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Proposal of a Mobile Medical Waste Incinerator with Application of Automatic Waste Feeder and Heat Recovery System as a Novelty in Poland

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Abstract: The paper presents and discusses the issues of medical waste (including hazardous ones) and the problems regarding their proper management in Poland. Inappropriate handling of infectious medical waste directly endangers human health and the environment. Infectious waste must be properly disposed of—in practice, the only method of their disposal available in Poland is a thermal treatment in the incinerators tailored for this purpose. This causes many problems to smaller entities such as the local health centers, but also to the beauty and tattoo salons. As a solution to these problems, the mobile medical waste incinerator was proposed. During designing an incinerator unit, a diverse morphological composition of the medical waste should be taken into account, however, there are no inspection reports available in Poland. Based on a few data concerning the composition of the medical waste, the article presents designing considerations in regard to the incinerator's chamber dimensions. The calculations were carried out for several variants of the waste morphological composition. The own construction of a mobile medical waste incinerator, which conforms to the regulations in Poland and the European Union, was presented. It should be emphasized that it is a novelty on the Polish market, due to the automatic waste feeder into the combustion chamber, adapted to a mobile unit.

Keywords: medical waste disposal; incineration; automatic waste feeder; heat recovery

1. Introduction

A medical waste is generated in connection with a provision of the health services and conducted research and scientific experiments in the field of medicine [1]. It is estimated that 85% of the medical waste produced worldwide does not pose a threat to the environment (for example, household waste) [2]. The remaining 15% are infectious, radioactive, pathological or toxic waste [2], which are a direct threat of infection due to their contact with patients and a high content of the microorganisms, bacteria, viruses, parasites, toxins or other forms capable to transfer genetic material. Incorrect management of the medical waste, especially with sharp objects, can lead to a numerous infections. According to the World Health Organization (WHO), the re-use of injection needles, that have been incorrectly sterilized or not properly sorted for recycling, caused in 2010 over 33,000 HIV infections, 1.7 million hepatitis B cases, and 315,000 for hepatitis C [3].

It should be emphasized that nowadays the medical waste does not include only that produced in the hospitals and outpatient clinics, but also the results of home treatment (dialysis, diabetes treatment, chronic diseases) and of beauty salons or tattoo studios, as well as often not considered: prisons, universities, schools, and training facilities [4]. All these suggest that a larger part of the society, not just qualified hospital personnel, is exposed to a potentially hazardous and infected waste. According to the Coalition for Safe Community Needle Disposal [4], 7.5 billion syringes are used every year in the households. In 2011 in the United States, 1 in 12 households used injections for home-made treatment of diabetes, migraines, allergies, osteoporosis, HIV, hepatitis and other diseases [5]. The resulting waste could be, in some part, mixed with municipal waste, which causes another problem concerning an improper handling of hazardous waste. There are a few recommended methods for its disposal, in which the most common is the thermal treatment in an adapted incinerator. By conducting the waste incineration process with a proper parameters and with the use of flue gas cleaning equipment, a significant reduction in the volume of waste is achieved, destroying all the pathogens and viruses present in them. Despite the proven thermal technology of waste treatment, there are still cases of illegal storage of the hazardous medical waste in landfills or of mixing them with an uninfected waste. Such cases have been noted during an inspection carried out in the hospitals, among others in Bangladesh, Pakistan and Iran [6–8].

Issues of Medical Waste Composition

An extremely problematic issue regarding medical waste is their morphological composition. Their character is determined by various factors, which include, for example, the size of the facility and the specificity of individual wards, their level of development, as well as the prevailing rules regarding the waste segregation system (or lack of such a system). Therefore the morphological composition of medical waste differs for each facility. In addition, in some countries (for example Poland) it is forbidden to reopen a sealed container or a bag of medical waste, which precludes such tests [9]. Differences in the law and in the nomenclature regarding the medical waste management worldwide are highlighted by Windfeld et al. [10]. This review pointed out the constant changes in the regulations and the difficulty in selection of an appropriate metrics for comparison of the data from various health facilities from the world.

There are publications, which addressed the subject of the medical waste comparison. Voudrias et al. [11] analyzed the composition and production rates of the pharmaceutical and chemical waste, including the hazardous one, in Xanthi General Hospital in Greece. They classified the waste in six categories: antibiotics, digestive system drugs, analgesics, hormones, circulatory system drugs and other [11]. The study showed the percentage composition of the hazardous waste in terms of the total one, produced by the hospital.

Komilis et al. [12] also conducted research on the medical waste in the private medical microbiology laboratories. This waste was divided into hazardous and non-hazardous (urban) ones. Presented research was published in 2017, and as the authors emphasized, there was no such information about this kind of healthcare centers worldwide so far. This paper highlighted a problem of the composition of medical waste data shortage, especially in the facilities other than large municipal hospitals.

All of abovementioned works are very useful in terms of overall medical waste management system, however, they are not useful for an optimal design of the devices for the thermal treatment. The waste components, presented in them, do not allow the thermodynamic calculations due to an insufficient information on the calorific value of the substrates. Determination of the morphological composition is important for the design of devices based on the thermal treatment of the medical waste, which in many countries is the most commonly used method, and in some, including Poland, the only one allowed by law. However, there are the publications about an average morphological composition of the medical waste from the hospitals located in different parts of the world, which can be used for the thermal calculations. Often, there is data from the 1990s and at present, when an intensive medicine development and improvement of the hygiene conditions in the hospitals occur, the values presented there may differ from the current state. Table 1 lists the average morphological composition of the medical waste from the hospitals in Yemen, Iran, Kuwait, Jordan and Italy [13–15] These countries were selected because of the data reliable sources, which enable a comparison of the waste compositions between each other and their suitability for further thermodynamic analysis.

In order to illustrate the differences between the waste compositions in particular countries, the data from Table 1 is also shown in Figure 1.

Table 1. Material composition of the medical waste [13–15].

Component	Percentage Content [%]				
	Yemen (2016)	**Iran (2012)**	**Kuwait (2005)**	**Jordan (2005)**	**Italy (1992)**
Paper and cardboard	22	12	32	38	34
Plastic	22	40	18	27	46
Glass	11	6	10	10	7.5
Metal	10	2	9	5	0.4
Food	27	-	12	-	-
Textiles	-	19	11	11	-
Liquids	-	17	-	-	12
Other	8	4	8	9	0.1

Analyzing the data presented in Table 1, it is not possible to determine upward or downward trends in the percentage of individual wastes in dependence on the year in which the study was conducted. Therefore, the most important impact on the morphological composition of the medical waste may have a degree of development of the health care of a given country. This means that the design of devices for the thermal treatment of the medical waste, for which determination of a percentage of the morphological composition is crucial, is difficult in countries such as Poland. Moreover, an optimization of the process without precise data on the composition is practically impossible.

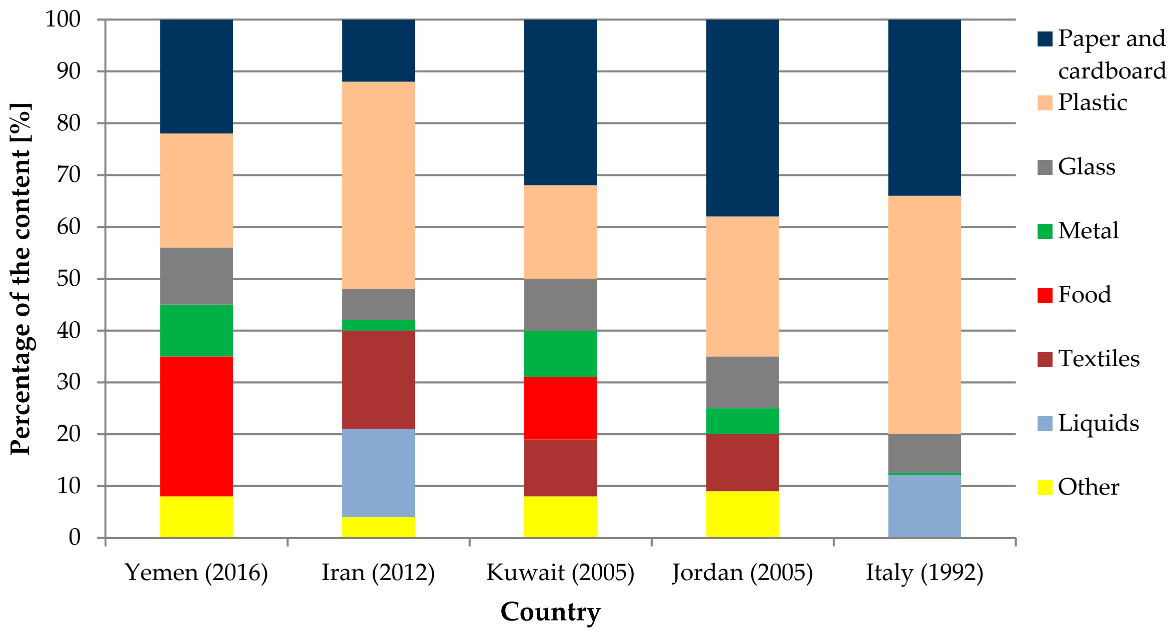

Figure 1. Material composition of the medical waste in discussed countries.

2. Medical Waste Management in Poland

Poland, as a country belonging to the European Union, must meet all requirements of the European law in the field of medical waste handling. It is governed by the Waste Act [1], which is in line with Directive 2008/98/EC of the European Parliament and of the Council on Waste. This Act, together with the regulations issued on its basis, sets out precise guidelines that should be followed in a management of the waste. Their observance allows to minimize a negative influence of the waste on the natural environment as well as on human health and life. However, in Poland there are situations when these regulations are not respected. The inspection carried out in 2014 by the Supreme Audit Office revealed serious irregularities regarding the management of the medical waste in 2011–2013. No information on the disposal of about 6.9 thousand tonnes of waste (5.7% of their total production) was found, which may indicate that they have not been disposed of in accordance with the regulations [16].

2.1. Transportation

One of the most important rules regarding the management of medical waste, including hazardous waste and those with infectious properties, the respect of which is required and carefully controlled, is the Proximity Principle. According to this principle, all produced waste, which cannot be recycled, must be disposed of at the facility that produced it. If this is not possible, the waste should be transported to the nearest disposal unit, located within the same voivodeship. The exception is possible when the plant disposing waste, although located in the neighboring voivodeship, is closer to the place where the waste was generated than the installation disposing waste in the same voivodeship. This principle reduces an unnecessary transport of the medical waste over long distances, which could contribute to the development of various epidemics. The above-mentioned inspection from 2014 also showed that this principle was not respected. The waste was often transported over long distances, which depended on price of its disposal and its lowest level [16]. An ideal situation would be to meet the requirements for the disposal of medical waste at the place of their production. This is possible thanks to hospital waste incinerator plants, but there are not many of them in relation to the operating health care facilities. Therefore, it is necessary to transport the waste to the nearest installations. This problem could be solved by a mobile medical waste incinerator that would meet the Polish regulations and European law. It eliminates the need for medical waste transportation.

2.2. Thermal Treatment

Due to a fact that currently in Poland the only acceptable method of the medical waste disposal is its thermal treatment in the hazardous waste incineration plants, this process is regulated by various rules. It must meet all of them regardless of processing capacity. According to the Regulation of the Ministry of Health on the requirements and methods of the medical and veterinary waste disposal [17], a process of the thermal treatment of medical waste, possessing infectious and non-infectious properties, must take place under strictly defined conditions. It is required that the temperature of the flue gas, measured near the inside wall of the combustion chamber, after the last air supply is at least 850 °C for the non-infectious waste, and at least 1100 °C for the waste with the infectious properties. This temperature must be maintained for at least two seconds, even under the most adverse conditions (for example unstable work of the burners).

An installation for the medical waste incineration should be equipped with a number of devices to maintain safety during the process and ensure its proper workflow. The incineration plant must contain at least one auxiliary burner in each combustion chamber, which will start automatically when the temperature of the flue gas is lower than the required value. Its additional tasks include maintaining the required temperature during the start-up and shut-down of the incinerator and during the failure of the main burner. Because it is forbidden to place the medical waste in the combustion chamber before reaching the required temperature, the unit disposing the medical waste must also have an automatic waste feeder system. It also prevents the waste from being placed in the combustion chamber when the temperature of the flue gas during the incinerator's work is lower than specified in the regulations, and also in the case of exceeding the permissible emission levels of the harmful compounds into the atmosphere. It also protects an operator of the incinerator against direct contact with a heated interior of the combustion chamber. The heat generated in the installation during the waste incineration should be recovered as much as possible, using appropriate equipment. The flue gas generated during the process should be removed to the atmosphere, after its purification, reducing an emission of the harmful compounds. The medical waste incinerator must be sealed to prevent contamination of the soil or surface water. The entire process should be controlled primarily by continuous monitoring of the basic parameters characteristic for the thermal treatment (temperature and pressure of the flue gas in the combustion chamber, oxygen concentration and the content of water vapor in the flue gas).

2.3. Existing Incinerators

There are companies offering, on the international market, the waste incinerators, adapted to a trailer. These include, i.a. Inciner8 products, offering the general-purpose incinerators (which can be placed on a trailer, thus creating a mobile incinerator), the animal crematoriums, as well as the medical waste incinerators, with the condition that they are intended for sale mainly outside the European Union [18]. It is due to the lack of an automatic feeder system of the waste.

Another example of the medical waste incinerator is products by Matthews Environmental Solution company [19]. Designed units (container incinerators, skid-mounted incinerators, or transported on a trailer—Figure 2) are used for incineration of the hospital waste and are mainly used in the least-developed countries that face the epidemics of various diseases, as well as in the places of different types of disasters. The producer ensures an implementation of the project for a special order, but the offer does not contain a mobile medical waste incinerator that could be admitted to work in Poland. The reason is also a lack of the automatic waste feeder system for the combustion chamber.

Figure 2. A view of the Matthews Environmental Solutions mobile incinerator [19].

A similar solution is the Helios 0.3 mobile, small-scale incinerator by GEI Works (Figure 3a). It is used in hospitals and other health care facilities, as well as in police stations (disposal of drugs and confiscated things) [20].

The last example of the mobile medical waste incinerator is the MediBurn small-scale unit by Elastec company, the view of which is shown in Figure 3b [21]. The company ensures that this unit disposes of the medical and veterinary waste with low emission of harmful compounds to the atmosphere. These incinerators were purchased by the The United Nations Children's Fund (UNICEF) organization to prevent the Ebola virus spreading in Liberia and also were purchased by the US Army stationing in Afghanistan and Iraq.

None of the above-mentioned units can operate in Poland, mainly due to a lack of the automatic feeder system to the combustion chamber, accented in the Regulation of the Minister of Health [9]. Some of them also have too short a retention time, which is the minimum time for which flue gases must remain in the combustion chamber at a certain temperature (required by law).

(**a**) (**b**)

Figure 3. Types of mobile waste incinerators: (**a**) Helios 0.3 mobile waste incinerator [20]; (**b**) MediBurn small-scale incinerator [21].

In this paper, own solution of a mobile medical waste incinerator that meets the strict requirements of Polish law is proposed. Currently, there is no such unit on the Polish market. The thermal and flow calculations, based on the Ministry of the Environment of Ontario documentation, regarding the waste composition [22] are presented, leading to estimation of the incinerator dimensions. Moreover, two heat exchangers are considered and calculated, to recover part of the thermal energy of exhaust gases. The results of comprehensive thermal and flow calculations of the incinerator's equipment are presented.

3. Calculation of the Incinerator Combustion Chambers Dimensions

For the waste composition presented by the Ministry of the Environment of Ontario, stoichiometric calculations were conducted for the assumed mass of waste equal to m = 50 kg and the duration of the combustion process of 3 h ($\dot{m}$ = 16.67 kg/h). Table 2 presents an example of the percentage share of the individual components and their higher heating values in accordance with the Canadian assumptions [22].

Table 2. Composition and characteristics of the infectious medical waste in accordance with the Canadian assumptions [22].

Component	Percentage Content [%]	Mass Input [kg/h]	Empirical Formula	Higher Heating Value [kJ/kg]
Paper, textile	35.70	5.95	$C_6H_{10}O_5$	18,568
Plastic	27.30	4.55	$(C_2H_4)_x$	46,304
Glass & sharps	8.50	1.42	SiO_2 & Fe	0
Liquids	24.00	4.00	H_2O	0
Other (tissue)	4.50	0.75	$C_5H_{10}O_3$	20,471
Total	100	16.67		

For comparison, calculations for the infectious medical waste were carried out with the composition presented in the research conducted in Isfahan (Iran) city [14] in 2012 and in the studies carried out in the hospitals in southern Italy in 1992 [15]. The composition considered in these studies is so precise that it is possible to make some additional assumptions and make stoichiometric calculations. The data exhibited a diversity of the waste compositions, revealing the spectrum of substances and their percentage. It is supposed that the waste coming from Poland are within this range. For the calculations, the guidelines of the Ministry of the Environment of Ontario [22] were utilized. The technical assumptions, formulated by Ministry of the Environment of Ontario, are consistent with Polish law. All of its guidelines overlap with the requirements of Polish law, i.e., on the flue gas retention time and temperature. The assumptions on the temperature, air composition or latent heat of vaporization of water are also in-line with Polish conditions. Therefore all cases were considered with the following assumptions based on the mentioned guidelines:

- input temperature of the waste and air delivered to the chamber: T_i = 15.5 °C,
- mass composition of the air: 23% O_2, 77% N_2,
- the air contains 0.0132 kg_{H2O}/kg dry gas at relative humidity of φ = 60% and T_a = 26.7 °C dry bulb temperature,
- volume of 1 kmol of an ideal gas: V_{ig} = 22.4 m^3, at the temperature of 0 °C and pressure of 101.3 kPa,
- latent heat of water vaporization at 15.5 °C: r_{H2O} = 2460.3 kJ/kg,
- flue gas retention time at T_{req} = 1100 °C for the infectious waste: τ = 2 s.

In the case of waste from the Iranian and Italian hospitals, it was assumed that the liquids were represented by the water; the glass and sharp objects were treated as the ash; the textiles and paper collectively treated in combustion reactions as the cellulose; the tissues were used as the other. Tables 3 and 4 present a percentage share of the individual components and their higher heating values in accordance with the above-discussed assumptions, depending on the country of the waste origin.

Table 3. Composition and characteristics of the infectious medical waste from Iranian hospitals [14,22].

Component	Percentage Content [%]	Mass Input [kg/h]	Empirical Formula	Higher Heating Value [kJ/kg]
Paper, textile	31.04	5.17	$C_6H_{10}O_5$	18,568
Plastic	40.28	6.71	$(C_2H_4)_x$	46,304
Glass & sharps	7.89	1.32	SiO_2 & Fe	0
Liquids	17.34	2.89	H_2O	0
Other (tissue)	3.45	0.58	$C_5H_{10}O_3$	20,471
Total	100	16.67		

Table 4. Composition and characteristics of the infectious medical waste from Italian hospitals [15,22].

Component	Percentage Content [%]	Mass Input [kg/h]	Empirical Formula	Higher Heating Value [kJ/kg]
Paper, textile	34.00	5.67	$C_6H_{10}O_5$	18,568
Plastic	46.00	7.67	$(C_2H_4)_x$	46,304
Glass & sharps	7.9	1.32	SiO_2 & Fe	0
Liquids	12.00	2.00	H_2O	0
Other (tissue)	0.10	0.01	$C_5H_{10}O_3$	20,471
Total	100	16.67		

The dimensions of the combustion chamber were designed on the basis of its assumed shape and the mass of the input material (Equation (1)):

$$V_{cc} = \frac{m}{\rho}, \tag{1}$$

where V_{CC} is the volume of the combustion chamber (m^3), m is the mass of the waste (kg) and ρ *is* the waste density (kg/m^3).

The least favorable case, when the waste are characterized by low density—according to the Ontario Ministry of the Environment, these are beddings, gauzes and dressings with a density of 80 kg/m^3 [22]—was also considered.

A basis for the calculation of the secondary chamber dimensions is the volumetric flow of flue gas produced from the combustion process in the combustion chamber. First of all, the analysis of the combustion reactions of individual components was carried out, leading to the total stoichiometric amount of oxygen required for the waste incineration. The stoichiometric amount of the, needed to incinerate the waste, was calculated on the basis of the assumed oxygen content in the air:

$$\dot{m}_{a,stech} = \Sigma O_2 \cdot \frac{100}{23}, \tag{2}$$

where $\dot{m}_{a,stech}$ is the stoichiometric amount of the air needed to incinerate the waste (kg/h) and ΣO_2 is amount of oxygen in the waste.

The waste must be burnt in an excess air. Only after reaching the required temperature of 1100 °C, the excess air ratio should be high enough to ensure a control of the combustion process, and prevent an uncontrolled temperature increase in the chamber. The medical waste includes flammable materials and sometimes they have a higher heating value, which could disturb the control over the combustion process. In connection with the above, a relatively high excess air coefficient of λ = 2.3 [22] was assumed for the calculations. An amount of the dry air needed to incinerate the waste was therefore:

$$\dot{m}_a = \lambda \cdot \dot{m}_{a,stech}, \tag{3}$$

where $\dot{m}_a$ is the amount of dry air (kg/h).

An amount of the moisture in the air supplied to the combustion chamber was calculated as:

$$\dot{m}_m = X \cdot \dot{m}_a, \tag{4}$$

where $\dot{m}_m$ is the amount of the moisture in the air (kg/h) and X is the moisture content, X = 0.0132 (-).

The total mass flow rate of the input material, the air and the moisture was obtained from:

$$\dot{m}_t = \dot{m} + \dot{m}_a + \dot{m}_m, \tag{5}$$

where $\dot{m}_t$ is the total mass flow rate of the input material (kg/h) and $\dot{m}$ is the assumed mass flow rate of the incinerated waste (kg/h). Then, a mass balance was done to check the equality of an amount of the substrates and combustion products. The mass flow rate of the nitrogen contained in the air and the excess air was calculated as follows:

$$\dot{m}_{N2} = \frac{77}{100} \cdot \dot{m}_{a,stech}, \tag{6}$$

$$\dot{m}_{\lambda} = \dot{m}_a - \dot{m}_{a,stech}, \tag{7}$$

where $\dot{m}_{N2}$ is the mass flow rate of nitrogen in the air (kg/h) and $\dot{m}_{\lambda}$ is the mass flow rate of the excess air (kg/h).

Taking into account a total amount of the carbon dioxide, produced during the waste incineration, the total mass flow rate of the dry combustion products was obtained:

$$\dot{m}_{dcp} = \dot{m}_{\lambda} + \dot{m}_{N2} + \Sigma CO_2, \tag{8}$$

where $\dot{m}_{dcp}$ is the mass flow rate of the dry combustion products from the waste (kg/h) and ΣCO_2 is the total amount of produced carbon dioxide (kg/h).

In the next step, the total water content, which consisted of the water contained in the waste, the air humidity and the total moisture obtained from the combustion reaction, was calculated:

$$\dot{m}_{t,H2O} = \dot{m}_{H2O} + \dot{m}_m + \Sigma H_2O, \tag{9}$$

where $\dot{m}_{t,H2O}$ is the total water content (kg/h), $\dot{m}_{H2O}$ is the total amount of water in the waste (kg/h) and ΣH_2O is the total amount of the moisture from the combustion reaction (kg/h).

The total mass of all combustion products, obtained during an one-hour incineration in the unit, was a sum of the mass of the dry combustion products, the total water and the ash in the waste. It was equal to a mass of the substrates delivered to the chamber, which proved a correctness of the calculations:

$$\dot{m}_{c,t} = \dot{m}_{dcp} + \dot{m}_{H2O} + \dot{m}_{ash} = \dot{m}_t, \tag{10}$$

where $\dot{m}_{c,t}$ is the total mass of all combustion products (kg/h).

Heat balance of the combustion chamber was calculated in order to determine the burner power, an amount of the additional gaseous fuel and the volumetric flue gas flow rate, which defined the size of the combustion chamber. Knowing the higher heating values of the tissues, dressings, plastics and paper, the heat flow rates generated during the combustion of individual waste components were obtained, and then summed up:

$$\dot{Q}_t = \Sigma\dot{Q}_i = \Sigma\dot{m}_i \cdot HHV_i, \tag{11}$$

where $\dot{Q}_t$ is the total rate of heat (kJ/h), $\dot{Q}_i$ is the heat rate of each component (kJ/h), $\dot{m}_i$ is the mass flow rate of each component (kg/h) and HHV_i is the higher heating value of each component (kg/h).

To obtain a temperature of 1100 °C in the chamber, an additional heat flow rate should be supplied from the combustion of another fuel. In order to determine the required burner power and an amount of the gaseous fuel, the heat rates needed to be supplied to warm up the ash, water and dry combustion products (to the required temperature level) were calculated, according to the formulas:

$$\dot{Q}_{dcp} = \dot{m}_{dcp} \cdot c_{p,dcp} \cdot \left(T_{req} - T_i\right), \tag{12}$$

$$\dot{Q}_{ash} = \dot{m}_{ash} \cdot c_{p,ash} \cdot \left(T_{req} - T_i\right), \tag{13}$$

$$\dot{Q}_{H2O} = \dot{m}_{H2O} \cdot c_{p,H2O} \cdot \left(T_{req} - T_i\right) + \dot{m}_{H2O} \cdot r_{H2O}, \tag{14}$$

where $\dot{Q}_{dcp}$ is the rate of heat needed to heat the dry combustion products to the required temperature of 1100 °C (kJ/h), $c_{p,dcp}$ is the mean specific heat of dry products, $c_{p,dcp}$ = 1.086 (kJ/kg·K) [22], T_{req} is the required temperature in the chamber (K), T_i is the input temperature of the waste (K), $\dot{Q}_{ash}$ is the rate of heat needed to heat the ash to the required temperature of 1100 °C (kJ/h), $c_{p,ash}$ is the mean specific heat of ash, $c_{p,ash}$ = 0.831(kJ/kg·K) [22], $\dot{Q}_{H2O}$ is the rate of heat needed to heat the water to the required temperature of 1100 °C (kJ/h), $c_{p,H2O}$ is the mean specific heat of water, $c_{p,H20}$ = 2.347 (kJ/kg·K) [22] and r_{H2O} is the latent heat of water vaporization at 15.5 °C (kJ/kg·K).

A lost, by the radiation, rate of heat was assumed to be at the level of 5% [22]:

$$\Delta\dot{Q}_r = 5\% \cdot \dot{Q}_t, \tag{15}$$

where $\Delta\dot{Q}_r$ is the heat rate lost by the radiation (kJ/h).

Summing up Equations (12)–(15), for all considered components, the following formula was obtained:

$$\Sigma\dot{Q} = \dot{Q}_{dcp} + \dot{Q}_{ash} + \dot{Q}_{H2O} + \Delta\dot{Q}_r, \tag{16}$$

where $\Sigma\dot{Q}$ is the total required heat rate (kJ/h).

A difference between the heat rate coming from the incineration of the waste and the value representing the sum of rates needed to raise the temperature of individual components determined the required energy from the additional fuel, including 5% of radiation loss [22]:

$$\Delta\dot{Q}_f = 1.05 \cdot \left|\dot{Q}_t - \Sigma\dot{Q}\right|, \tag{17}$$

where $\Delta\dot{Q}_f$ is the total heat rate required from fuel (kJ/h).

The minimal burner power was calculated by the given formula:

$$P_f = \Delta\dot{Q}_f \cdot \frac{1}{3600}, \tag{18}$$

where P_f is the minimal burner power (kW).

The gas demand (the volumetric flow rate of gaseous fuel) was calculated on the basis of the heat rate that can be obtained from 1 m^3 of the natural gas at 1100 °C, burned with the excess air ratio $\lambda = 1.2$ [22]:

$$\dot{V}_f = \frac{\Delta\dot{Q}_f}{q_f}, \tag{19}$$

where $\dot{V}_f$—the volumetric flow rate of gaseous fuel (m^3/h) and q_f is the available heat from natural gas, q_f = 15,805.2 (kJ/m^3) [23].

The dry combustion products and the resulting moisture must be taken into account in the flue gas flow rate. Using the gas combustion reactions, the mass of dry products per 1 m^3 of burned natural gas (14.41 kg/m^3) and moisture (1.59 kg/m^3) [23] was determined. Therefore the mass flow rates of the above-mentioned components were expressed by the following formulas:

$$\dot{m}_{f,dcp} = 14.41 \cdot \dot{V}_f, \tag{20}$$

$$\dot{m}_{f,H2O} = 1.59 \cdot \dot{V}_f, \tag{21}$$

where $\dot{m}_{f,dcp}$ is the mass flow rate of the dry products from the fuel (kg/h) and $\dot{m}_{f,H2O}$ is the mass flow rate of the resulting moisture from the fuel (kg/h).

A total amount of the dry combustion products of the waste and the fuel was:

$$\dot{m}_{dcp,t} = \dot{m}_{dcp} + \dot{m}_{f,dcp}, \tag{22}$$

where $\dot{m}_{dcp,t}$ is the total mass flow rate of the dry combustion products (kg/h).

A total amount of the moisture (steam) from the combustion of the waste and the fuel could be calculated as:

$$\dot{m}_{m,t} = \dot{m}_{H2O} + \dot{m}_{f,H2O}, \tag{23}$$

where $\dot{m}_{m,t}$ is the total moisture (water vapor) from the waste and the fuel (kg/h).

The flue gas mass flow rate was treated as the air in the calculations. On this basis, from the Clapeyron equation, for the isobaric process, the volumetric flow rate of dry combustion products and moisture (water vapor) at 1100 °C were determined:

$$\dot{V}_{dcp,t} = \dot{m}_{dcp,t} \cdot \frac{V_a}{m_a} \cdot \frac{T_{dcp,t}}{T_a} \cdot \frac{1}{3600}, \tag{24}$$

$$\dot{V}_{m,t} = \dot{m}_{m,t} \cdot \frac{V_{H2O}}{m_{H2O}} \cdot \frac{T_m}{T_{H2O}} \cdot \frac{1}{3600}, \tag{25}$$

where $\dot{V}_{dcp,t}$ is the volumetric flow rate of the dry combustion products (m^3/s), $\dot{V}_{m,t}$ is the volumetric flow rate of the moisture (water vapor) (m^3/s), V_a and V_{H2O} are the volumes of 1 kmol of the air and the moisture, equal to 22.4 (m^3/kmol) [22], m_a is the molar mass of the air, equal to 29 (kg/kmol) [22], m_{H2O} is the molar mass of the moisture, equal to 18 (kg/kmol) [22], $T_{dcp,t}$,T_m are the required temperatures of the dry products and the moisture, equal to 1373.15 (K) and T_a, T_{H2O} are the standard temperatures of the air and the moisture, equal to 273.15 (K) [22].

The total exhaust gas (combustion products) volumetric flow rate was the sum of Equations (24) and (25):

$$\dot{V}_{c,t} = \dot{V}_{dcp,t} + \dot{V}_{m,t}, \tag{26}$$

where $\dot{V}_{c,t}$ is the total volumetric flow rate of the combustion products (m^3/s).

The volume of the secondary chamber was determined on the basis of the flue gas volumetric flow rate and the flue gas required residence time at given temperature. The residence time of the flue gas in the secondary chamber, could be defined as:

$$\tau = \frac{V_{sc}}{\dot{V}_{c,t}}, \tag{27}$$

where τ is the flue gas retention time for the infectious waste (s), which should be equal to 2 s in accordance with Polish law, and V_{SC} is the volume of the secondary chamber (m^3).

The required minimum volume of the secondary chamber could be calculated as:

$$V_{sc} = \dot{V}_{c,t} \cdot \tau, \tag{28}$$

The obtained results for the waste composition presented by the Ontario Ministry of the Environment and by Iranian and Italian hospitals, for the same weight of input material (50 kg) and burning time (3 h), are summarized in Table 5.

Table 5. Comparison of the calculation results for the Canadian, Iranian and Italian hospitals.

Medical Waste Composition	Air Required [kg/h]	Dry Products [kg/h]	Moisture [kg/h]	Auxiliary Fuel [m^3/h]	Minimal Burner Power [kW]	Total Volumetric Flow Rate [m^3/s]	Secondary Chamber Volume [m^3]
Canadian	228.19	229.91	16.26	2.93	12.88	0.33	0.66
Iranian	299.8	300.35	18.75	3.38	14.86	0.418	0.836
Italian	329.53	329.86	19.34	3.25	14.25	0.449	0.898

For the waste composition coming from more recent studies [14], the amount of additional fuel only slightly increased, as well as the power of the burner. A larger amount of air also increases the volumetric flow rate of the fan that pushes it into the chamber. From the incinerator operation point of view, this is not a problem due to the fact that devices such as a burner or fan are selected by the designer, taking into account a change in the working conditions. However, attention should be paid to the change in the total volumetric flue gas flow rate, which determines the dimensions of the secondary chamber. A chamber with too small volume does not provide sufficient retention time for the exhaust gases at the required high temperature, ensuring a destruction of the pathogens and microorganisms. It is also a key issue for a design of the entire device dimensions, in the case of smaller scale incinerators—especially mobile. Its size is limited mainly by traffic regulations, regarding the installations carried on trailers, therefore the most optimal solution, characterized by the smallest dimensions, is searched for. Oversizing of the device is associated with higher investment and operating costs and it can also completely eliminate the possibility of unit adaptation to the traffic regulations.

It should be remembered that the calculations were carried out for the same, relatively high value of the excess air coefficient λ, which was a key factor influencing the final volumetric flue gas flow rate and the volume of the secondary chamber. Due to the hazardous nature of medical waste, its high values are recommended in order to minimize the risk of incomplete combustion and to provide residual oxygen in the flue gas at a minimum level of 6% [22]. It is possible to reduce the combustion chamber volume by reducing λ. However, it has its limitations, for example, a reduction of λ from 2.3 to 2, in the case of waste from Italian hospitals, caused a temperature increase in the chamber above assumed (1100 °C). The heat rate, generated during burning waste with this composition, was higher than the rate of heat needed to raise the temperature of dry products and ash material to the required value and evaporation of moisture. On the other hand, in the case of waste from Iranian hospitals, with the $\lambda = 2$ factor, such a situation did not occur.

4. Proposal of Mobile Medical Waste Incinerator

On the basis of the calculation scheme presented in the previous section and taking into account the Polish legal regulations, regarding units disposing of medical waste, a mobile medical waste utilization unit has been proposed. Figure 4 presents its view with the most important parts marked with the numbers, while Figure 5 its overall visualization.

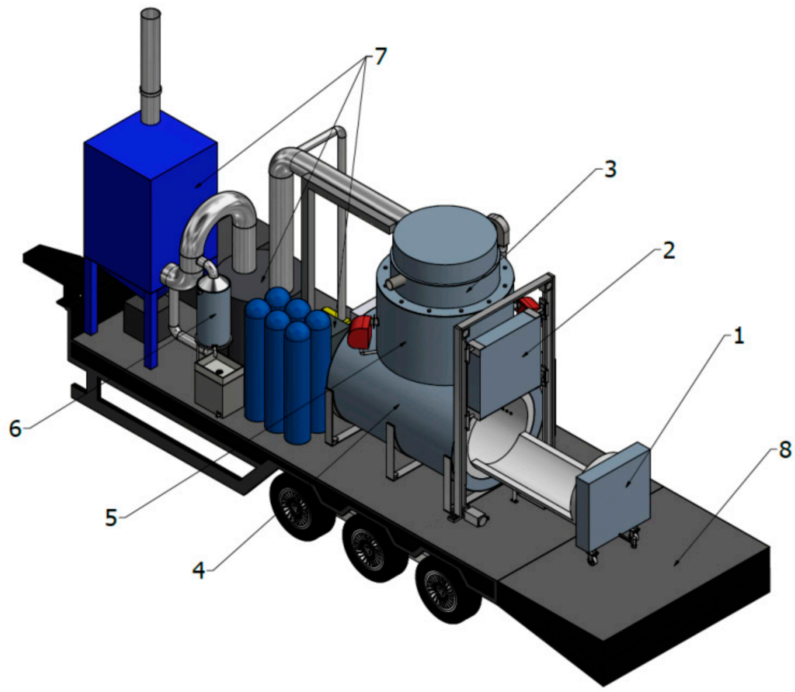

Figure 4. A view of the mobile medical waste incinerator: 1—Automatic waste feeder, 2—Fire door, 3—Metallic radiation recuperator, 4—Combustion chamber, 5—Secondary chamber, 6—Heat exchanger for hot water preparation, 7—Three stages of air pollution control system, 8—Trailer.

Figure 5. Visualization of the mobile medical waste incinerator.

The mobile medical waste incinerator consists mainly of a cylindrical horizontal combustion chamber (4) with a cylindrical vertical secondary chamber (5). In each combustion chamber there are two burners, ultimately supplied with natural gas due to low emission of the dust and the harmful compounds and the chemical stability of ashes during combustion [24]. The dimensions of the chambers and the choice of appropriate burners ensure the required exhaust gases temperature and their appropriate retention time (2 s).

The waste is delivered to the combustion chamber by means of an automatic waste feeder (1), while its elements are at the same time closing the chamber-loading hole, which during heating (up to 1100 °C) is closed by a special fire door (2), moving on the trolleys placed in the guides. The feeder also serves as a gate, due to the gutter shape matched to the cylindrical chamber. It eliminates the problem of removing residues after the combustion process—they are leaving the chamber with the feeder. The feeder gutter shape also prevents potential spillage of liquid substances contained in the waste (e.g., when introducing the waste into the combustion chamber). The feeder is moved by a rack-and-pinion drive with an electromechanical actuator, and its position is changed by a remote controller and an encoder placed in the actuator driving the gear. Proposed automatization of the waste feeding system can be easily obtained due to the utilization of off-the-shelf components from sliding gate systems.

4.1. Heat Recovery

In the proposal the units for the physical enthalpy of exhaust gases recovery, after leaving the secondary chamber are also considered. The gases, behind the chamber, have high temperature, and the law requires usage of the waste heat recovery equipment whenever it is possible [17]. Therefore, the radiation recuperator (3) was designed. It heats the air supplied to the combustion chamber and burners and allows reaching, by the combustion air, the temperature up to 200 °C. Considering the safety and hygiene during the process of medical waste utilization, it was also decided to use the flue gas to heat domestic water, intended for disinfecting hands and maintaining cleanliness of the workplace. The shell-and-tube heat exchanger (6) was proposed. Installation is capable to heat 50 kg of water from 10 to 40 °C in about 11 min, assuming that the flue gas temperature at the inlet of heat exchanger is 300 °C.

4.2. Exhaust Gas Cleaning Instalation

The observance of emission standards during a disposal of the medical waste in the mobile unit is guaranteed by the flue gas cleaning installation. Due to the lack of information about the exact chemical composition of flue gas produced in the designed unit (it will be possible to determine only after testing the prototype unit), a three-stage installation (7) was set up to reduce harmful compounds to an acceptable level. It was designed to be compact and resistant to high temperature for the most unfavorable conditions. It includes a selective non-catalytic reduction system SNCR, a spray scrubber, which uses a wet exhaust gas cleaning method and a filter for separation of the solid particles and dust. It should be noted that a significant part of harmful compounds is eliminated due to the proper design of the main and secondary combustion chambers, as well as maintaining appropriate conditions during the treatment of medical waste and the use of modern low-emission burners.

The exhaust gases are removed into the atmosphere by means of an exhaust fan through the chimney, which is installed upon arrival at the place of waste incineration. Thanks to this, the dimensions of the unit during transportation are reduced. It is important from the Polish traffic regulations point of view, according to which the total height of the vehicle (as well as the trailer with the load) should not exceed 4 m, measured from the ground level.

4.3. Energy Flow Diagram

Figure 6 presents the Sankey diagram of the energy flow in the mobile medical waste incinerator. All streams of chemical energy, being a substrate in the process, were counted. During the calculations, heat accumulation in the construction materials of both chambers was taken into account, as well as assumed heat losses. The calculations also include recuperation, because heating the air supplied to the combustion chamber allows to reduce the demand for fuel. According to the calculations of heat balance, in that case the heat flow required to conduct the process at 1100 °C decreases from 102.99 kW to 62.42 kW. Because the heat rate equal to 90.43 kW is supplied by the high calorific value of the waste, an amount of the natural gas necessary to be added during the entire process decreases from 9 m^3 to 3 m^3.

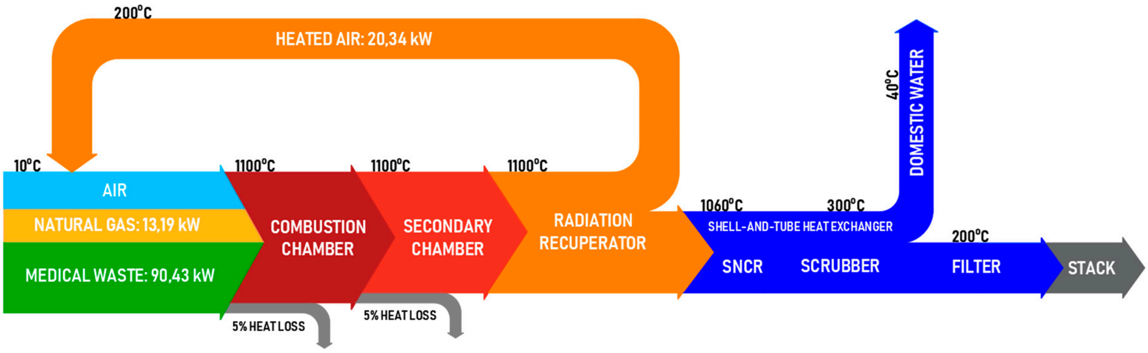

Figure 6. Sankey diagram of the energy flow in the designed incinerator.

4.4. *Auxilary Components*

The entire process is monitored by the control and measurement equipment selected on the basis of calculations. Due to it, it is possible to control a process of the medical waste incineration, as well as to interrupt it when any of the parameters exceed the admissible value. For the reasons of safety and continuity of the measurements, the sensors and some of their drivers have been doubled. The most important parameters, with values that are constantly monitored, are: exhaust gas temperature, pressure and composition, content of the oxygen.

The designed unit is attached to the trailer, which makes the unit mobile and able to be transported to the place of waste disposal. All devices have been designed or selected to not exceed the permissible height from the ground level, as well as its width, which is also limited by the provisions of traffic regulations. Thanks to utilization of construction and insulation materials of low density, the unit is characterized by a relatively low total weight. There is also an additional space on the trailer for the fuel tank, required power generator and container for residues after the combustion process. The initial, minimum length of the trailer, enabling the placement of all necessary equipment for operation, is about 8 m, but it must be kept in mind, that it might be overestimated, since at the moment it is not possible to determine the exact dimensions of the exhaust gas cleaning installation. An appropriate layout of the installation on the trailer provides access to each device, facilitating possible replacement or repair. Table 6 sums up the most important parameters of the mobile medical waste incinerator.

Table 6. The most important parameters of designed mobile medical waste incinerator.

Parameter	Value
Standard operating temperature	850–1100 °C
Capacity	16.67 kg/h
Burners	4× (10–41) kW
Fuel	natural gas
Fuel consumption	3 m^3/h
Maximum vehicle speed	80 km/h
Chamber material	ceramic
Insulation material	Aerogel
Heat recovery system	Radiation recuperator (flue gas/air) Shell-and-tube recuperator (flue gas/water)

5. Discussion

Introduction of the proposed solution to the market requires the analysis of its advantages and disadvantages, as well as evaluation of a profitability of the entire investment. A helpful technique for conducting such a recognition and creating an appropriate marketing strategy is the SWOT analysis (Strengths Weaknesses Opportunities Threats) [25].

The profitability analysis started with strengths. In first place is the uniqueness of the proposed solution and its conformity with the law in Poland. The Polish market currently does not have a mobile unit for the disposal of medical waste which would meet the legal requirements, especially in regard to the automatic waste feeder. The second advantage of the proposed solution is a mobility of the unit. Thanks to this, it can work in various locations, depending on the needs of the environment. Not only health care units located away from larger waste incineration plants, but also the places of the disasters or epidemic outbreaks may be among the recipients of the service. Thanks to the mobility of the unit and modern solutions used in it, it can compete with the offers of other companies on the international market. The unit can also dispose of other types of waste. Therefore, during a reduced demand for the disposal of medical waste, the incinerator can work as an animal crematorium or incineration plant for the non-infectious waste.

The weaknesses of the proposed unit include, above all, a large investment costs. Usage of innovative materials, as well as devices at non-typical dimensions and features, mostly designed against order, is associated with an increase in the construction costs.

The factors formulated as opportunities have a significant impact on determination of the mobile medical waste incinerator profitability. The most important are the environmental and legal aspects. The medical waste, due to its properties, is hazardous and the issue of its correct disposal is extremely important. The designed unit ensures neutralization of the waste in a manner that is required by very restrictive Polish law. Usage of the three-stage flue gas cleaning system ensures consistence with emission standards, while the relatively small maximum weight of the waste once incinerated and unit capacity as well as the automation of the process allow for immediate interruption in the case of any irregularities. Mobility of the unit reduces the risk of spreading infectious substances, because the waste is disposed of at the place of origin. It solves the problem of waste transportation, special equipment of the cars for this purpose, re-storage of the waste at the landfill belonging to a given stationary incineration plant and a subsequent transport to the incinerator. In addition, by disposing of medical waste at the place where they were created, it is not possible to violate the Proximity Principle, which is the overriding rule for dealing with the hazardous waste. It is also easier to record documentation related to the entire disposal procedure. By burning the waste only from one clinic, cabinet or other health care facility, it is possible to determine the weight of waste for disposal and its composition without any problem. This minimizes a risk of mistakes and omissions regarding the completion of documents confirming the disposal of waste, and such information can be issued immediately for the owner of the institution transferring the waste for incineration. Due to an increasing number of small health care facilities producing small amounts of waste, the mobile incinerator would allow for their safe disposal, while meeting all legal regulations and maintaining environmental requirements. It could also support the work of larger incinerators in the case of sudden shutdowns of the installation.

An implementation of the project also involves threats. Despite an adaptation of the installation to the law applicable in Poland, the legal regulations may change. The awareness of the observers of the treatment of medical waste plays an equally important role. A large number of the opponents of thermal treatment usage for the medical waste could adversely affect the perception of the designed unit. Therefore, the society should be informed about the principles of operation of such an installation and the technologies used in it.

A significant threat is connected with a possibility of the new method of medical waste utilization appearance. If the new, cheaper method, without the combustion process is proposed and additionally it meets all the requirements of the Act, this would lead to a lack of demand for the designed unit.

However, the unit can be improved towards the new requirements and still be competitive with the new solution.

Figure 7 shows a matrix diagram regarding an initial SWOT analysis, containing the most important aspects regarding the strengths, weaknesses, opportunities and threats related to the construction of the proposed mobile medical waste incinerator.

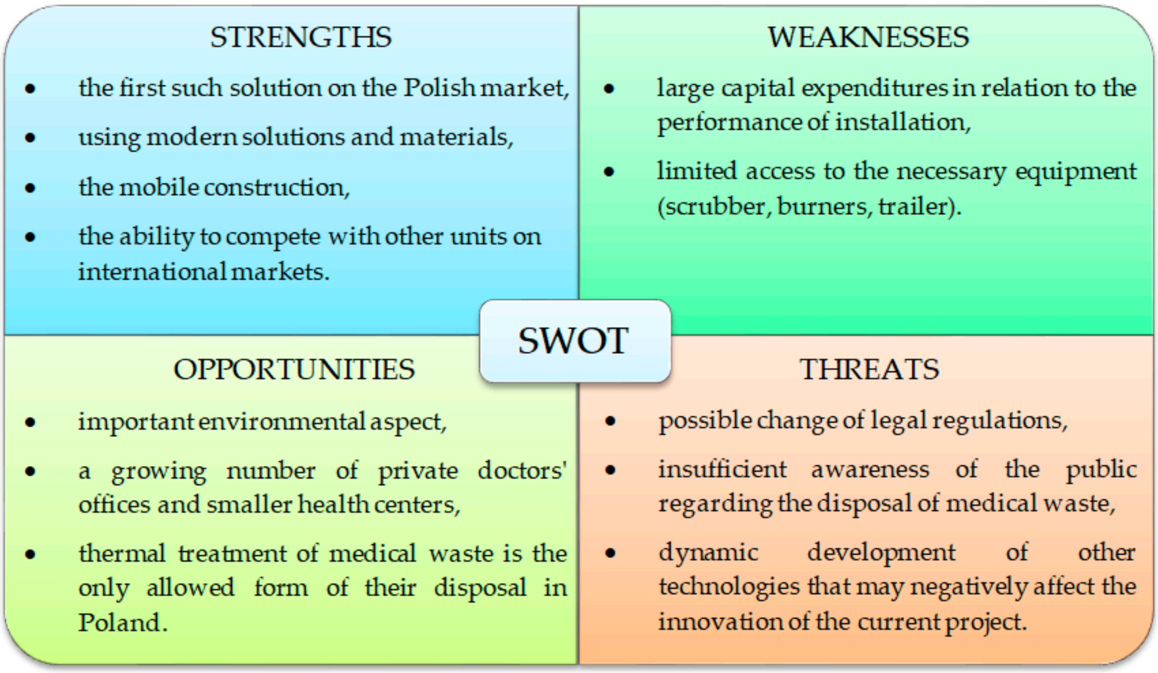

Figure 7. SWOT matrix for proposed mobile medical waste incinerator.

6. Summary

A problem of the medical waste proper management is growing, especially taking into account the continuous increase in the level of health services (e.g., by using disposable equipment), and new solutions should be implemented to enable their safe disposal.

The fundamental issue for the mobile medical waste incinerator design, due to specificity of these waste, is knowledge of the percentage content of their individual components. Data regarding the composition of the medical waste from the hospitals, located in various countries, exhibits its diversity. It can significantly affect the final dimensions of the designed installation. Using the available algorithms, it was shown that knowledge of the approximate composition of the waste characteristics for a given region or country enables adaptation of the proposal by modification of some parameters, for example the excess air coefficient. For some countries (e.g., Poland), the design of a mobile installation for the thermal treatment of the medical waste is difficult due to the lack of any data on the morphological composition of the waste, which are necessary to carry out preliminary thermal calculations.

The proposed unit is a novelty on the national scale, because it considers all Polish legal requirements and its implementation is forward-looking. Since Polish regulations are the most strict (especially in the field of automatic waste feeding system) and the calculation were based on variety of the composition, the incinerator design can be useful in many countries.

Preparatory works on the prototype unit of the incinerator are going on. It will be used to conduct an experimental research and ultimately to optimize its construction.

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References

1. The Act of 14 December 2012 on Waste. Available online: http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20130000021/U/D20130021Lj.pdf (accessed on 19 October 2018).
2. World Health Organization. Health-Care Waste. Available online: http://www.who.int/en/news-room/fact-sheets/detail/health-care-waste (accessed on 8 February 2018).
3. Pépin, J.; Abou Chakra, C.N.; Pépin, E.; Nault, V.; Valiquette, L. Evolution of the global burden of viral infections from unsafe medical injections, 2000–2010. *PLoS ONE* **2014**, *9*, e99677. [CrossRef] [PubMed]
4. Woolridge, A.; Hoboy, S. Medical Waste. In *Waste*; Academic Press: Cambridge, MA, USA, 2019; pp. 517–530.
5. Gold, K. Analysis: The Impact of Needle, Syringe, and Lancet Disposal on the Community. *J. Diabetes Sci. Technol.* **2011**, *5*, 848–850. [CrossRef] [PubMed]
6. Hassan, M.M.; Ahmed, S.A.; Rahman, K.A.; Biswas, T.K. Pattern of medical waste management: Existing scenario in Dhaka City, Bangladesh. *BMC Public Health* **2008**, *8*, 36. [CrossRef]
7. Kumar, R.; Shaikh, B.T.; Somrongthong, R.; Chapman, R.S. Practices and challenges of infectious waste management: A qualitative descriptive study from tertiary care hospitals in Pakistan. *Pak. J. Med. Sci.* **2015**, *31*, 795–798. [CrossRef]
8. Taghipour, H.; Mosaferi, M. Characterization of medical waste from hospitals in Tabriz, Iran. *Sci. Total Environ.* **2009**, *407*, 1527–1535. [CrossRef]
9. Regulation of the Minister of the Health of October 5, 2017. On the Detailed Way of Dealing with Medical Waste. Available online: http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20170001975/O/D20171975.pdf (accessed on 19 October 2018).
10. Windfeld, E.S.; Brooks, M.S.-L. Medical waste management—A review. *J. Environ. Manag.* **2015**, *163*, 98–108. [CrossRef] [PubMed]
11. Voudrias, E.; Goudakou, L.; Kermenidou, M.; Softa, A. Composition and production rate of pharmaceutical and chemical waste from Xanthi General Hospital in Greece. *Waste Manag.* **2012**, *32*, 1442–1452. [CrossRef] [PubMed]
12. Komilis, D.; Makroleivaditis, N.; Nikolakopoulou, E. Generation and composition of medical wastes from private medical microbiology laboratories. *Waste Manag.* **2017**, *61*, 539–546. [CrossRef] [PubMed]
13. Chartier, Y.; Emmanuel, J.; Pieper, U.; Prüss, A.; Rushbrook, P.; Stringer, R.; Townend, W.; Wilburn, S.; Zghondi, R. *Safe Management of Wastes from Health-Care Activities*, 2nd ed.; World Health Organization: Geneva, Switzerland, 2014.
14. Ferdowsi, A.; Ferdosi, M.; Mehrani, Z.; Narenjkar, P. Certain hospital waste management practices in Isfahan, Iran. *Int. J. Prev. Med.* **2012**, *3*, 176–185.
15. Definition and Characterization of Health-Care Waste. Available online: http://www.who.int/water_sanitation_health/medicalwaste/002to019.pdf (accessed on 19 October 2018).
16. Report on the Results of Control by the Supreme Audit Office on the Treatment of the Medical Waste. Available online: https://www.nik.gov.pl/plik/id,7783,vp,9754.pdf (accessed on 14 November 2017).
17. Regulation of the Minister of the Health of October 21, 2016. On the Requirements and Methods of Disposal of Medical and Veterinary Waste. Available online: http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20160001819/O/D20161819.pdf (accessed on 19 October 2018).
18. Inciner8 Company. Available online: http://www.inciner8.pl/ (accessed on 19 October 2018).
19. Matthews Environmental Solutions Company. Available online: https://matthewsenvironmentalsolutions.com/en/89-home-waste-incineration/law-enforcement/317-trailer-mounted-compact-incinerator (accessed on 19 October 2018).
20. GEI Works Portable Incinerator. Available online: https://www.erosionpollution.com/portableincineration.html (accessed on 19 October 2018).

21. Mediburn Case Studies. Installations for Liberia—Haiti—United States Military. Available online: https://www.elastec.com/wp-content/uploads/2017/09/Mediburn-Case-Studies.pdf (accessed on 20 October 2018).
22. Ontario Ministry of Environment. *Incinerator Design and Operating Criteria. Volume II—Biomedical Waste Incinerators*; Her Majesty the Queen in Right of Ontario; Ontario Ministry of Environment: Toronto, ON, Canada, 1986.
23. Danielson, J.A. *Air Pollution Engineering Manual*, 2nd ed.; United States Environmental Protection Agency: Research Triangle Park, NC, USA, 1973.
24. Barczyński, A.; Grządzielski, W. High-efficiency energy processes using natural gas. In Proceedings of the V National Conference GAZTERM 2002, Międzyzdroje, Poland, 27–29 May 2002. (In Polish).
25. SWOT Analysis. Discover New Opportunities, Manage and Eliminate Threats. Available online: https://www.mindtools.com/pages/article/newTMC_05.htm (accessed on 18 July 2019).