred to the H_2. Another heat exchanger (HX2) is attached to utilize any further energy lost by the WGSR. This thermal energy is also directed towards TA resonator. The mixture of H_2 and CO_2 is passed through absorption column to separate CO_2 from H_2, which is fed to fuel cells to generate electricity (Figure 3). The separated CO_2 is pressurized at 80 bar and 25 °C (298 K). In such conditions the CO_2 is in liquid form and represents a marketable byproduct.

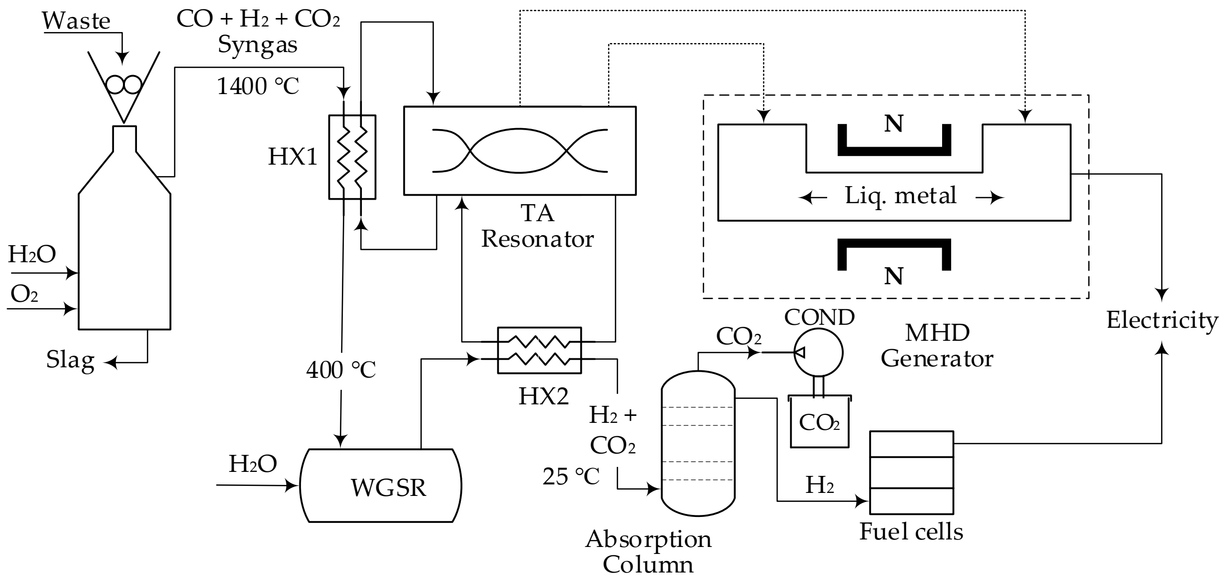

Figure 2. Process concept of the power plant.

3.1 Mass and Energy Balance

The **Table 4** represents the energy content carried by each type of waste in mixed municipal solid waste.

Table 4. Content of energy by waste type.

Component	% Waste by mass	% Moisture content	Energy content (MJ/kg)	Dry mass (kg)	Total energy (MJ)
Tin cans	2	4	0.70	1.92	1.40
Food waste	15	70	3.65	4.50	54.75
Garden waste	10	50	6.60	5.00	66.00
Wood	6	20	18.60	4.80	111.60
Cardboard	10	5	14.30	9.50	143.00
Plastic	10	15	30.60	8.50	306.00
Paper	45	6	18.75	42.30	843.75
	98			76.52	1,526.50

The net energy produced 100 kg of mixed municipal waste is 1,526.50 MJ (15.265 MJ/kg). To evaluate the net energy of dry mass, first the percentage of moisture content (%MC) is calculated as follow (19):

$$\begin{aligned}\%\text{ Moisture Content (MC)} &= \frac{\text{Total mass} - \text{Dry mass}}{\text{Total mass}} \times 100\% \\ &= \frac{98.00 - 76.52}{98.00} \times 100\% = 21.92\%\end{aligned} \tag{19}$$

Then, the energy content pertaining to dry mass is evaluated as follows:

$$\begin{aligned} \text{Energy content} &= \text{Total energy} \times \frac{1}{1-\%\text{MC}} \\ &= 15.265\ \text{MJ/kg} \times \frac{1}{1-0.2192} = 19.550\ \text{MJ/kg} \end{aligned} \tag{20}$$

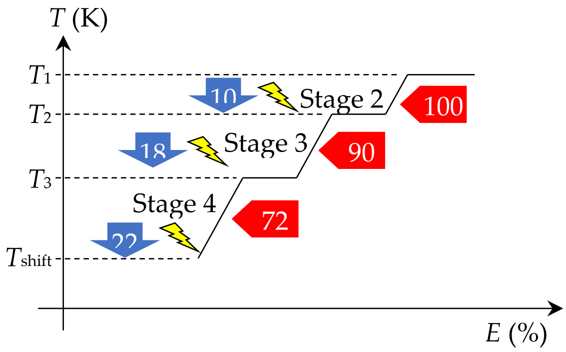

Figure 3. The energy production with each stage of fuel cell.

The temperature at the boiler reaches at 1400 °C which is very high, while the heat exchanged with the TAR at the first stage reduced the temperature to 400 °C, the reduction of 1000 °C, and at the second stage of heat exchanger, the temperature reaches up to ambient temperature, i.e. 25 °C. This continuous exchange heat with the TAR is too much to produce enough pressure wave which is capable of oscillating liquid NaK in the permanent magnetic field, resulting in the generation of electricity up to 500 W. Also, the production of hydrogen gas from the separation of H2 and CO2 gases at the absorption column is utilized in the fuel cells to generate further electricity. The electricity generation is a surplus as the main objective is to reduce mixed solid waste in a manner that it does not add any emissions in the atmosphere.

5. Discussion and Conclusion

Energy loss and environmental degradation are major issues in the power generation process. In some processes, all the thermal energy is lost to the surroundings rather than making use of it and other processes add too much pollution in the environment. One of the main causes of energy loss is due to the mechanical frictional loss which is an essential component of any power plant. As far as pollution is concerned, most processes produce a lot of greenhouse gases, and these gases are left in the atmosphere after power generation.

This model of the power plant does not contain any moving part and no mechanical frictional loss is observed as well as it can generate alternating current without any further process. It does not exhaust any greenhouse gas in the atmosphere which makes the system eco-friendly.

The system is wasted-fired, as a result of which it also addresses alarming conditions environment degradation. This model will not only generate green energy as well as reduce a tremendous amount of waste especially in those areas which lack proper waste management systems. The open dumps and landfills will be reduced, and more green energy can prevail.

Thermoacoustic technology can be applied in energy research in several ways: (a) *waste heat recovery:* TA devices can efficiently recover waste heat from industrial processes, power plants, or other heat sources and convert it into useful acoustic energy, which can then be converted into electricity [6]; (b) *solar energy*: TA systems can be integrated with solar thermal collectors to enhance the conversion of solar energy into electricity. This application can be particularly useful in solar power plants; (c) *nuclear energy*: TA technology can be employed in nuclear power plants to improve heat transfer and energy conversion processes, contributing to more efficient and safer energy generation; (d) *low-grade heat utilization*: TA devices can be used to tap into low-grade heat sources, such as geothermal or waste heat from industrial processes, which are traditionally challenging to utilize effectively; (e) *alternative cooling technologies*: TA refrigeration and cooling systems can replace conventional cooling methods in various applications, reducing energy consumption and environmental impact; (f) *cryogenic applications*: TA devices can also be utilized for cryogenic cooling in certain specialized energy research applications; (g) *research and development*: TA technology itself remains an area of active research, and further advancements could lead to breakthroughs in energy conversion and efficiency.

Overall, thermoacoustic technology's application in energy research aims to enhance energy efficiency, explore alternative energy sources, and contribute to sustainable and environmentally friendly energy solutions.

The model described in the paper not only addresses hyped environmental issues like proper processing of waste but also help reducing the emission of greenhouse gases into atmosphere. The system is more efficient as it does not contain any mechanical moving parts which causes energy losses in the form of friction.

Conflicts of Interest: The authors declare no conflict of interest.

List of Nomenclature

Quantity (Symbol)	SI Unit
Bulk viscosity (ζ)	Pa·s
Charge (q)	C
Current density (J)	A/m^2
Density (ρ)	kg/m^3
Efficiency (ε)	
Electric conductivity (σ)	S/m
Electrical power (P_{el})	W
Fluid dynamic viscosity (η)	Pa·s
Generic internal power source (S_{int})	
Gravitational acceleration (g)	m/s^2
Heat capacity ratio (γ)	
Identity tensor (I_d)	
Load factor ratio (K)	
Lorentz force (F)	N
Magnetic field (B)	T
Open circuit voltage (V_0)	V
Pressure (p)	Pa
Specific gas constant ($\Re$)	J/(K·mol)
Specific gravity force (ρg)	N/m^3
Specific heat at constant pressure (c_p)	J/(kg·K)
Specific heat at constant volume (c_v)	J/(kg·K)
Standard molar formation enthalpy of X ($\Delta H^{\ominus}_{f\,X}$)	kJ/mol
Stress tensor (τ)	Pa
Temperature (T)	K
Temperature of cold source (T_c)	K
Temperature of hot source (T_h)	K
Thermal conductivity (k)	W/(m·K)
Total energy per volume unit (e)	J/m^3
Velocity (v)	m/s
Wall heat transfer per volume unit and time unit (Q_{wall})	W/m^3

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