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NOVEL APPROACH FOR WASTE-TO-ENERGY HIGH EFFICIENCY PROCESS

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ABSTRACT

Waste-to-energy process is essential part of modern and future integrated waste management solutions. The waste-to-energy process using municipal solid waste as a fuel was studied in detail for complete understanding of these phenomena especially in terms of energy conversion into electrical power and the influence on the environment. The goal of our research was to substantially upgrade the waste-to-energy process from grate combustion into gasification for more efficient electrical power production and even lower the negative influence on the environment of the whole process.

Our research team has remodeled inclined grate combustion chamber into gasification reactor. The reactor is possible to operate in updraft or downdraft mode enabling the more adequate process adoption based on the input waste characteristics. The produced synthetic gas has relatively high calorific value and temperature, both can be turned into useful heat and electrical power.

The complete technology has been equipped with advanced sensors for process control. The most advanced is the utilization of fluorescence high temperature optical sensors for contact free measurement temperatures in gasification reactor.

KEYWORDS

Municipal solid waste, high efficiency electrical power production, waste-to-energy process optimization, high temperature optical sensors, low air emissions.

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INTRODUCTION

Modern societies produce large quantities of waste. Habits and living standard in developed countries is comparable to those of developing countries when speaking about waste generation. Statistically, every inhabitant of developed country produces around one and a half kilograms of municipal solid waste per day compared to developed countries where the waste generation is between half to one kilogram of municipal solid waste per day.[7][4] Taking into account the average calorific value of municipal solid waste round the globe its energy potential per kilogram equals to logging wood. Having in mind the yearly generation of waste the quantity of energy of the waste is great. This energy potential is presently mostly deposited in landfills across the globe thus not utilizing the energy potential and causing emission of green-house gases, production of polluted leaching water and shortage of deposition space.

The utilization of this energy source represents great environmental challenge. Waste-to-energy plants present an important step towards utilization of domestic available energy source, reduction of fuel import dependence and fulfillment of global environmental standards and agreements.

This paper presents a novel technology that enables not only the utilization of the energy of the waste but also the potential for high efficient transformation of released energy into electrical power.

MUNICIPAL SOLID WASTE FOR WASTE-TO-ENERGY PROCESS

Waste treatment technology is nowadays a highly developed and advanced activity with constant and extensive public control. Specially developed combustors for waste incineration are inevitably needed in every modern and civilized society.

Nowadays, bed combustion on grate is the most common way to incinerate municipal solid waste and generate electrical power and heat. [1] The combustion in these plants is very specific due to the characteristics of municipal solid waste which depends on collection, pretreatment, season of the year, etc. [6] The goal of every technology producer on one side and the operators on the other side is the optimal thermal conversion of calorific energy of waste into electrical power and heat with minimal emission of the pollutants to the environment.

Energy and environmental aspect make the energy utilization of waste justified and this process is obligatory in Europe to fulfill European waste directive demands. [2][3] Thermal waste processing must meet all legal requirements that define the process of waste incineration which is rather called waste recovery operations. [3] Heat generated can be used to produce electrical power, hot water for heating and cool media for cooling.

Main waste-to-energy process task is total thermal decomposition of hydro carbon materials in waste and the utilization of the energy, deposited in waste. Thermal conversion process products are inert materials. The quantity and toxicity of the remains and quantity of formed pollutants is primarily dependent of the process quality in the reaction chamber.[1]

The average waste material utilized in waste-to-energy process is composed of materials that add up to the calorific value of the waste. This waste stream is usually called “refuse derived fuel” – in abbreviation RDF, and is made up of paper, cardboard, plastic, foils, textile and wood. The RDF is initially processed in the mechanical biological treatment plant from the municipal solid waste. Table 1 shows the results of the investigated materials included in the RDF.

The average fraction composition of RDF, based on our investigations, is quite versatile but can still be presented with data in the Table 2. The data in the table is based on the research of Slovenian RDF produced from municipal solid waste.

The mechanical biological plant prepares the RDF according to the waste input stream quality, their technical capabilities and operation permits. Sometimes, to lower the operational costs, operators leave out certain sorting and processing systems thus produce coarser, lower-grade fuel with higher moisture and ash content. Still the RDF should be produced in accordance with the limits, set in the Table 3 otherwise problems may arise during thermal treatment of RDF.

Main emphasis of this work is dedicated to optimize the conversion process to enhance the electrical power production of the waste-to-energy process.

The waste gasification process has been studied on existing pilot scale waste-to-energy plant with capacity of 50 kg/h presented on Fig 1.

PROBLEM DEFINITION

The waste-to-energy technologies utilize Rankin cycle for the production of electrical power. Generally the cycle operating media is water being within the cycle compressed and heated to superheated stem and on the other side after led through steam turbine condensates to liquid state.

Due to high corrosion problems within the boiler most plants operate with superheated steam of up to 400 °C and condensate the steam at temperatures well above 60°C. These operating conditions limit the possibility for electrical power production to around 25% of input waste energy. This can be roughly calculated with simplified Eq. 1 having in mind that complete cycle total isentropic efficiency is calculated by multiplying all isentropic efficiencies of the cycle. This value is generally for waste-to-energy plants technology applied around 0.7.

$$\text{Electrical power production eff.}_{\text{Rankine c.}} \approx 1 - \frac{\left(\frac{\text{Temperature of steam condensation [K]}}{\text{Temperature of steam superheating [K]}}\right)}{\text{Cycle total isentropic efficiency}} \qquad (1)$$

Legislation in European Union [3] has set strict limits for the beneficial utilization of energy produced by waste thermal treatment. The thermal treatment can only be regarded as "recovery operations" and not "disposal" if plants reach the energy efficiency of at least 0.65 set by Eq. 2.

$$\text{Energy efficiency}=\frac{\text{Energy produced - Energy from fuels - Other energy imported}}{0.97\times(\text{Energy of waste input + Energy from fuels})} \quad (2)$$

All energies in Eq. 2 are calculated in GJ/year. The term Energy produced in Eq. 2 means annual energy produced as heat or electrical power. It is calculated with the energy in the form of electrical power being multiplied by 2.6 and heat produced for commercial use multiplied by 1.1. The factor 0.97 is a factor accounting for energy losses due to bottom ash and radiation. To reach the set efficiency the most practical way is to maximize the electric power production.

To get a building permit for a waste thermal treatment in Europe today the new plant must in most cases fulfill this recovery standard.

Developed countries also largely support production of electrical power from renewable energy sources. Every country has developed its own scheme to support this production and they are called feed in tariffs. These tariffs add up to regular prices of electrical power, making this electrical power production very lucrative business.

TECHNOLOGY BACKGROUND OF HIGH EFFICIENT WASTE-TO-ENERGY THERMAL CONVERSION PROCESS

The development of the high efficient electrical power production system could go into the direction of utilizing more advanced, high corrosion and stress resistant steels for boiler production or use or corrosion resistant plating on boiler tubes. The other possibility is to modify the whole waste-to-energy process and this is the investigation we undertook.

Our research group has large experience in multi stage combustion systems. The laboratory equipment allows us to execute advanced research in this field.

Two stage combustion systems have been originally designed for industrial, medical and hazardous waste incineration since in the past the legislation of developed countries had set higher environmental and technical standards for treating these wastes then treating the municipal solid waste. Those incinerators had small capacity and were mostly batch fired. The main intention for installing the second combustion chamber was to improve complete combustion of all organic components in gases leaving primary chamber [1]6].

Multi stage incineration systems have made their first appearance some fifty years ago. All two (or multi) stage technologies share the common idea of two (or more) divided chambers (reactors). The two chamber combustion technology is in principle based on the air shortage in the primary chamber and excess air in the secondary chamber, what together assures good combustion conditions, low emissions and lower consumption of added fuel [1] 6].

Originally our pilot plant waste-to-energy system was developed as two-stage combustion process for waste incineration.
The primary combustion chamber was during this work remodeled to assure good gasification conditions for the production of high calorific value synthetic gas. For remodeling the advanced computer based engineering tools were used and optimization compared to other researchers was made. [9] 10].

The schematic presentation of gasification reactor or primary chamber and combustion or secondary chamber is presented on Fig. 2.

The whole waste thermal treatment process is based on two groups of physical - chemical processes:

- Warming, drying, semi-pyrolitic gasification of the waste in the primary chamber and
- Mixing of the synthetic gases with air, ignition and complete combustion in the secondary chamber.

Prepared and mixed RDF is transported to the hoppers above the RDF screw feed dosing units situated above the reactor. These screw feeders provide a continuous and steady RDF feed into the primary chamber. As compared with discontinuous feeding (ram feed), with the continuous screw feeding system, a more uniform processing of RDF is assured.

The investigated technology is regarded as modular waste processing on the grate. Waste processing is conducted in two stages – the designed process enables to upgrade the investigated system with utilization of high calorific synthetic gas in gas turbine or internal combustion gas engine instead of burning it in secondary chamber. The system utilized in laboratory is schematically presented on Fig. 3 and the system for high efficient electrical power production is presented on Fig. 4. All performed tests were made as shown on Fig. 3, but for real high efficient electrical power production the scheme in Fig. 4 should be applied. This utilization of synthetic gas in gas engine or turbine is only possible if high calorific synthetic gas is produced. The literature shows that the gases with the calorific value of between 4 and 6 MJ/Nm^3 can be produced and the complete data is presented in Table 4. [8] The gas turbine can run on gases with calorific values as low as 2.5 MJ/m^3.

Our goal was to investigate and design a reactor to reach up to 4 MJ/Nm^3 with average composition of RDF produced in Europe. Thus the system was built to allow downdraft (hatch D on Fig. 2 closed) or updraft (hatch U on Fig. 2 closed) operation to be able to adjust the gasification to the properties of waste treated.

In the primary chamber the gasification process is carefully managed with an exact air supply and temperature control. The system operates with air deficiency – compared to the theoretically required air for combustion, so pyrolytic gasification processes prevail. This is carefully controlled with under the grate air supply to ensure proper gasification process along the grate. The only possibility to overlook the gasification process along the grate in detail is to measure the temperature of the grate. As the upper side is covered with waste the only possibility is to measure the bottom side of the grate. This is done with advanced non-contact method presented in next chapter.

The whole process of gasification was controlled with the quantity of waste input into the chamber, the velocity of waste movement along the grate and quantity and distribution of air. The search for optimal operating conditions was based on the known composition of waste and operating experience.

Generated synthetic gases are on the pilot scale system measured in the duct between primary and secondary chamber. The interesting results of early test can be seen on Fig. 5. The upper lines depict average temperature in primary and secondary chamber measured with thermocouples and the lower line shows the average calorific value of synthetic gas measured with Wobbe index analyzer [5]. The temperature in primary chamber was kept more or less constant just over 600 °C and the air supply was controlled during test period. The generation of higher calorific value syngas after 7 a.m. was produced with increased input of the waste but the amount and distribution of air remained the same. This resulted in the rapid increase of average temperature in secondary chamber where synthetic gas was completely combusted. The measurement results are occasionally scattered around average value that can be partially explained with measurement problems and still small test plant where small changes have great effect on the results. After a period of over 8 hours the cooling of secondary chamber was needed and the test was aborted. We feel the relative stability of the results and the duration of it on this pilot scale device show the real operation potential of stable and long lasting operation of full scale device.

The pilot scale equipment tests have shown that this technology can offer production of synthetic gases of over 4 MJ/Nm^3. The generation of gas is highly dependent of the calorific value of the RDF. Our test show that RDF with around 11 MJ/kg produces synthetic gases with around 2 MJ/Nm^3 and only RDF with calorific value of 15 MJ/kg or over enables the production of synthetic gas of 4 MJ/Nm^3 and over.

The on-line measurements were only performed for the measurements of calorific value. Some measurements were also made so investigate the composition of syngas showing the H_2, CO and CH_4 are the main components of the formed syngas, which have the energy value, and together with CO_2, N_2, O_2 and H_2O represent more than 93% of the components in syngas. The rest are higher order hydro-carbons (ethane, propane, butane, benzene,...), some cyclical hydro-carbons (benzene, toluene,...) and other gases (HCl, HF, SO_2,...). Higher-order hydro-carbons and cyclical hydro-carbons do have higher calorific value than H_2, CO and CH_4, but are found in the syngas in very low, negligible quantities.

Our research also showed that the newly designed thermal process, run as a system presented on Fig. 2 produces less pollutants in flue gases then run in standard two-stage combustion mode. This can easily be explained as the process of gasification is based on much lower gas velocities compared to combustion entraining fewer particles into flow from primary chamber. The combustion of high calorific synthetic gases is at much higher temperatures what contributes to complete combustion of all organic components in gases. This together more easily fulfills the standards set by European Waste Incineration Directive [2].

TEMPERATURE MEASUREMENTS WITH FLUORESCENT SENSORS

Luminescence thermometry has been used for many years to measure temperatures in high-temperature combustion processes in which non-contact monitoring is necessary. Since it is a non-contact method it is especially applicable on moving parts of the investigated or operated equipment.

The luminescence properties of thermographic phosphors are very sensitive to variations in temperature. Most thermographic phosphors exhibit a broadband absorption in the UV region and few more narrow absorption lines in the visible region. Thermographic phosphors are mostly a fine ceramic powder or monocrystals that efficiently fluoresce when suitably excited. Several methods can be used for excitation, such as laser radiation (pulsed or continuous), particle beams, chemical reactions or thermal excitation in flames. The excitation is usually performed by an ultraviolet or a visible laser beam. Following excitation, the subsequent emission due to the relaxation of electrons from the excited state to the ground state can be used for non-intrusive thermometry. Two methods of inferring the temperature can be employed, the temporal and the spectral method. Both methods allow one-point or two-dimensional measurements to be performed.

The temperature dependence of phosphors is a function of their base crystal structure and a small quantity of added "dopant" ions, usually rare-earth ions or lanthanides, transition metals and heavy metals, which are optically active, capable of absorption and emission in the visible spectrum. For sensing applications at high temperatures, the selection of appropriate dopants is most restrictive since the luminescence signal must be detectable against the blackbody radiation from the surroundings.

A number of phosphors based on yttrium and the lanthanides have been studied for high-temperature luminescence. A highly pure measuring crystals (~99.99 wt%) of doped yttrium aluminate garnets (YAG, $Y_3Al_5O_{12}$), doped yttrium aluminate perovskites (YAP, $YAlO_3$), doped yttrium oxides (Y_2O_3), doped alumina (Al_2O_3), doped spinel ($MgAl_2O_4$) and gadolinium oxide (Gd_2O_3), have been prepared according to Verneuil method and combustion synthesis.

Of special note are Dysprosium (Dy), Terbium (Tb) and Thulium (Tu) doped YAG materials which have been shown as the particularly promising for high temperature measurements and have been easily applied to temperatures up to 1500 °C. Other prepared phosphors have also shown measurable signals up to 1200 °C, thus allowing a combination of phosphors to be used in high-temperature applications to make surface temperature measurements from ambient to over 1500 °C. Particularly promising for the implementation of high temperature measurements have been proven YAG materials doped with a combination of inorganic constituents Terbium and Thulium ((Tb,Tm):YAG) which showed fluorescence in the blue and green area and are also suitable for two-color thermometry at high temperatures. Other yttrium-based oxides that have been studied include rare-earth ortho-aluminates (general formula: $LnAlO_3$), Y_2O_3, and YVO_4. Although these have not been examined as extensively as YAG, they generally possess good optical properties.

The Fig. 6 schematically shows the system applied on our pilot scale system. Strong laser beam (e.g. green laser 532 nm or 405 nm UV laser) is used for excitation, which enables the measurements at a distance of up to around 2 m. Thus, dichroic mirrors and filters must be adapted to the light source. In our case, a fluorescent material in powder is pre-integrated into a high-temperature coating of bottom side of the grate, what ensures the proper measurement of operating temperatures up to 1600 °C.

CONCLUSION

Wastes no longer present a problem but rather an opportunity; in our investigated case a domestic source of energy. The energy production and utilization is possible with the appropriate system that operates within the legally permissible environmental impact. Such system must create electrical power and heat or cold, which are distributed to the citizens or industry.

The concept and technologies tested in our work have shown a very promising and marketable technology where high subsidiaries exist for electrical power production from waste. The technology can easily fulfill European and our national legislation. Utilization of waste in waste-to-energy plants means reducing greenhouse gas emissions, more rational management of energy and limited space for waste disposal.

The tests on the pilot scale system have on various operating conditions with different quality RDF produced desired results. The RDF utilized in tests was produced on full scale technology in normal operation thus producing comparable material already available in Europe in very large quantities.

The operating conditions of waste gasification and produced results on experimental device shows clear potential for high efficient electrical power production. The process solution proposed is based on tested and proven components thus present environmentally and financially safe investment. The achieved calorific values of synthetic gases are in the range of literature data what show the accomplishments comparable to them.

Development of high-temperature fluorescent sensor means an innovation of highly efficient temperature control system for supervision of gasification or combustion processes and thus contributes to lower emissions of harmful substances into the environment. Developed high-temperature fluorescence sensor system enables accurate and fast data acquisition and control of the whole process with a central control system.

Experimental work has produced positive results in the development of equipment for fluorescence thermometry, which allows easy adaptation to different types of phosphor materials. The measuring system enables the use of different measuring crystals for various temperature ranges, and can be used in different types of applications.

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TABLES AND FIGURES

Table 1: Combustion properties of RDF components.

	MATERIAL COMBUSTION PROPERTIES			
	Moisture	Ash	Combustibles	Heating value
Combustible fraction		(%)		(MJ/kg)
Textile	7,56	5,76	86,68	16,65
Chard board	6,85	11,88	81,27	17,49
Soft paper	23,99	12,43	63,58	10,1
Plastic foil	0,51	13,24	86,25	40,14
Hard plastic	0,4	5,28	94,32	40,12
PET bottles	0,42	0,15	99,43	21,51
Wood	12,52	2,31	85,17	16,32

Table 2: The average composition of RDF.

Fraction	Mass share [%]
Textile	12 - 16
Chard board	10 - 15
Soft paper	30 - 40
Plastic foil	10 - 15
Hard plastic	9 - 11
PET bottles	4 - 6
Wood	2 - 4

Table 3: Limit values of certain properties of RDF.

Parameter	Value
Moisture content:	between 20 and 45%
Metals content:	up to 2 %w
Ash content:	between 15 and 30%
Chlorine (Cl) content:	up to 1 %w
Fluorine (F) content:	up to 0,2 %w
Nitrogen (N) content:	up to 1 %w
Sulphur (S) content:	up to 0,3 %w
Calorific value:	between 10 and 14 MJ/kg

Table 4: Calorific value of synthetic gas produced with air and various gasifier types [8].

Gasifier type	Calorific value of the product gas [MJ/Nm^3]
Downdraft	4 – 6
Updraft	4 – 6
Fluidized bed	4 – 6
Fluidized bed - steam	12 – 18
Circulating fluidized bed	5 – 6.5
Cross flow	4 – 6
Rotary kiln	4 – 6

Fig. 1: Pilot scale waste-to-energy plant during experiments and investigations.

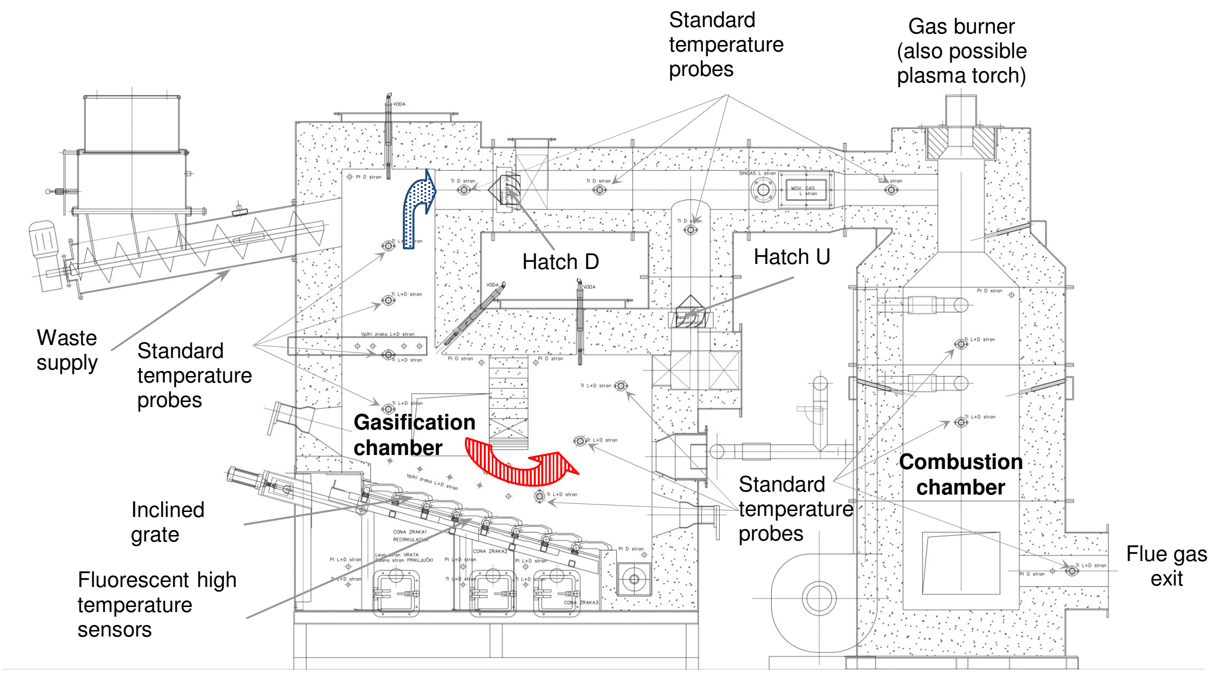

Fig. 2: The schematic presentation of gasification and combustion chambers of pilot scale waste gasification unit.

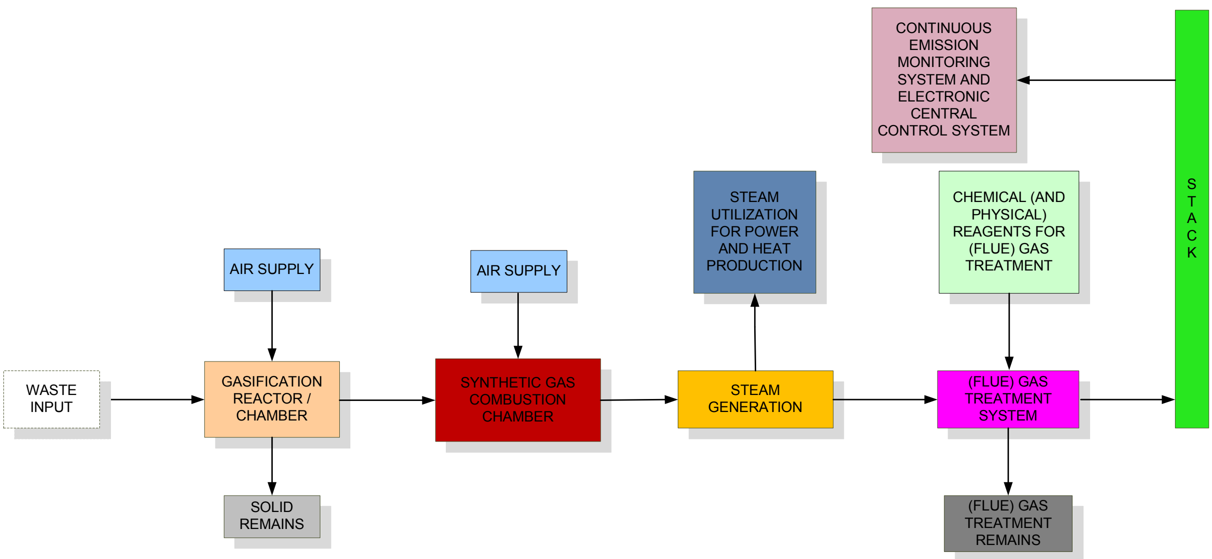

Fig. 3: The schematic presentation of complete laboratory waste gasification system.

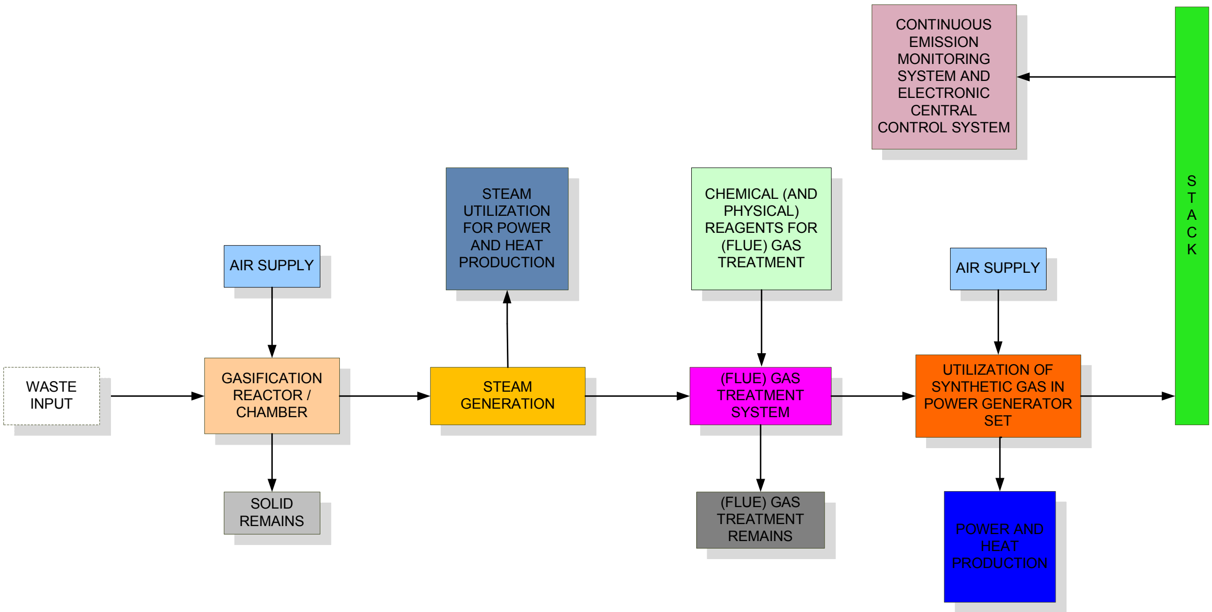

Fig. 4: The schematic presentation of complete gasification system with high efficient electrical power production unit.

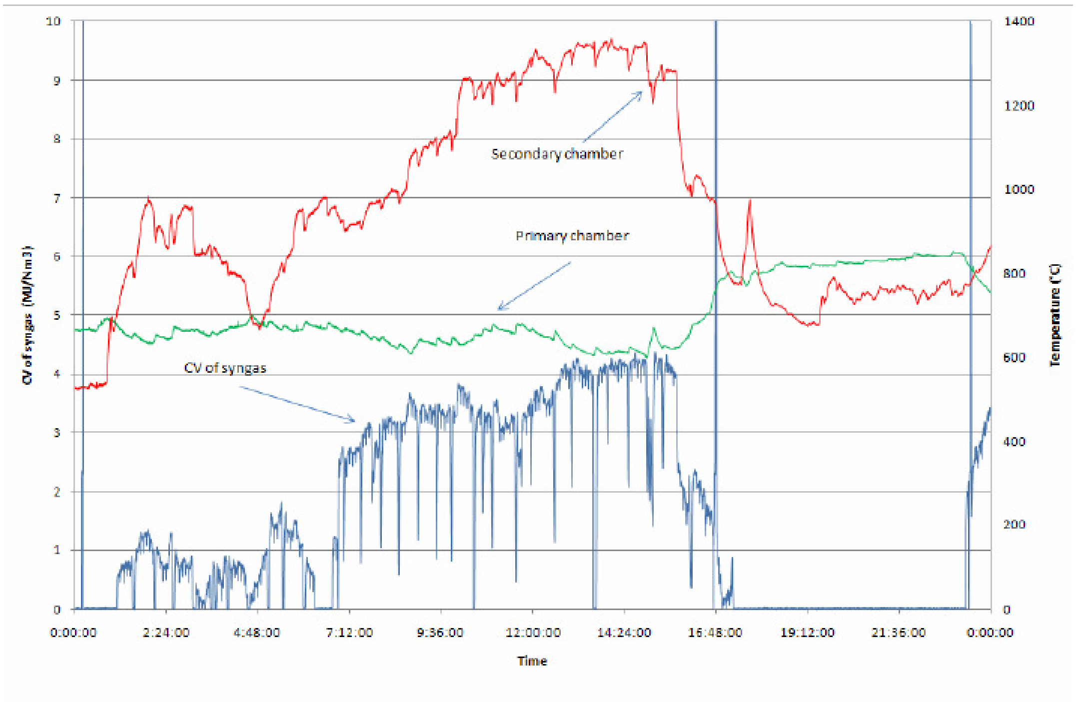

Fig. 5: Calorific value of generated synthetic gas and temperatures in primary and secondary chamber of pilot scale plant unit during experiments.

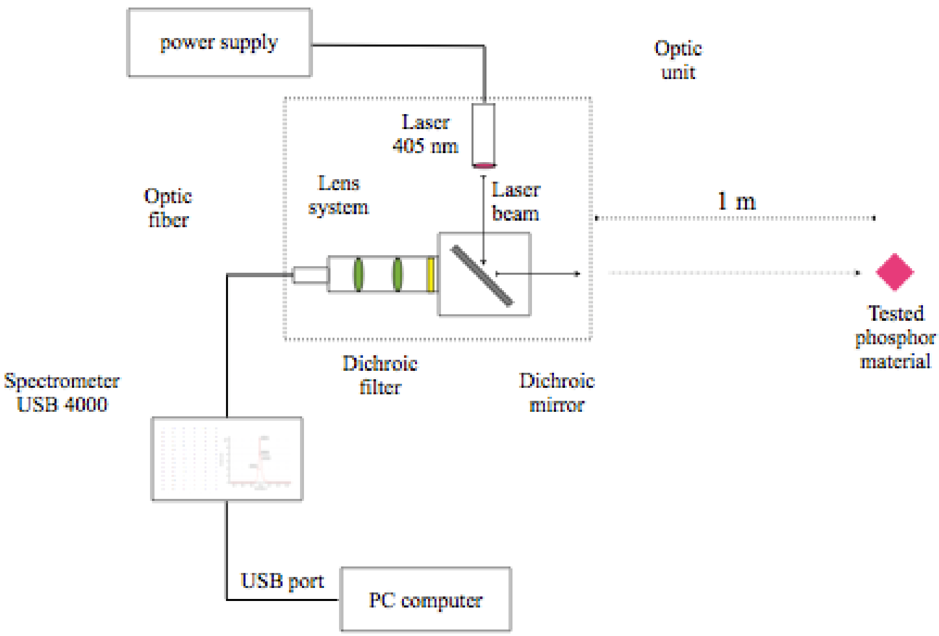

Fig. 6: Non-contact fluorescent high temperature measurement system.