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Evaluation of Safety Scenarios for Fires in Waste Disposal Facilities through Numerical Simulations

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After several high-profile fires in waste and recycling facilities, the industry is put under pressure, especially as the materials processed in waste recycling are getting increasingly dangerous. Fire is an ever-present possibility at most waste management sites requiring proper preventive and mitigative strategies because it can cause significant damage to people, property and the environment. Fire risk assessment may benefit from applying the concept of fire safety engineering and numerical tools to approach the phenomena quantitatively. However, the complexity of such fire scenarios requires a detailed analysis that also involves an insight into fundamental processes, including pyrolysis of solid waste matrices and combustion of pyrolizate. These steps are critical for defining safety features of fire scenarios in waste disposal facilities, but the availability of input data may limit the modelling capability of numerical tools. The present work deals with modelling a fire scenario of a bale of plastics starting from literature data in which both pyrolysis and combustion are addressed. Having an accurate reaction model is of paramount importance in modelling solid waste fires. However, full-scale fire tests in open fields will be required to validate and systematize how piles of material burn dependently on boundary conditions.

1. Introduction

Fires in waste facilities represent a critical social, economic, and environmental challenge requiring urgent concern and fire safety strategies. In fact, although the awareness of fire scenarios waste disposal facilities, large challenges remain, including technical and management solutions for prevention and mitigation.

According to statistics, a considerable amount of waste production is measured in Europe, totalling about 215 Mton (Eurostat, 2004) from 2004 to 2016. In addition, the 21st century has seen an increase in municipal waste incineration that has gone with an increasing need for waste storage. A wave of waste management EU directives also accompanied this fact, e.g. the EU Council Directive 1999/31/EC, imposing limitations on organic waste disposal in landfills (Stenis and Hogland, 2011).

In 2016, the United Nations adopted a series of SDGs, Sustainable Development Goals, as part of the 2030 Agenda to increase sustainability goals, including limiting materials, energy, and waste. Responsible production and consumption have fostered recycling strategies of various waste, including paper, plastics, and aluminium. However, unless a sustainable intention, the spread of waste disposal facilities has considerably grown, and recently the critical issue of fires in waste disposal facilities has emerged.

Statistics display a prominent framework of the increasing impact of such fires. According to the 4th Annual Reported Waste & Recycling Facility Fires US/CAN (Fogelman, 2021), fires at waste and recycling facilities in the U.S. and Canada continue to be a significant problem for the industry. The report reported that fires totalled 272 in 2016, 290 in 2017, 365 in 2018, 345 in 2019, and 317 in 2020, meaning a 5-year average of about 318 events/yr. Reported fires occurred in facilities that process waste, paper, or plastic (158), scrap metal (108), organics (20), and a minor number with chemicals (5), construction and demolition (8), and rubber (7). These fire scenarios resulted in 23 reported injuries and 3 deaths in 2020.

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In Europe, statistics on fires in waste disposal facilities and landfills vary on a regional basis because some countries tend to have much better practices and collection coverage than others. For example, Western and Northern countries have almost 100 % collection coverages, with distributed waste collection and treatment facilities in the territory. On the contrary, other countries have poor collection rates, and it seems that open burning is likely an issue due to these low collection rates and poor disposal mechanisms. In both cases, the occurrences of waste fires have increased enormously in the last years, with subsequent monetary and infrastructural losses that have reached a new peak (Ibrahim et al., 2013).

The impact of such fires can be significant, and good fire management can protect the local environment, workers, local infrastructures, and the local community. Moreover, a proper prevention and mitigation strategy can save money and support the business reputation.

On this framework, the qualitative and quantitative assessment of waste fires impacts on people, environments and goods is strategical for introducing regulations and strategies that will curtail these fires in the future. Such approaches can help understand how to identify and manage the hazards and risks of fire in waste and resource recovery facilities (Mocellin et al., 2021). The identification and quantification of risk scenarios are strictly linked to conducting and documenting a fire risk assessment in such a way as to store and manage combustible recyclable and waste materials minimizing the risk of harm to human health and the environment so far as reasonably practicable. Additionally, the preparation of emergency plans benefits from understanding the fire hazards associated with waste disposal facilities and their impact.

In the present work, we discuss the application of fire safety engineering principles to fires of waste piles. An advanced numerical approach to phenomena occurring in a waste pile fire made of plastics is applied to a fire scenario that involves polyethylene and polypropylene, focusing on the applicability of numerical approaches to pyrolysis and combustion in scenario of waste disposal fire.

2. Fires in waste sites

Fires in waste disposal facilities are unfortunately common, can be very difficult to extinguish, and may need a lot of resources for long periods. in fact, fire is an ever-present possibility at most waste management sites because, but not only, many wastes are readily combustible. Such fires can severely affect public health, the environment, safety to firefighters and local communities. These can be classified in short or long term effects, and they include the public in evacuation, the public health impacts on emergency responders and communities, environmental impacts with pollution of air, surface, and groundwater, high demand on fire and rescue services, and large-scale financial losses and disruption.

Fires involving wastes can induce significant harm to people and the environment because:

- risk of death and/or severe injury and health damage exists from high thermal energy and smoke inhalation;
- combustion products release airborne pollutants with an effect on health and environment;
- firewater can transport pollutants into drainage systems and water supplies;
- fires but also explosions can harm people and damage goods.

According to some authors, the primary ignition sources in waste facilities are self-ignition of combustible materials, re-ignition from past fires, heat transfer (ignition caused by a hot surface), and arson (Mikelsen et al., 2021). Self-ignition is referred to both self-heating and thermal runaway in batteries, but also for friction-started fires. Both unintentional via hot works or intentional via arson, human activity and technical and electrical faults are among the initiating events for severe fires in waste disposal facilities. However, the causes for many fire scenarios are still unknown.

According to historical data, waste commonly encountered and involved in fires are:

- paper, cardboard, plastics, and wood;
- natural or synthetic rubber;
- component waste, including components from vehicle dismantling;
- refuse fuels;
- waste electrical and electronic equipment that contain combustible materials.

However, statistics datasets show that the most common fire materials are general and residual wastes, shredder light fractions, organic wastes and ash (Lonnermark et al., 2018).

Different factors affect how waste fires develop in waste piles. As an example, some authors classify surface fires according to Table 1.

Table 1: Models for surface fires of municipal solid waste.

Surface fire	Features
Impermeable fuel bed	Pile of materials crushed to form a single homogeneous mass preventing the movement of convection through it
Semi-permeable fuel bed	Pile of materials with sufficient tensile strength to allow convective mechanisms to pass through the mass of the pile. The flame passage into the mass of the pile is prevented, resulting in a surface fire controlled by ash and char.
Permeable fuel bed	Pile of materials with sufficient tensile strength to allow convective mechanisms to pass through the mass of the pile. The flame passage into the mass of the pile is allowed because the repose of individual particles creates holes greater than the flame height.
Deep-seated fire	The fire initiates within the mass of the pile with a core having T > 250 °C that develops anaerobically. It passes across the pile and, ultimately, breaches the surface.
Stacked bale fire	It involves material stacked above 1m in height. A surface fire affects the vertical space among pillars generating sufficient vortices to strip any ash and char away from the fuel material, accelerating phase change.

According to Table 1, permeable fuel beds result in the whole pile being involved in fire when it has enough tensile strength to maintain sufficient ventilation allowing flames to pass into the pile mass.

During deep-seated fire, once the breach provides air supply to the hot core, the fire is fuel-controlled at the peak HRR of the material. Fires that evolve according to a stacked bale fire result in an unusually high HRR for any given material. In addition, piles made of plastics suffer a vaporisation of the fuel bed, resulting in a significant reduction of the calving mechanism that usually affects stacked bales in a fire.

Although different materials are involved in fires, plastics should be carefully analysed because, during combustion and pyrolysis, many substances with negative health impacts (e.g. dioxins, furans, and polychlorinated biphenyls) are emitted.

Reaction to fire and temperature vary according to the fuel matrix, composition, moisture content, and material thickness (Table 2). In addition, heat release rate and heat flux, total fire load, burn duration, and fire spread are typically identified for each stockpile made of combustible waste. Where a stockpile contains a mixture of fuels, the worst-case fire scenario is considered; sometimes, the burn temperature and fire risk are assumed to represent the most predominant waste material, if assessable. Experiments under pilot flame have shown that typical materials can be associated with critical radiant heat flux and surface temperature for ignition (Drysdale, 1998)ref). for example, wood can ignite at about 28 kW m^{-2} and 350 °C. Polyolefins, including polyethylene (PE) and polypropylene (PP), at about 15 kW m^{-2} and 330-360 °C. Polystyrene (PS), instead, can undergo ignition at about 13 kW m^{-2} and 366 °C.

Table 2: Typical ignition and burn temperatures of combustible waste materials (Fire and Rescue NSW, 2020), (Babrauskas, 2001).

Material	Ignition temperature, °C	Burn temperature, °C	Risk of fire
Paper	150-250	850	Average
Wood	370 (immediate), 230-270 (char)	860	Average
Plastic	320-500	1200	High
Rubber	250-320	1150	High
Refuse derived fuel	Depending on composition	900	Average
Solid recovered fuel	Depending on composition	950	Average

In general, the behaviour during initial fire growth is sensitive to different parameters that include the fuel type, the geometrical features of the waste pile, and to a lesser extent, the ventilation. From a theoretical perspective, the most common relationship that describes the heat release rate (HRR) growth in time is the time-squared growth. It embeds a fire growth coefficient α (kW s^{-2}) associated with relevant growth rates and timing to reach a conventional HRR of about 1MW. Specific values of α are selected to characterize the growth rate of standardised fire scenarios (slow, medium, fast, and ultra-fast). According to Babrauskas (Babrauskas, 2016), fires of thick fuel matrices made of wood grow slowly; on the contrary, paper and wood-based thin materials result in fast or even ultra-fast scenarios. Plastic materials are typically associated with medium to fast fire scenarios, with thin plastic materials that can even determine ultra-fast fires. The Italian technical fire prevention standard suggests the ultra-fast behaviour for predefined fires in non-civil activities with 500-1000 kW m^{-2} HRRPUA, except for more onerous cases that emerge from risk analysis and scenario identification.

3. Numerical modelling of fire scenarios in waste disposal facilities

According to the Fire Safety Engineering concept, the design fire scenarios must be identified, selected, and quantified in a risk analysis approach. Among many possible fire scenarios, the procedure requires quantifying the different features of the fire starting from input data appropriate for the calculation methodology chosen. The quantitative characterization includes considering fire as a source of thermal energy and combustion products (ISO/TR 13387). This can be approached with different strategies, among which estimation methodologies based on models and refined calculation tools can be helpful for specific unconventional and complex scenarios. In this framework, field fire simulation models represent valuable tools for designers approaching the topic of fires in waste disposal facilities, typically based on computational fluid dynamics (CFD). They are of particular interest also because of the availability of greater hardware resources and can provide more and more accurate results as a function of the accuracy of the input data to come to results that adhere to real conditions (Vianello et al., 2014; Mocellin and Maschio, 2016). Fire Dynamics Simulator (FDS) belongs to this category and is a CFD calculation model (Mocellin et al., 2018). It numerically solves a form of the Navier-Stokes equations appropriate for a low velocity, thermally powered flow, specifically focused on smoke and heat transport. It is considered one of the most versatile, validated and verified models for fire engineering calculations.

Starting from ver. 6.6.0 of FDS, the possibility of modelling atmospheric conditions and, therefore, fires in open spaces through proper boundary conditions have been introduced. In addition, FDS can accommodate the modelling of pyrolysis of solid matrixes at different degrees of detail, including mass and heat transfer mechanisms that determine the overall pyrolysis behaviour and kinetics pyrolysis. In the simplest case, the reaction rate of pyrolysis depends on the temperature according to an Arrhenius-type equation.

Pyrolisis and combustion occur simultaneously in a fire of waste materials, making it a complex process.

The first is an endothermic phenomenon that makes fuel gas available for combustion in the gas phase through a heat feedback loop. The latter results in a thermal effect because of radiated energy through convection and radiation.

In general, the pyrolysis modelling is designed to predict the mass loss rate (MLR) that feeds the gas phase combustion and, therefore, the heat release rate. The MLR is calculated from a heat balance at the surface of the material, where it is assumed that all MLR occurs. In FDS, the temperature distribution in the solid is calculated according to the 1-D heat conduction equation.

It is often assumed that the pyrolysis reactions occur as per the Arrhenius equation to express the kinetic reactions of materials through the fraction of conversion. The chemical kinetics of the material is determined by three parameters (kinetic triplet), namely activation energy, pre-exponential factor, and reaction order. Kinetic data can be obtained by proper thermogravimetric experiments (TGA) under different heating rates and cone calorimetry (Ahmad, 2015).

Input parameters required by FDS are reported in Table 3, along with data used for simulating PE and PP pyrolysis. Both conductivity and specific heat can be set according to temperature.

Table 3: Fire Dynamic simulator inputs

Solid-phase properties	Polyethylene (PE)	Polypropylene (PP)
Thermal conductivity (W m^{-1} K^{-1})	0.34	0.24
Density (kg m^{-3})	930	910
Specific heat (kJ kg^{-1} K^{-1})	1.5	2.7
Emissivity (-)	0.9	0.95
Absorption coefficient (m^{-1})	1300	960
Heat of reaction (kJ kg^{-1})	920	1300
Heat of combustion (kJ kg-1)	43400	42600

The reaction of pyrolysis can be implemented to produce from a solid material (Mat) a gaseous mixture ($Pyrolizate$) and a solid residue ($Char$) once the surface is exposed to an effective heat load $\dot{Q}$ according to the following equation:

$$Mat_{(s)} + \dot{Q} \rightarrow Pyrolizate_{(g)} + Char_{(s)} \tag{1}$$

The pyrolizate will feed the combustion reaction in the gas phase. It is characterized by different components depending on the solid matrix, and data on such mixture components are essential to simulate in FDS effectively the overall process. Pyrolizate components can be reactive in the gas phase, contributing to the associated HRR. Different approaches and associated degrees of detail can be managed in FDS for implementation, namely the simple chemistry or the complex stoichiometry. The simple chemistry considers a single reaction in the gas phase as a surrogate for all potential fuel sources. On the contrary, complex stoichiometry requires specifying multiple gas species and stoichiometry of the gas reactions. The model of complex stoichiometry can help implement a model properly for the fire of plastic waste materials. On this topic, it should be considered that the pyrolizate of polymers includes a variety of gas-phase products that may require a detailed description in terms of contribution to the combustion. For example, the literature suggests that gas-phase products of polyolefins pyrolysis include hydrogen, C_1-C_4 paraffins, C_2-C_4 olefins, and butadiene (ref).

It would be crucial to improve eq. (1) when dealing with numerical approaches to fires of plastic waste materials by including liquid-phase products and not only volatile fuels. A liquid phase can be itself flammable, contributing to the fire scenario, and by flowing away, it can enlarge the fire. For example, polyolefins decompose in liquid fractions that include a wide range of paraffinic, olefinic, and naphthenic hydrocarbons, requiring proper modelling.

We used in FDS the pyrolysis data of Onwudili et al., 2009 and Ahmad et al., 2015 for the PE and PP. From these data, we obtained the main components of the pyrolizate, and we imposed a combustion stoichiometry in FDS. The numerical simulation consisted of a homogeneous pile of PE and PP arranged in an open space characterized by atmospheric wind and environmental temperature.

The simulation setup included a 3-D domain with a size 20x20x10 m in which a 1 m^3 cubic waste bale was arranged. The domain was meshed with about 1e6 cells; the smallest adopted side of each cell was 0.05 m. the simulation takes about 54 h to

In this work, the following assumptions were imposed:

- homogeneous solid fuel matrix;
- constant wind speed and direction, resulting in neutral stability class;
- no liquid-phase products are modelled and tracked;
- the ignition source was effective in igniting the plastic cube.

The reactive fuels considered were hydrogen, methane, and C2-C4 paraffins and olefins for a total number of 5 gas-phase reactions, respectively, for PE and PP pyrolysis products. Each component has combustion heat, according to Table 4.

Table 4: Heat of combustion of primary components of PE and PP pyrolizate

Gas pyrolizate component	H_2	CH_4	C_2H_4	C_2H_6	C_3H_6	C_3H_8	C_4H_6	C_4H_8
Heat of combustion (10^4 kJ kg^{-1})	14.1	4.9	4.3	4.7	4.0	5.0	4.7	4.6

Simulations results are discussed below.

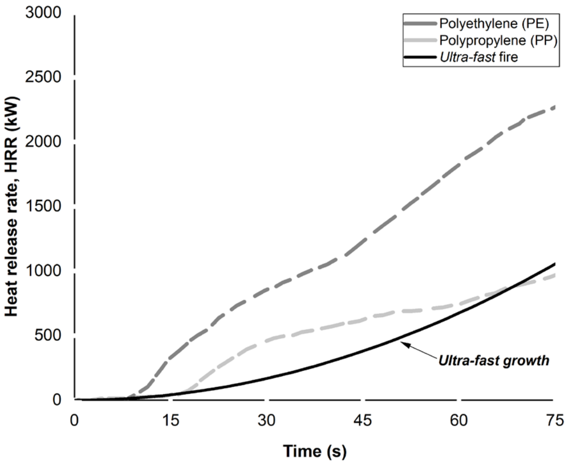

Figure 1: Heat release rate (HRR) of 1 m^3 stack of plastic and ultra-fast fire growth.

Table 5: Results of the fire scenario involving PE and PP plastic stack

	PE, 1 m^3	PP, 1 m^3
Total MLR (g s^{-1})	48	37
HRR_{max} (MW)	3.8	2.9
Time for HRR 1 MW (s)	65	90

The implementation of the pyrolysis step and combustion of pyrolizate mixture resulted in data reported in Table 5. Accordingly, the estimated maximum heat release rate was 3.8, and 2.9 MW for a stack of 1 m^3 made respectively of polyethylene and polypropylene. This value corresponds to the scenario of the developed fire scenario, during which the maximum total mass loss rate of pyrolizate is measured. We estimated a heat release rate per unit area of fire (HRRPUA) in the range 750-1500 kW m^{-2}.

A comparison of the calculated growth behaviour of PE and PP fires and that of an ultra-fast t^2-fire is given in Figure 1. The ultra-fast fire has α of 0.1876 kW s^{-2}, i.e. a growth time of about 75 s. The fire involving a stack of 1 m^3 of PE is faster, achieving a value of about 1 MW in less than 45 s. Instead, the HRR associated with a similar geometry of PP is almost comparable to the ultra-fast growth.

4. Conclusions

Although the awareness of fire scenarios in waste disposal facilities and associated consequences has recently increased, it emerges that critical open fire safety issues and challenges remain. If not handled properly in prevention and mitigation, fires involving waste materials can harm people and the environment. In fact, they usually collect and hold large quantities of wastes that may initiate or contribute to severe fire scenarios.

Understanding and managing the fire hazard and risks is crucial for effective waste disposal management and for choosing appropriate controls in a continuous process of identification of hazards, risk assessment, check of controls and implementation. In other words, operators should ensure they have adequate controls to prevent fires and, should a fire occur, minimise the risks to human health and the environment.

The application of fire safety engineering principles can be beneficial in defining proper design goals and management strategies that deal with design fire scenarios involving waste materials, including plastics. Calculation models can assist in approaching the complexity inherent in pyrolysis and combustion of waste matrixes. FDS, Fire Dynamic Simulator, was used to reproduce the fire behaviour of piles made of polyethylene and polypropylene in terms of pyrolysis and combustion of pyrolizate. The mass loss rate (MLR) was estimated, and the growth behaviour was compared to an ultra-fast t^2-fire. As high as 3.8 and 2.9 MW, heat release rates were obtained respectively for the fire of 1 m^3 of PE and PP. The HRRPUA is in the range from 750 to 1000 kW m^{-2}.

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