Heat pipe based municipal waste treatment unit for home energy recovery

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ABSTRACT

A heat pipe based pyrolysis chamber has been developed and tested as an efficient, cost effective and space saving municipal waste treatment unit. The performance of the chamber was evaluated based on the temperature distributions inside the chamber, its electricity consumption and the chemical characteristics of the final pyrolysis products (bio-chars and pyro-oils) obtained from the process and validated by three test runs. In all the three tests, the type of waste treated was municipal waste obtained from households. In addition, special cases of challenging waste configurations, such as mixed domestic plastics and PVC are reported. The chemical analysis of the pyrolysis and the ash residues from the municipal solid waste showed no toxic elements in their composition. The main component of the char was calcium, the fluid oil obtained from the initial stages of pyrolysis had a similar composition to that of water, while the dense oil produced during the final stage of the process showed traces of iron and a potential composition match to commercial additive oils. The chemical analysis of the chars and ash obtained from the mixed domestic waste showed no toxicity for the mixed plastic char but a potential toxicity of the PVC char due to the existence of lead and chlorine. Calculations regarding the coefficient of performance (COP) of the heat pipe based pyrolysis unit indicated that the COP decreased with the increase of moisture content of the waste stream. For 0% moisture content in the waste stream the COP of the unit was 9.4 and the carbon footprint of the unit was 0.0782 kg CO_2e per kg of treatment. On the other hand, for a maximum moisture content of 100% the COP was 0.53 and the CO_2 emissions were 0.3873 kg CO_2e per kg of treatment.

1. Introduction

The term municipal solid waste (MSW) refers to waste materials discarded by a typical household, such as food, paper, plastics, metals, glass, ceramics, textiles, garden waste and other miscellaneous everyday materials. The total waste generated from households in England in 2013 was more than 21.5 million tonnes, with the average yearly waste production per person being 403 kg [1]. The key principle of European and UK waste legislation is the hierarchy of waste management options, where the most desirable option is to prevent waste production in the first place and the least desirable to dispose of the waste to landfill with no recovery of either materials or energy [2].

Table 1 describes the typical composition of the MSW found in UK households for 2011.

The chemical composition of each waste category is as follows:

1.1. Paper products

Cellulose fibre is the main constituent of paper products, while additional ingredients may be used to change the appearance and texture of the paper. For example, to produce the glossy paper of magazines, calcium carbonate is added and to produce brown packaging paper, sodium sulphate is used. In addition, the chemical composition of the ink should be considered; compounds such as calcium carbonate, titanium oxide, barium sulphate, aluminium

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Table 1
Composition of waste from households, 2011 [1].

Category	Value (wt %)
Organic waste (food, garden, wood for composting and other compostable waste)	35.8
Furniture, mattresses, soil, miscellaneous combustible and non-combustible, sanitary, hazardous and other unspecified waste	14.9
Paper	14.0
Glass	6.8
Dense plastic	6.6
Card packaging	5.2
Plastic films	3.8
Wood	3.8
Metals	3.7
Textiles	2.9
Electrical and electronic equipment waste	2.3

hydrate, organic resins and humectants, etc. are commonly used.

1.2. Plastics products

Plastics are generally polymer sheets derived from fossil fuels or vegetable oils. Most plastic packaging of domestic products is made from Poly Propylene (PP), Poly Ethylene (PE) and Poly Ethylene Terephthalate (PET), with smaller quantities of Low Density Poly Ethylene (LDPE), High Density Poly Ethylene (HDPE), Poly Styrene (PS) and Poly Vinyl Chloride (PVC) [3,4]. Plastic bottles are mainly made from PET and HDPE. LDPE and HDPE belong to the family of aliphatic hydrocarbons made from the monomer ethylene, PP has a propylene group structure and PS is made from vinyl benzene monomers. Finally, PVC consists of vinyl chloride.

1.3. Organic products

The organic waste category includes mainly garden and food residues. The main components of yard waste are leaves and wood made of cellulose, hemicellulose and lignin. Cellulose and hemicellulose are both glucose polymers, while lignin is a complex aromatic polymer which is not as degradable as the glucose polymers. On the other hand, the main components of food are proteins, fat, carbohydrates, water, polysaccharides fibre, vitamins and several minerals. However, the proportions and the exact composition depend on the food item. For example, bone is mainly composed of hydroxyapatite and collagen, meat contains mostly water, proteins, fat and minerals such as calcium, phosphorus, sodium, potassium and sulphur, while, for example, 80% of potatoes consists of water and the remainder carbohydrates, proteins, lipids, minerals and vitamins.

1.4. Metal products

Most metals found in MSW are iron or aluminium. However, heavy metal traces are very often present, such as antimony, arsenic, cadmium, chrome, copper, lead, mercury, nickel, selenium, tellurium, thallium, tin, manganese and zinc. These elements are highly toxic for the environment and human health. Heavy metals can be found in virtually all MSW materials at some concentration. For example, some sources could be ink on papers or magazines, part of wood products, textiles, glass, rubber, plastic packaging or batteries etc.

1.5. Glass products

The main component of glass is silica (silicon oxide) and the additional compounds are sodium or potassium carbonate, calcium oxides, lead oxide and boric oxide. Metal oxides are usually added to provide the colouring of the glass products.

1.6. Textile products

Textiles may be derived from animal, vegetable or synthetic products, such as wool, silk, cashmere or cotton, linen or acrylic, nylon, polyester. Thus, textiles may contain various components. For example, wool is mainly composed by keratin-type proteins, cotton is a cellulose and acrylics are acrylonitrile polymers.

2. Thermal treatments in MSW management

Currently, domestic waste must be transported and disposed of in landfills or be burned in mass incinerators. However, recent developments in the waste management sector are favouring more environmentally friendly treatments. Advanced Thermal Treatments (ATT), such as gasification and pyrolysis are designed to recover energy (in the form of heat, electricity or fuel) and can contribute to reduce the biodegradable waste volume of landfills [5]. MSW pyrolysis is an innovative treatment and management process that utilises waste to produce different chemicals and fuels [6,7]. Pyrolysis offers many advantages over conventional MSW incineration. Firstly, the quantities of nitrogen oxides (NO_x) and sulphur oxides (SO_2) produced during the pyrolysis process are much lower than with incineration. In addition, the final products of pyrolysis are syngas, oils and chars, which can be recovered from the process and used as fuels [8]. Finally, for pyrolysis, the greenhouse gas emissions from the process are reduced compared to incineration and the quality of the solid residues is enhanced [9].

However, despite the proven benefits of ATT methods, there is only a relatively limited experience of MSW pyrolysis. Many examples of ATT processes have been established for various waste streams (e.g. biomass, industrial wastes, tyres etc.) but again only a limited number have been applied to MSW management.

ATT technologies refer primarily to incineration, pyrolysis and/ or gasification, with incineration, the combustion of the waste, already a mature and well established technology. These three treatments are the most commonly used methods which enable the extraction of energy from waste [10]. Combustion is a heat transfer process through the oxidation of a mass; its energy generating efficiency is around 10% and it is considered to be a source of substantial pollution [11,12]. Pyrolysis transforms the initial solid mass of material into chars, gases and liquids, by the application of a high thermal flux without the presence of an oxidizing agent [13,14]. Gasification is a partly oxidizing process that converts a solid mass into completely gaseous fuel.

2.1. Incineration

For incineration to take place, enough oxygen needs to be introduced to the process to allow full oxidisation. During MSW combustion, carbon dioxide and other greenhouse gases are released, while the non-combustible materials remain as residues in the chamber in the form of ash. Typical incineration temperatures are around 850 °C.

2.2. Pyrolysis

Pyrolysis causes the thermal degradation of the waste with oxygen being totally absent. In order for pyrolysis to take place an external heat source is required to maintain the chamber at a threshold temperature. The final products of pyrolysis are a solid residue (bio-char), oils and a synthesis gas (syngas). Pyrolysis
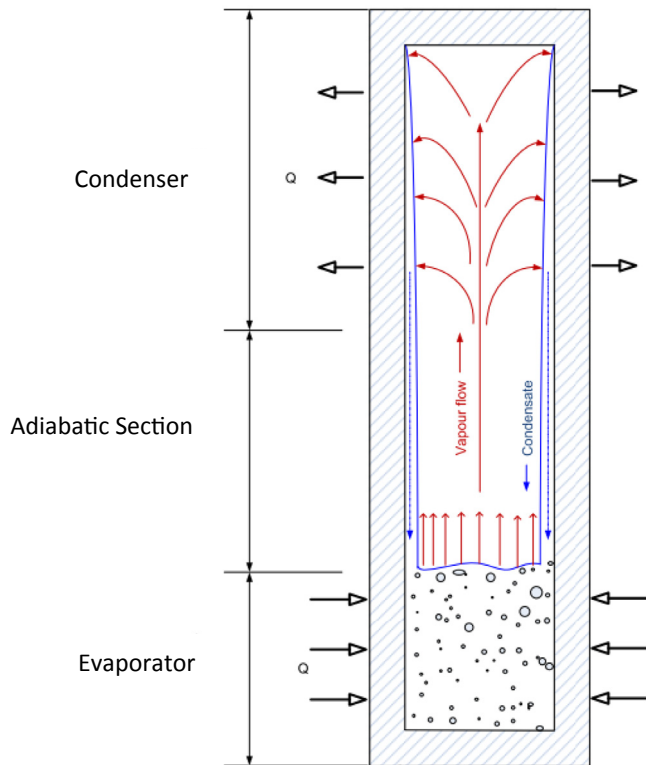
Fig. 1. Heat pipe's working cycle [33].

temperatures vary between 300 and 900 °C and the yields and composition of the pyrolysis products depend on the temperatures applied [15–27]. Pyrolysis at temperatures between 500 and 550 °C is used when oils are the desired product, while temperatures of 700 °C or higher are used to produce primarily high quality syngas [8]. The solid residue is in the form of a high carbon content char. The syngas is a mixture of combustible gases, such as carbon monoxide, hydrogen and methane, as well as a broad range of other volatile organic compounds, a proportion of which can be condensed to produce oils, waxes and tar.

It is widely accepted that pyrolysis occurs in two steps; a primary pyrolysis phase between 200 and 400 °C, which results in bulk product volatilization and the formation of a solid char residue, and the second phase of temperatures above 400 °C, during which the char residue undergoes further chemical and physical transformations as part of an aromatization process [13].

2.3. Gasification

Gasification can be described as a treatment which lies between combustion and pyrolysis. During gasification, the waste is partly oxidized, which allows the conversion of a solid mass into a gaseous fuel. This means that although oxygen is present, the amount of it is not sufficient to allow complete combustion of the waste, just enough to maintain the ignition of the waste. Typical gasification temperatures are around 650 °C. The main product of the process is syngas, which contains carbon monoxide, hydrogen and methane, and solid ash, which has a relatively low carbon content.
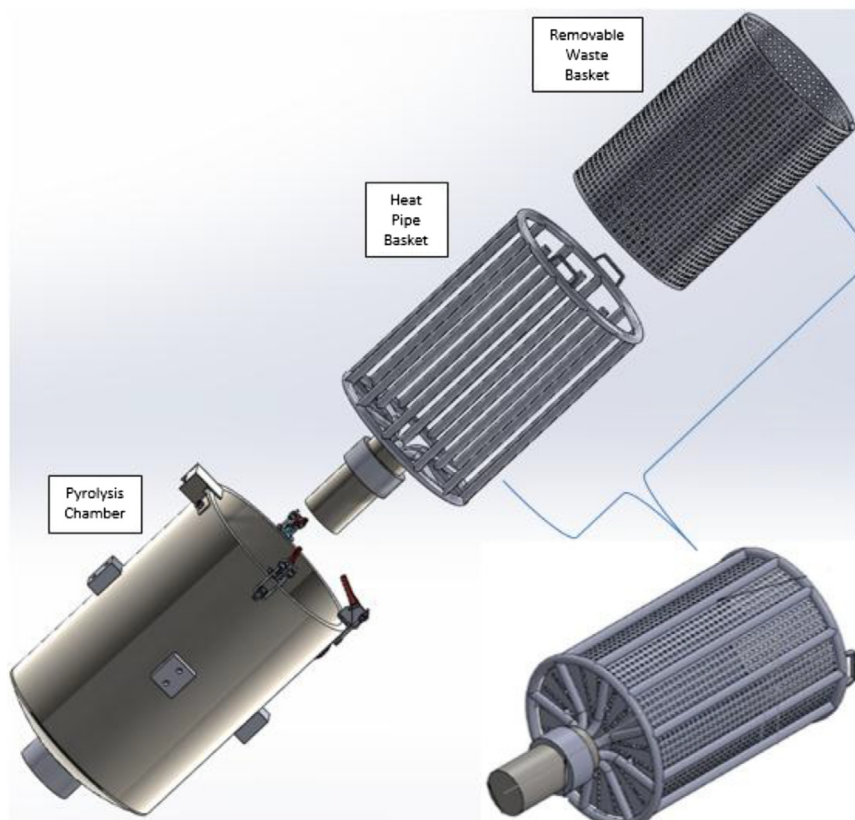

Fig. 2. Design designs of HERU – exploded view.

3. Heat pipe based waste treatment unit for home energy recovery

The majority of pyrolysis reactors reported in the literature are fixed-bed reactors, rotary kilns and fluidised bed reactors [8]. Current pyrolysis systems rely on direct heating techniques, such as electric heaters, heating with naked flames or exposure to hot media [28]. These approaches have two major shortcomings; firstly, they cannot cope efficiently enough with the changing heat transfer from the heated walls to the materials during the pyrolysis process, particularly as the water moisture content decreases [29]. Secondly, they require the development of very high temperatures on the chamber walls to overcome the thermal resistance within the reactor [8]. To deal with this issue, various procedures are normally required to prepare the waste prior to its thermal treatment to ensure that the pyrolysis process will take place throughout the volume. A common practice is to separate the waste according to its moisture content, then dry the material and grind it into small pieces before placing it in the pyrolysis chamber [14,20,21,30–32].

An innovative pyrolysis system is introduced in this paper. The heat pipe based waste treatment for the Home Energy Recovery Unit (HERU) does not involve any pre-treatment of the waste stream. The key feature of HERU is that heat is injected into the treated matter with a controlled working temperature rather than with controlled heat fluxes. Further innovative aspects of HERU are the use of heat pipe technology to achieve high uniformity of the heat distribution within the chamber and high energy recovery.

Two phase heat transfer systems, of which heat pipes are an example, offer key advantages over conventional single-phase systems. Firstly, they are capable of transporting the same amounts of energy as single phase liquid or gas systems, but with considerably smaller mass flow rates, due to the high thermal capacity (latent and sensible) of their working fluid. As a result, heat pipes offer smaller sized systems with much greater heat transfer coefficients than the conventional single-phase systems. The amount of heat that can be transported through the use of latent heat is typically several orders of magnitude greater than that transported by sensible heat for a geometrically equivalent system. Secondly, heat pipes can be manufactured in a variety of shapes, such as right-angle bends, S-turns, spirals, or even in flat configurations, with no limitation on their length. Finally, heat pipe systems do not require the use of any external mechanical systems, such as pumps or fans, to circulate the working fluid, increasing their reliability and minimising their maintenance requirements and operating costs.

There are four main applications for using heat pipes:

- Heat transfer with a small temperature difference
- For isothermal applications, where reduction of pre-existing temperature gradients within a body and operation with isothermal surfaces is the primary purpose
- For temperature control applications, where the heat pipe controls the temperature of a body
- For heat flux transformation applications, where the heat source and the heat sink require different heat fluxes

A heat pipe is a passive thermal transfer device able to transport large amounts of heat over relatively long distances isothermally, without moving parts, using phase-change processes and vapour diffusion. The main structure of heat pipes consist of an evacuated tube partially filled with a working fluid that exists in both liquid and vapour phase. The following figure demonstrates the basic operation of heat pipes. (see Fig. 1).
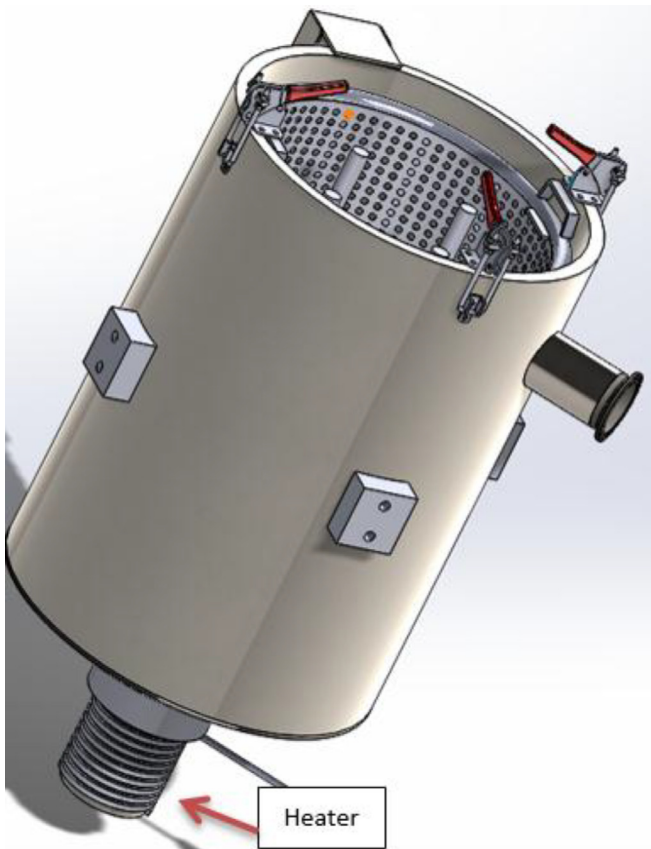

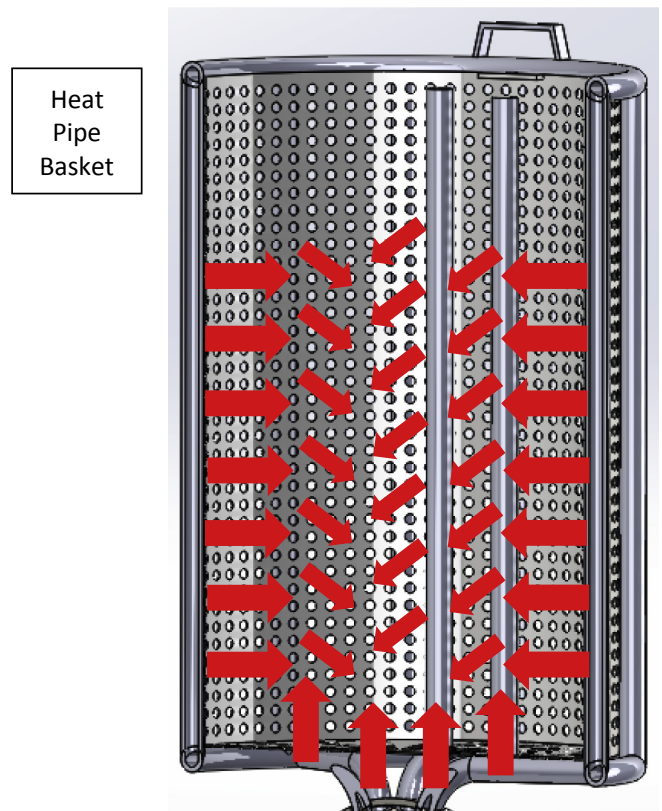**Fig. 3.** The mechanical design of HERU.

Fig. 4. Cross section of heat pipe basket and heat distribution.

The lower part of the heat pipe is the evaporator and the upper part is the condenser. When a high temperature is applied at the evaporator section of the heat pipe, the working fluid existing in the liquid phase evaporates and flows with high velocity towards the cooler end of the pipe - the condenser. As soon as the vapour reaches the condenser section, it condenses and gives up its heat. Then the liquid working fluid returns to the evaporator part of the pipe, by the influence of gravity (thermosyphons) or by some sort of capillary wicking structure (heat pipes).

The benefits of the implementation of heat pipes in various thermal processes have been extensively reported in the literature. Jouhara et al. investigated experimentally the effect of the filling ratio on thermal performance and on the pool boiling and thin film evaporation phenomena of two-phase closed thermosyphons charged with water and the dielectric heat transfer liquids FC-84, FC-77 and FC-3283 as working fluids at normal operating condition [34]. Fadhl et al. presented a comprehensive CFD modelling to simulate the two-phase flow and heat transfer phenomena during the operation of a wickless heat pipe charged with water as working fluid [35]. Their results were validated by experimental measurements using the same operating conditions. Later on, Fadhl et al. investigated the application of CFD modelling to simulate the two-phase heat transfer mechanisms in a thermosyphon filled with R134a and R404a refrigerants [36].

Heat pipes have been implemented in various applications. Spacecraft, electronic systems, solar thermal water heating, heat exchangers, permafrost cooling, cooking, air-conditioning and ventilation systems, nuclear etc are some of the fields that they found application [33,37—41]. The performance of a heat pipe based solar PV/T roof collector and its potential contribution to district heating applications was reviewed and tested by Jouhara et al. [42]. The results showed that the system could cover between 60 and 100% the hot water demands of a conventional dwelling, depending on the solar radiation input. A theoretical model indicated that the use of heat pipe based systems for electronics cooling could save up to 75% of energy [43]. Finally, a Heat pipe-based radiator for low grade geothermal energy conversion in domestic space heating showed exceptionally high power density and very fast response time compared with conventional wet radiators [44].

The successful track record of heat pipe technology and years of research lead to the development of the presented pyrolysis system (HERU) described in this paper. The HERU technology has been patented (WO/2015/104400) and enables the pyrolysis of waste at a constant temperature of 300 °C [45]. The experimental apparatus consists of the pyrolysis chamber, a 3 kW heater at the base of the chamber, a temperature control unit, a heat exchanger and an oil collector. The heat pipes are arranged around the edges and in the central part of the pyrolysis chamber. Figs. 2 and 3 show the SolidWorks designs of the heat pipe based pyrolysis chamber.

The heat pipe basket consists of 17 aluminium wickless heat pipes charged with water; 4 of them are placed in the centre of the basket and the rest form the basket. The application of heat in the waste stream is conducted uniformly as it represented by the red arrows in Fig. 4.

The loading of the waste is performed through the top of the HERU chamber, which is sealed by a lid. A temperature control unit regulates the heater power supply, using a feedback loop from the temperatures developed at the heater and the inside of the chamber. Three proportional integral derivative (PID) controllers, two of them operating as the control loop and one as a safety monitor, function as on/off switches to ensure the proper operation of the system, so the heater temperature does not exceed 480 °C and the temperature inside the chamber is maintained below 300 °C. The whole structure is covered by white insulation of 90 mm thickness enabling operating temperatures up to 1200 °C. (see Fig. 5).

The initial stage of the pyrolysis process is the removal of the moisture content from the waste. As soon as all the water is removed, the actual pyrolysis occurs. A heat exchanger, placed above the HERU, collects the vapours from the process and through a constant flow of fresh water the water, oils and the gases derived from the pyrolysis can be separated by condensation of the 'oil' (a mixture of water and oils). During the final stages of pyrolysis the treated waste is transformed into char and the condensate oils
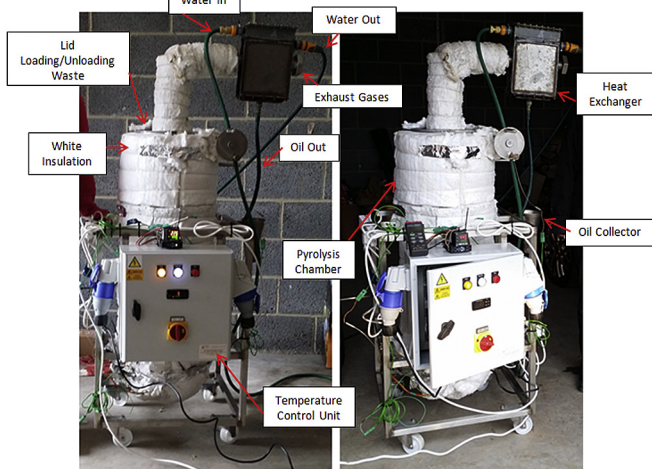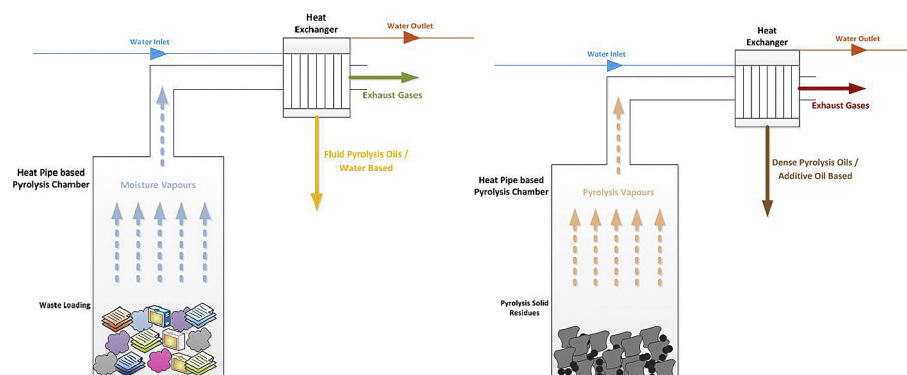

Fig. 5. Experimental apparatus of HERU.

Fig. 6. 2D schematic of pyrolysis process.

become more dense. A two dimensional schematic of the process is shown in Fig. 6. Once the pyrolysis process is completed and all the products have been transformed into char small amounts of

oxygen are introduced into the chamber, which allow the ignition of the char. The heat obtained from the exothermic process of the char's combustion is used to warm up water stored in a tank, which can be later used to cover domestic hot water (DHW) demands (Fig. 7).
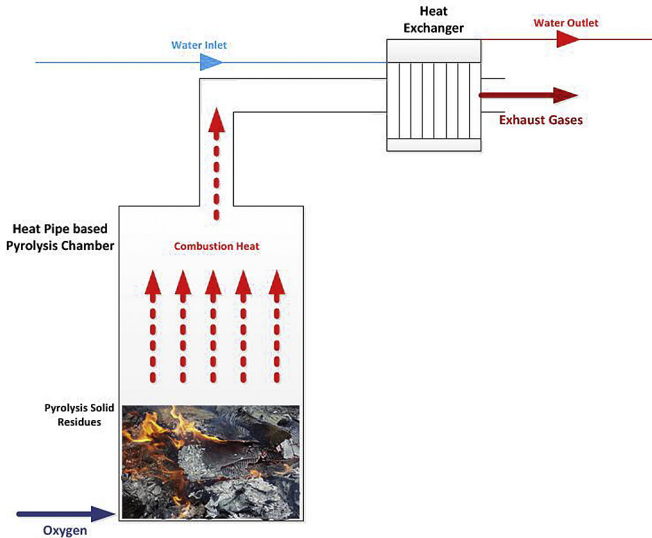

Fig. 7. 2D schematic of combustion process.

Fig. 8. Waste loading.

4. Experiments

The chamber was fully loaded with approximately 7 kg of various mixtures of MSW materials. The waste consisted of a variable mix of bread, lemon slices, onions, apples, carrots, mangetout, peppers, cabbage, chicken breasts, potatoes, pancakes, courgettes, rice, cardboards, plastics, papers, metal cans, nappies, latex gloves, plastic bags and plastic bottles. (see Fig. 8).

K-type thermocouples were placed in the waste, in the bottom, middle and top of the pyrolysis chamber and on one of the heat pipe legs of the waste loading basket, and in the core of specific food products with different moisture contents. These thermocouples were positioned in four waste products: a used nappy, a chicken breast, a bread baguette and a milk bottle. (see Fig. 9).

The experiment lasted 7 h, with the chamber achieving a temperature of 300 °C after 5 h of operation; drying the waste took approximately 5 h and the actual pyrolysis time was around 2 h. The temperatures of the chamber and the waste were constantly monitored and recorded. The graph below represents the thermal data from the experiment.

Fig. 10 shows clearly a linear temperature rise of the chamber in the first 5 h of the HERU's operation and then the temperature is maintained at 300 °C in all the positions inside the chamber.

Fig. 11 shows the core temperatures of four waste products inside the HERU 20 min from the start of the experiments and for a period of 4 h.

At the beginning of the pyrolysis process all the waste products appeared to react in a similar way to the thermal energy applied. However, after the first hour, the temperature of the products with very low moisture content, i.e. the milk bottle, increased rapidly, followed by the next driest item, the bread baguette. In contrast, waste products with high moisture levels (chicken breast, nappy) maintained stable temperatures (at water boiling point) for the first 3.5 h, and then they experienced a slight increase. The obvious

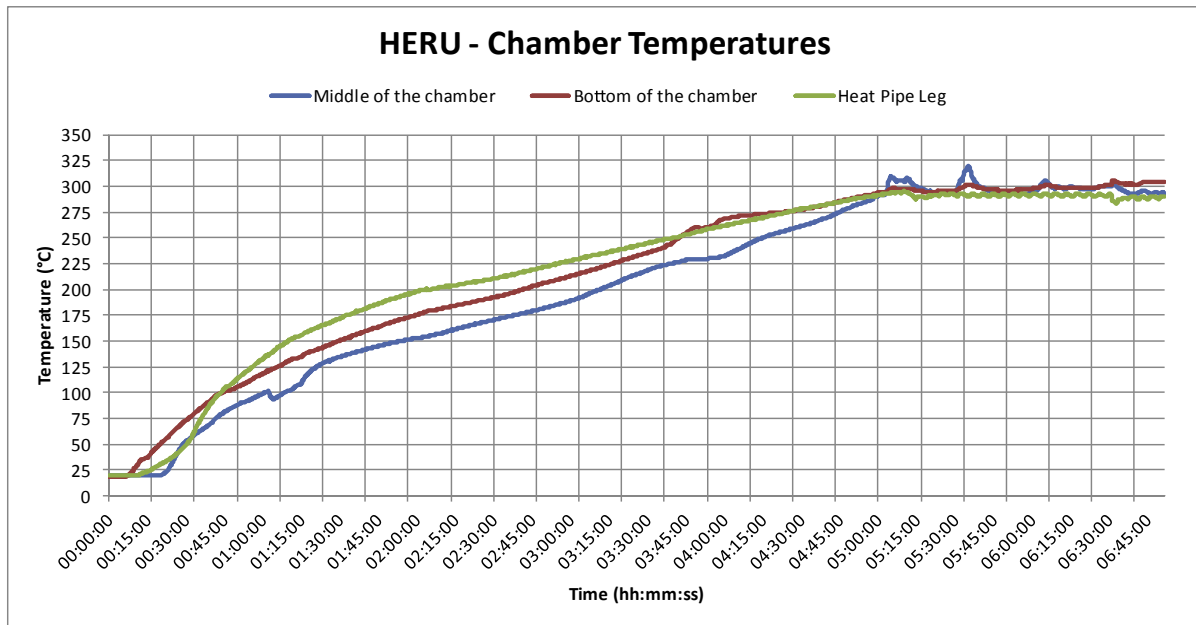**Fig. 9.** Thermocouple positions.

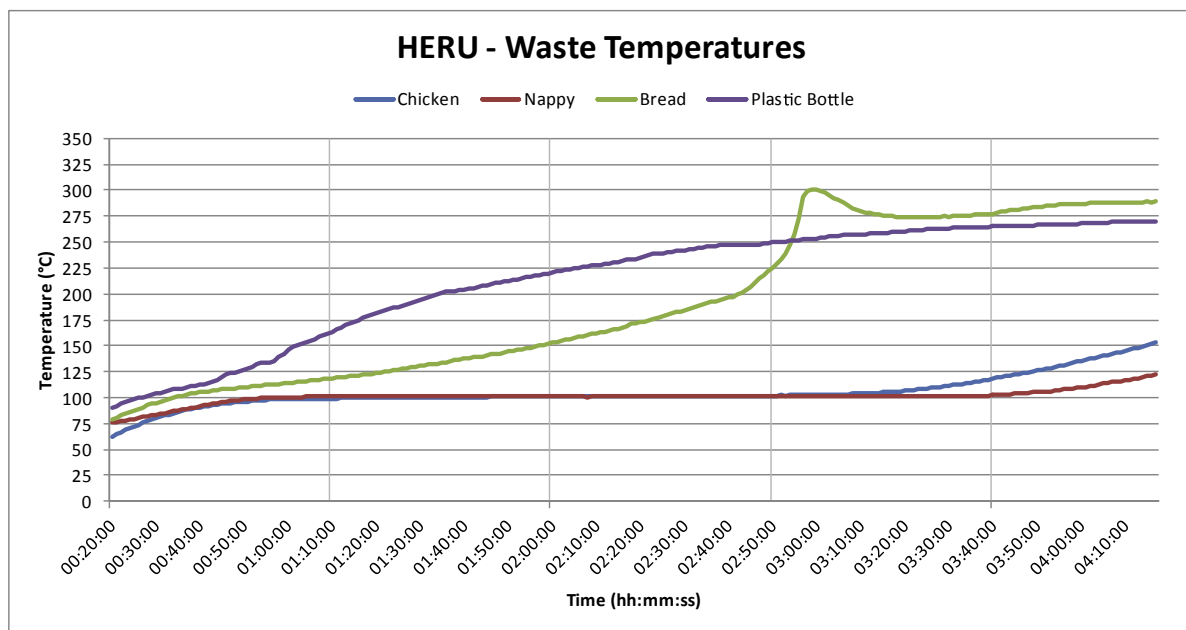**Fig. 10.** Thermal data of 7 h of MSW pyrolysis.

Fig. 11. Thermal data of waste products' pyrolysis.

reason for this thermal step behaviour is that all the thermal energy applied to the wet products is initially used to evaporate the water content. Once all the moisture has been removed, the thermal energy of the chamber is fully applied to thermo-chemically decompose the organic material.

5. Results

At the end of the pyrolysis process the mass fractions of the products were as follows: 75% of the initial waste loading was converted into solid mass (bio-chars), 5% was dissipated as oils and 20% was exhausted as pyrolysis gases.

Regarding the oil production it was observed that the oils became darker in colour and denser as the pyrolysis treatment was proceeding. The oils of the initial stages of the pyrolysis had a light brown colour and watery density; however, the oils at the end of the treatment were black and viscous. Some oil samples collected during the pyrolysis process are shown in Fig. 12.

After 7 h of the experiments the cumulative power consumption of HERU was 5.5 kWh and all types of waste were completely converted into bio-char. (see Fig. 13).

At the end of the pyrolysis process oxygen was introduced into the chamber, which led to the ignition of the chars obtained through the pyrolysis treatment. The dissipated heat of the char's
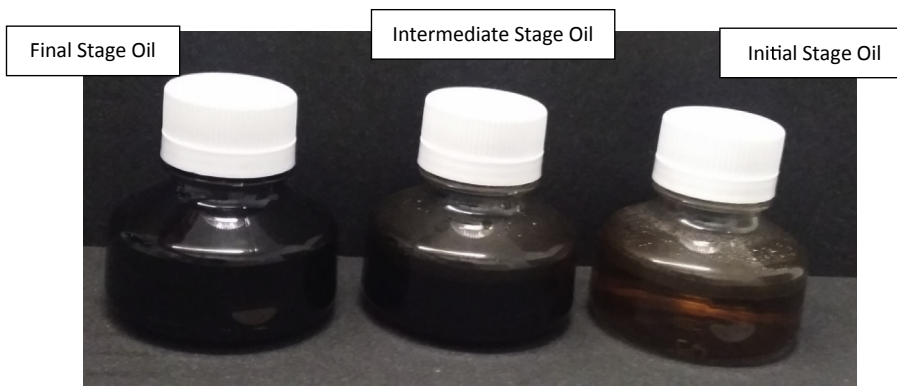
Fig. 12. Pyro-Oils obtained through the 7 h MSW pyrolysis.

combustion was recovered though the means of a heat exchanger to warm water stored into a tank. The efficiency of the system is further discussed in the next section of the paper. (see Fig. 14).

6. Chemical analysis of the bio-chars and pyro-oils

Char and oils derived from HERU were analysed using X-Ray Fluorescence (XRF — analysis of oils and char samples), Fourier Transform Infra-Red spectroscopy (FTIR - analysis of oils and char samples) and X-Ray Diffraction (XRD - analysis of char samples only). The aim of investigation was to identify the composition and the toxicity of the samples. All the bio-char obtained was ground and mixed to homogenise it and provide a representative sample of the char composition. Finally, samples from the oils obtained during the initial (fluid oil) and final (dense oil) stages of pyrolysis were selected for analysis.

The following tables summarise the key findings of each experimental technique. For validation purposes the pyrolysis tests were repeated three times.

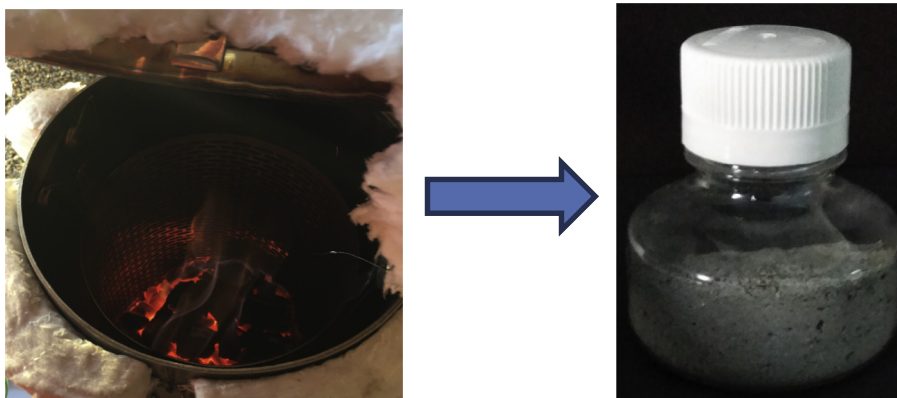**Fig. 13.** Bio-Chars obtained through the 7 h MSW pyrolysis.

6.1. XRF evaluation

The samples were scanned on an Oxford ED 2000 using 25 kV and a 4.5 mm aperture following a procedure developed at the Experimental Techniques Centre of Brunel University (ETC) for the evaluation of presence of heavy metals. The following graphs show the XRF spectrums for the char and the two oil samples. It is important to notice that in all XRF spectrums two peaks should be ignored; the argon (Ar) peak is due to the atmospheric composition in the XRF chamber and the silver (Ag) peak is an artefact of the tube (see Table 2).

The main element found in the bio-chars is iron (Fe), followed by a variety of low concentration elements, such as calcium, copper, zinc, potassium, chlorine, sulphur, phosphorus, bromine and strontium; with specific elemental inclusion depending on the initial composition of the treated waste.

For both oil samples, dense and fluid, the elemental analysis showed essentially the same composition. The main element is again iron.

6.2. FT-IR evaluation

The samples were scanned on a Perkin Elmer Spectrum One FTIR spectrometer, using a Specac Golden Gate Single Reflection ATR accessory, consisting of a Diamond crystal at a fixed angle of 45°. Spectra were collected over the 4000 cm^{-1} to 600 cm^{-1} wavenumber range, at a resolution of 4 cm^{-1}. 20 replicated tests were collected for each sample.

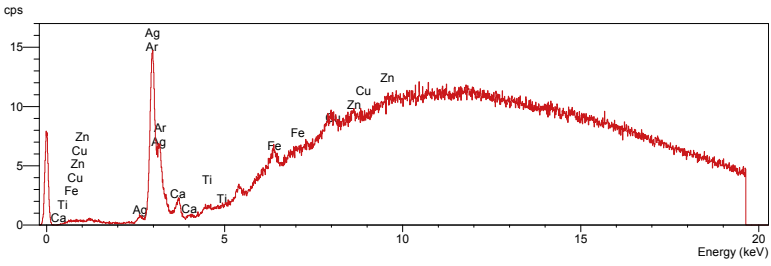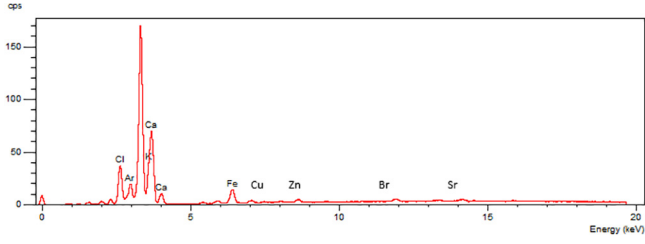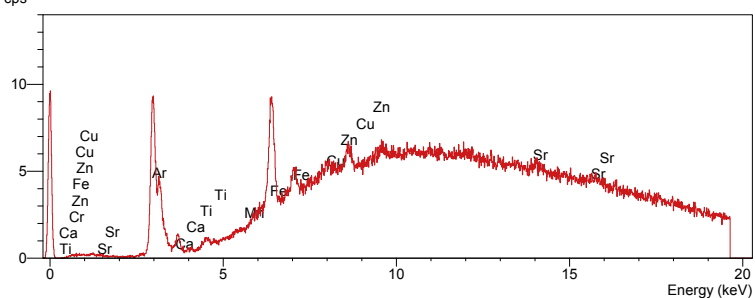In all the following graphs two different coloured lines are

Fig. 14. Char combustion and ash sample collected.

Table 2
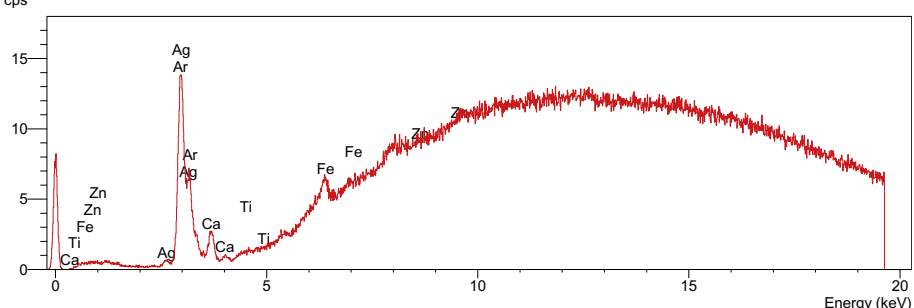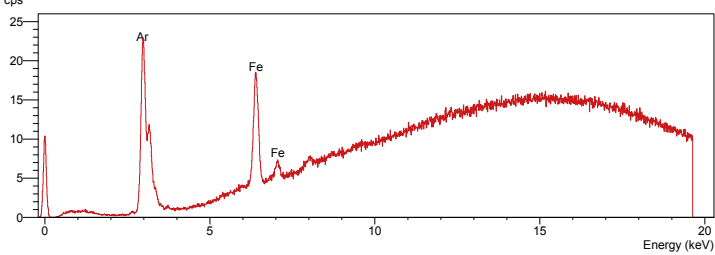XRF summary of results.

	Round Test	Key Findings	Graph
Char	1st batch	Calcium (Ca) Iron (Fe) Minor Copper (Cu) traces	
	2nd batch	Potassium (K) Calcium (Ca) Iron (Fe) Chlorine (Cl) and minor traces of Copper (Cu), Zinc (Zn), Sulphur (S), Phosphorous (P), Bromine (Br), Strontium (Sr)	
	3rd batch	Iron (Fe) and minor Zinc (Zn) traces	
Oil Fluid	1st batch	Calcium (Ca) Iron (Fe)	
	2nd batch	Iron (Fe) Copper (Cu)	

Table 2 (*continued*)

	Round Test	Key Findings	Graph
	3rd batch	Minor Chromium (Cr) traces	
Oil Dense	1st batch	Iron (Fe) and minor copper (Cu) traces	
	2nd batch	Iron (Fe) Copper (Cu)	
	3rd batch	Minor Chromium (Cr) traces	
Ash	1st batch	Minor Iron (Fe) and Zinc (Zn) traces	

Table 2 (*continued*)

Round Test	Key Findings	Graph
2nd batch	Potassium (K), Calcium (Ca), Chlorine (Cl), Titanium (Ti) and minor traces of Iron (Fe), Copper (Cu), Zinc (Zn), Sulphur (S), Strontium (Sr)	
3rd batch	Potassium (K), Calcium (Ca), Chlorine (Cl) and minor traces of Iron (Fe), Copper (Cu), Zinc (Zn), Sulphur (S), Strontium (Sr), Phosphorous (P)	

represented. The coloured line (blue, red or green) shows the profile of the tested sample (either char or oil) and the black line shows the profile of the closest compositional match from the software's library. (see Table 3).

The char composition in all the tests can be identified as organic materials. The fluid oils obtained from the initial stages of pyrolysis are mainly water, while the dense oils at the end of the pyrolysis process show a similar composition to additive oils, such as Lubrizol. It is important to notice that for the first and third batch of dense oil samples, the composition is also mostly water; a potential explanation is that when the oil samples were collected the pyrolysis process was not complete and therefore the samples show the same composition as the fluid oil samples.

6.3. XRD evaluation

The samples were scanned on a D8 Advance Bruker X-Ray Diffractometer equipped with copper tube and LynxEye position sensitive detector. The measurement was performed between a 2ϑ angle of 5–100, with a scan increment of 0.001° and a scan speed of 0.4 s per step. (see Table 4).

6.3.1. Chemical analysis of the bio-chars and pyro-oils: conclusions

Overall none of the elements determined using XRF, FTIR and XRD were found to be toxic. The higher concentration of iron and zinc in some of the XRF results does not indicate a hazard.

The oils show a non-toxic composition, both elementally and as compounds, being mainly water with minor iron and copper traces. Functional WA-24 found on the 1st batch of char during FTIR analysis is commonly used with a tackifier to prepare way lubes. Way lubes are premium-formulated lubricants for machine tool slides and ways.

The organic components identified by XRD are heptadecane, toluic acid and cholesteryl benzoate. Heptadecane does not have known toxic effects for human, and it is insoluble in water. Toluic acid and benzoate are of the same chemical family, they produce irritation with contact and toxic gases when heated. The inorganic components identified by XRD are carbonates which are harmless

and easily soluble in water. The presence of the carbonate phase is related to the waste composition, as micronized calcite is added to cellulose in the production of writing paper, wallpaper and cardboard, which was one of the types of waste treated by the pyrolysis unit.

The hydroxides nacrite, dickite and kalicinite were also found during the XRD analysis. The Nacrite/Dickite mixture is stable at around 350 °C as transformation of kaoline in an acidic environment. Kaoline as a raw material is commonly found in paper, plastics, cosmetics, and pharmaceuticals. Kalicinite is recognised as a safe compound, which is often used as a food additive. The calcites and the silicates are normally used as fillers for paper and cardboards.

Sylvite, potassium and arcanite were additionally found in the ash samples by the XRD analysis. Sylvite is a nontoxic mineral, often used as fertiliser and for food processing. Potassium hydrogen phosphite does not show any toxic behaviour. Arcanite is often found associated with the deposition of sulphates after the combustion of coal, hence its presence is fully justified in this context. The mineral itself is not considered toxic.

7. Challenging waste: domestic mixed plastic and PVC pyrolysis

Currently, mixed plastics are collected by the kerbside and they are often collected together with paper, card, cans and plastic bottles as a partially or fully co-mingled collection which requires sorting at a Materials Recovery Facility (MRF). However, this segregation process requires expensive automated equipment, which may not be available at all MRFs.

A primary separation machine is usually employed to separate papers and cardboards from plastic and metal containers (e.g. bottles, cans). Once the main fibre separation has been completed, a second separation stream follows by which the plastic and metal containers are segregated. Standard equipment is used to remove the steel and aluminium, which leaves a final mix of plastics and residual material. Any non-bottle plastics flowing through the sorting system are likely to remain in the residual fraction at the

Table 3
FTIR summary of results.

	Round Test	Key Findings	Graph
Char	1st batch	The composition is similar to the additive oil (WA-24)	
	2nd batch	Boron Nitride – Inorganic phase further investigation with XRD	
	3rd batch	Potassium Tetracyanocadmate – Inorganic phase further investigation with XRD	
Oil Fluid	1st batch	The composition is similar to water	

(*continued on next page*)

Table 3 (*continued*)

	Round Test	Key Findings	Graph
	2nd batch	The composition is similar to water	
	3rd batch	The composition is similar to water	
Oil Dense	1st batch	The composition is similar to water	
	2nd batch	The composition is similar to a Lubrizol type of additive oil	

Table 3 (continued)

	Round Test	Key Findings	Graph
	3rd batch	The composition is similar to water	
Ash	1st batch	Inorganic elements — further investigation with XRD	
	2nd batch	Inorganic elements — further investigation with XRD	
	3rd batch	Inorganic elements — further investigation with XRD	

end of the sorting process and be landfilled or sent for energy recovery [46].

The extreme scenario of the capabilities of HERU to treat waste streams of mixed plastic and PVC was tested and reported in the following section. Tables 5—7 shows the chemical analysis results derived from XRF, FTIR and XRD analysis for the chars obtained from the pyrolysis of mixed domestic plastics and PVC and for the ash derived from the combustion of PVC's char.

Table 4
XRD summary of results.

	Round Test	Key Findings	Graph
Char	1st batch	3 organic phases which are basic compounds of WA-4 oil 2 inorganic phases: calcite and magnesium carbonate hydrate	PDF 00-002-0623 Ca C O3 Calcite PDF 00-036-1590 C17 H36 n-Heptadecane PDF 00-023-1948 C8 H8 O2 m-Toluic acid PDF 00-010-0551 C34 H50 O2 Cholesteryl benzoate PDF 00-041-1403 Ca2 Mg11 (C O3)9 (H C O3)4 (O H)4 ·6 H2 O Sergeevite
	2nd batch	4 inorganic phases: calcite, nacrite, dickite, gupeiite	PDF 01-071-3699 Ca (C O3) Calcite, syn PDF 01-076-0533 Al2 Si2 O5 (O H)4 Nacrite-2M2 PDF 01-072-8193 Al2 (Si2 O5 (O H)4) Dickite PDF 01-072-4250 Fe3 Si Gupeiite, syn
	3rd batch	1 inorganic phases: calcite 1 organic phase: hexatetracontane 2 minor phases: potassium aluminium chloride oxide and rutile	PDF 00-005-0586 Ca C O3 Calcite, syn PDF 01-072-1148 Ti O2 Rutile PDF 01-073-0631 K Al Cl2 O potassium aluminium dichloride oxide | Potassium Aluminum Chloride Oxide PDF 00-050-2246 C46 H94 n-Hexatetracontane

Table 4 (*continued*)

	Round Test	Key Findings	Graph
Ash	1st batch	Sylvite, rutile, potassium aluminium chloride oxide, glauconite, calcium aluminium silicate and muscovite	
	2nd batch	Calcite, sylvite, calcium sulphate, carbon, muscovite and potassium aluminium sulphate	
	3rd batch	Sylvite, potassium hydrogen phosphite, arcanite and calcium magnesium aluminium silicate	

7.1. Conclusions for the mixed domestic plastics and PVC pyrolysis

The chemical composition of the samples shows potential toxicity from lead and chlorine: the full pyrolysis of the mixed plastic and the combustion of the PVC's char remove the toxic component (lead) from both types of residues. On the other hand, the combustion of the PVC's char does not remove chlorine.

The mineralogical observation of the mixed domestic plastics shows that the chlorinated phase is organic. The possible identification in chlorophenoxy butanoic acid excludes toxicity of the

Table 5
XRF summary of results.

	Round Test	Key Findings	Graph
Char	Mixed Domestic Plastics	Zinc (Zn) Titanium (Ti) and small traces of Iron (Fe) Calcium (Ca), Chlorine (Cl), Strontium (Sr) and Lead (Pb)	
	PVC	Calcium (Ca), Titanium (Ti), Zinc (Zn), Chlorine (cl) and small traces of Lead (Pb), Iron (Fe) and Strontium (Sr)	
Ash	PVC	Calcium (Ca), Titanium (Ti), Zinc (Zn), Chlorine (cl) and small traces of Lead (Pb), Iron (Fe) and Strontium (Sr)	

compound. The mineralogical observation of the residues of pyrolysis and further combustion of PVC indicate that the chlorine is present as $CaFeO_2Cl$ and $Zn_5(OH)_8Cl_2H_2O$. These compounds do not present any toxicity warnings. On the contrary, recent studies on the Zinc compound have proven that this corrosion product can produce an important improvement in the efficiency of solar cells [47].

The lead seems to be fully volatilised. In this case a fully fitted filter needs to be applied to the chamber to avoid environmental pollution.

8. Energy and mass balance

The experiments showed a strong correlation between the moisture content of waste and the efficiency of the HERU. The lower the moisture content of the waste treated, the higher the performance of the unit. In cases where the waste is characterised by high moisture content most of the thermal energy of the unit is consumed to vaporise the water molecules of the waste. As the HERU dries, pyrolyse and combusts the solid resultant of the treatment on the waste, most of the energy that was consumed during the drying process (latent) as well as the heat energy from the combustion of the char (sensible) is recovered to the home energy system through heating the water that flows in the HERU

heat exchangers. This fact leads to a positive energy balance for the HERU as of the newly generated fuel in the form of char that is combusted during the HERU waste treatment cycle. From this angle, the HERU would have a coefficient of performance that will define its function as a heat pump. The heat pipe based waste treatment unit COP is defined as follows:

$$COP = \frac{Q_{lat} + Q_{comb}}{E_h}$$

where:

Q_{lat} (kWh) is the latent heat that was given to the water flow in the heat exchanger when condensing the moisture that has departed from the waste during the drying stage.

Q_{comb} (kWh) is the heat that was recovered to the water flow in the heat exchanger from the exhaust during the char combustion stage.

E_h (kWh) is the electrical energy that was consumed by the electrical heater to complete the waste treatment cycle.

The relationship between the HERU COP and the moisture content is shown in Fig. 15.

HERU has been designed to achieve full pyrolysis of products with any moisture content, without the need of any kind of pre-treatment. The only parameter affected by the moisture content of the waste was the power consumption of the unit, which varied

Table 6
FTIR summary of results.

	Round Test	Key Findings	Graph
Char	Mixed Domestic Plastics	The composition is similar to PolyEthylene (PE)	
	PVC	The composition is similar to water	
Ash	PVC	Inorganic elements — further investigation with XRD	

from 0.19 to 0.94 kWh per kg of waste with moisture levels of 0—100%, respectively. The performance data are calculated based on treating 1 kg of MSW, at 300 °C, for 5 h.

9. Discussion

The performance of an innovative pyrolysis chamber design based on heat pipe technology has been described. The tests showed that in order to treat 7 kg of MSW 5.5 kWh of electricity was required; thus, approximately 0.78 kWh per kg of waste was consumed. According to UK government the CO_2 emission factor per 1 kWh of electricity usage is 0.41205 for the year of 2016, of which the 99.4% refers to CO_2 emissions, 0.5% refers to N_2O emissions and the remaining 0.1% refers to CH_4 emissions [48].

The CO_2 emissions of the HERU can be identified by calculating the electricity emissions of the unit. In the previous section it was mentioned that th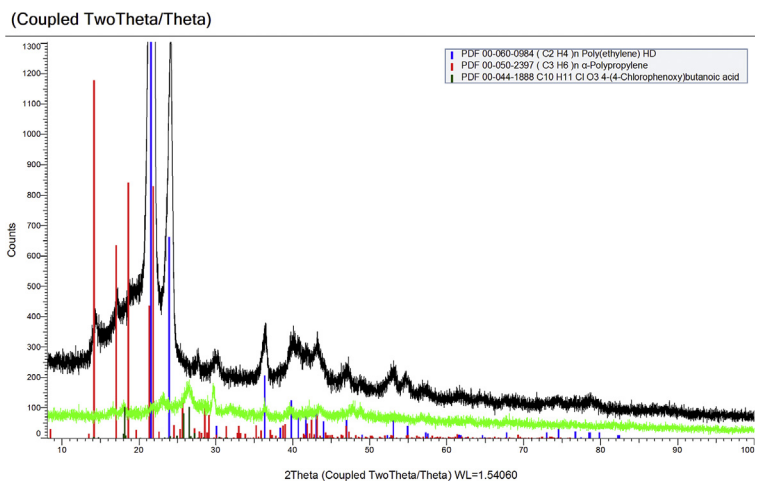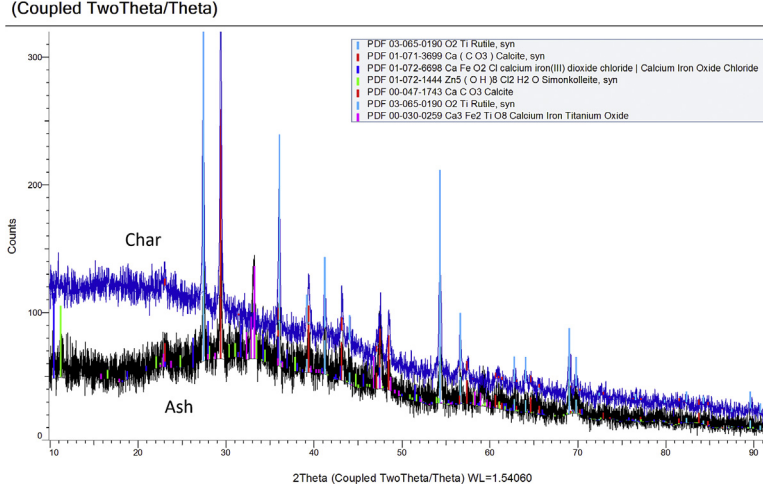e unit consumes between 0.19 and 0.94 kWh of electricity according to the moisture content of the treated waste. By multiplying this electricity consumption range by the electricity emission factor provided by the UK government it can be estimated that the HERU emits between 0.0782 and 0.3873 kg CO_2e per 1 kg of waste.

Currently, the UK produces 22.36 million tonnes of waste and 20.82 million tonnes equivalent of CO_2 are emitted for its waste management [49]. Thus, the current waste treatment systems emit 0.93 kg CO_2e to treat 1 kg of waste. Treating the waste with the HERU the total CO_2 emissions could be reduced by 58—92%.

10. Conclusions

The paper presents a novel heat pipe based pyrolysis unit and its performance in terms of heat distribution, power consumption, carbon emissions and chemical composition of the final pyrolysis products. The innovation of the system is that it provides efficient

Table 7
XRD summary of results.

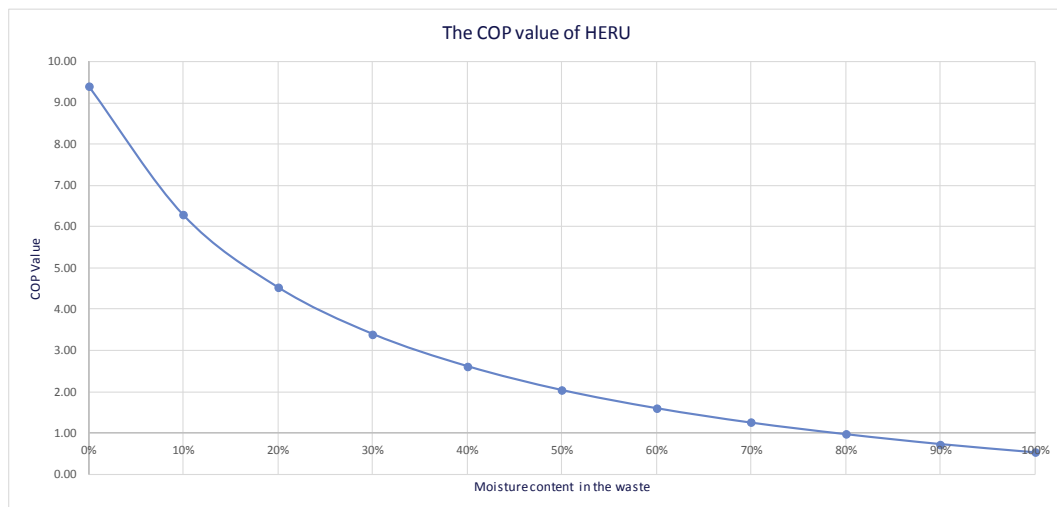|	Round Test	Key Findings	Graph
Char	Mixed Domestic Plastics	PolyEthylene (PE)	
	PVC Char and Ash	*Char*: Rutile, Calcite and Simonkalleite *Ash*: Ca3Fe2TiO8.	

Fig. 15. The COP value of HERU.

pyrolysis of the waste at low temperatures (below 300 °C) without the need of any kind of pre-treatment of the waste prior its loading.

At the end of the pyrolysis treatment the solid residues (chars) were ignited, providing combustion heat as a means to warm water for
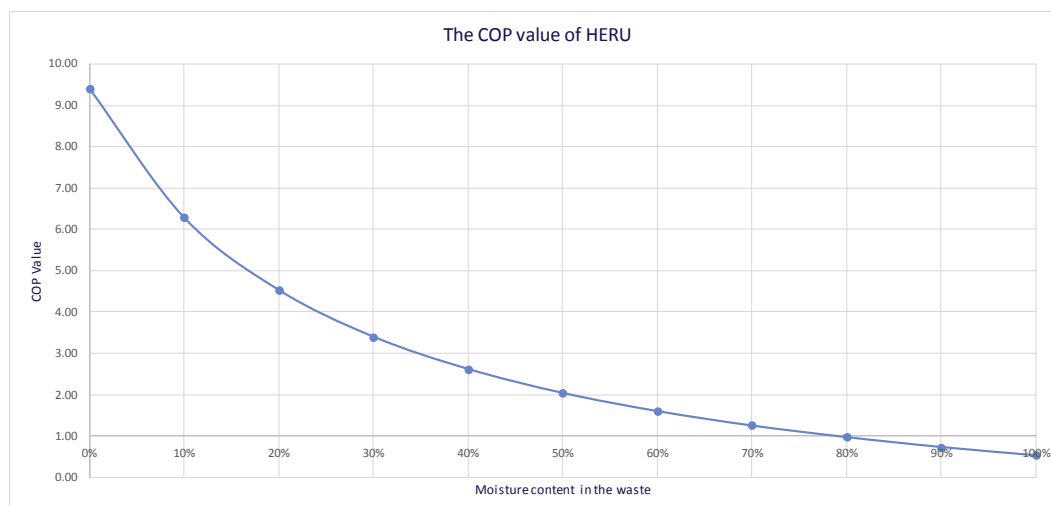
Fig. 15. (*continued*).

domestic applications.

Three rounds of tests were conducted, with the same composition and weight of MSW. According to the chemical analysis of the pyrolysis products and the ash residues after the combustion of the pyrolysised chars, no toxic elements were found in any of the tested materials. The main component of chars was calcium; the fluid oil obtained from the initial stages of pyrolysis had a similar composition to that of water, while the dense oil produced during the final stage of the process showed traces of iron and a potential composition match to commercial additive oils. The ash residues contained sylvite, potassium, kalcinite and arcanite, none of which is considered toxic.

The chemical analysis of the chars and ash obtained from the mixed domestic plastics and PVC waste showed no toxicity for the mixed plastic char and a potential toxicity for the PVC char due to the existence of lead and chlorine. However, the lead seems to be fully volatilised and captured in the oils of the pyrolysis. In that case, the potential toxicity of the lead traces can be addressed by fitting a filter to the HERU.

The coefficient of performance (COP) and the CO_2 emissions of the HERU varied depending on the moisture content of the waste treated. The highest COP and lowest kg CO_2e were found for the minimum moisture content of 0%, with a 9.4 COP and 0.0782 kg CO_2e per kg of treatment. On the other hand, for a maximum moisture content of 100% the COP is 0.53 and the CO_2 emissions 0.3873 kg CO_2e per kg of treatment.

Waste management is one of the most crucial challenges that developed countries are facing. The environmental, economic and social effects of current waste treatments prove their inefficiency. The HERU provides a green solution to the disposal of waste streams and at the same time a sustainable, renewable solution to power generation. The implementation of units either of small domestic scale or in macroscale as part of municipalities' waste treatments could reduce greenhouse gas emissions, diminish the biodegradable content of residual waste sent to landfill, generate fuels — in the form of char, syngas and oil — for reuse and help the government to achieve low emission levels as they comply with the EU Waste Incineration Directive (2000/76/EC). Finally, the macroscale application of the heat pipe based pyrolysis unit could help to mitigate the country's dependency on fossil fuels. For example, the UK is importing about 46% of its energy, in the form of coal, gas and oil [50], a figure that can be sharply reduced by the mass application of efficient waste-to-energy plants, such as the HERU

presented in this paper.

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