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SCALING UP SELF-SUSTAINED SMOULDERING OF SEWAGE SLUDGE FOR WASTE-TO-ENERGY

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1 Present address

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Abstract: Self-sustained smouldering combustion presents strong potential as a green waste-to-energy technique for a range of wastes, especially those with high moisture content like wastewater sewage sludge. While well demonstrated in laboratory experiments, there is little known about scaling up this process to larger, pilot commercial reactors. This paper addresses this knowledge gap by systematically conducting and analyzing experiments in a variety of reactors extending beyond the laboratory scale. This work reveals a robust treatment regime. However, it also identifies potential complications associated with perimeter heat losses at scale. Two key impacts, on the smouldering reactions and the air flux flow patterns, are shown to potentially degrade treatment if not properly understood and managed. Altogether, this study provides novel insight and guidance for scaling up smouldering science into practical, waste-to-energy systems.

Key words: Smoldering combustion, Local thermal non-equilibrium, Wastewater treatment, Sewage sludge, Process scale-up, Heat losses
Nomenclature

Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CEMS</td>
<td>Continuous emissions monitoring system</td>
</tr>
<tr>
<td>DRUM</td>
<td>Oil-drum sized reactor</td>
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<td>IPM</td>
<td>Inert porous media</td>
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<tr>
<td>LAB</td>
<td>Laboratory reactor</td>
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<tr>
<td>LTNE</td>
<td>Local thermal non-equilibrium</td>
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<tr>
<td>MC</td>
<td>Wet mass basis moisture content</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-dimensional time</td>
</tr>
<tr>
<td>TC</td>
<td>Thermocouple</td>
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<tr>
<td>WWTP</td>
<td>Wastewater treatment plant</td>
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Latin Letters

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<thead>
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<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$a_{sg}$</td>
<td>Specific surface area, m(^{-1})</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat capacity, J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>$d_p$</td>
<td>Particle diameter, m</td>
</tr>
<tr>
<td>$h_{sg}$</td>
<td>Interfacial heat transfer coefficient, W m(^{-2}) K(^{-1})</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity, W m(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>$\dot{m}''$</td>
<td>Mass flux, kg m(^{-2}) s(^{-1})</td>
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<tr>
<td>$\dot{\dot{m}}''$</td>
<td>Effective mass flux, kg m(^{-2}) s(^{-1})</td>
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<tr>
<td>$Nu$</td>
<td>Nusselt number, -</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number, -</td>
</tr>
<tr>
<td>$r_o$</td>
<td>Outer radius, m</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynold's number, -</td>
</tr>
<tr>
<td>$t_c$</td>
<td>Characteristic time, s</td>
</tr>
<tr>
<td>$t_{ig}$</td>
<td>Ignition time, s</td>
</tr>
<tr>
<td>$t_f$</td>
<td>Final time, s</td>
</tr>
<tr>
<td>$T_{peak}$</td>
<td>Maximum temperature, K</td>
</tr>
<tr>
<td>$T_{amb}$</td>
<td>Ambient temperature, K</td>
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<tr>
<td>$u_g$</td>
<td>Darcy flux, m s(^{-1})</td>
</tr>
<tr>
<td>$v_{oxid}$</td>
<td>Smouldering propagation velocity, m s(^{-1})</td>
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<tr>
<td>$v_{cool}$</td>
<td>Cooling velocity, m s(^{-1})</td>
</tr>
<tr>
<td>$x_c$</td>
<td>Characteristic distance, m</td>
</tr>
</tbody>
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Greek Symbols

<table>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$\delta$</td>
<td>Small dimensionless parameter, -</td>
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<tr>
<td>$\mu$</td>
<td>Dynamic viscosity, Pa·s</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Dimensionless distance, -</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density, kg m(^{-3})</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stephan Boltzmann constant, W m(^{-2}) K(^{-4})</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Dimensionless time, -</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Porosity, -</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference, K</td>
</tr>
<tr>
<td>$\Delta \theta$</td>
<td>Dimensionless difference between gas and solid temperatures, -</td>
</tr>
</tbody>
</table>
$A$  Constant, -

Subscripts
0  Initial
amb  Ambient
app  Approximate
bulk  Volume averaged
c  Characteristic
cool  Cooling
eff  Effective
f  Final
fit  Fitted
g  Gas/air
ig  Ignition
inj  Injected
r  Radial
s  Solid/sand
sf  Surface
x  Axial
1. Introduction

Smouldering combustion is emerging as a viable waste-to-energy approach (Gianfelice et al., 2019; Serrano et al., 2020; Wyn et al., 2020; Yermán, 2016). Across disciplines, smouldering is being used for environmentally beneficial purposes: to treat stockpiles of hazardous organic waste (Thomas et al., 2020; Zhao et al., 2021), clean contaminated land (Grant et al., 2016; Vidonish et al., 2016), provide off-grid solutions for sanitation challenges (Saberi et al., 2020; Somorin, 2020; Yermán, 2016), and recover resources from a variety of waste streams (Feng et al., 2020; Manelis et al., 2016; Wyn et al., 2020).

Smouldering presents especially strong potential in managing the sludge by-product from wastewater treatment plants (WWTPs), hereafter termed sewage sludge.

Sewage sludge is notoriously difficult to treat in WWTPs and its management is often responsible for more than 50% of a WWTP’s operating expenses (Spinosa and Vesilind, 2001). These high expenditures reflect the high-energy intensity of common sludge processing (e.g., thickening, dewatering, chemical treatment) and end-use techniques (e.g., incineration, land application, landfilling) (Metcalf and Eddy, 2003; Oleszkiewicz and Mavinic, 2002; Shannon et al., 2008). Currently, WWTPs are evolving to minimize their energy consumption, aiming to become net energy positive (McCarty et al., 2011; Tyagi and Lo, 2013). At the same time, WWTPs are retooling to better recover valuable resources (Harder et al., 2019; Peccia and Westerhoff, 2015). Smouldering combustion is emerging as a promising method to support both of these objectives (Torero et al., 2020; Wyn et al., 2020; Yermán, 2016).

Smouldering is a flameless form of combustion, typically observed as the red, glowing surface of charcoal in a traditional barbecue (Ohlemiller, 1985; Torero et al., 2020).
Smouldering is sustained as oxygen in the air directly reacts with the surface of a condensed phase fuel (solid or liquid) comprising or embedded within a porous medium. In most cases, smouldering is limited by oxygen diffusion from the bulk pore space to the reacting surface of the fuel (Ohlemiller, 1985; Williams, 1977). Consequently, the smouldering heat release rate is often controlled by the porous media properties and results in low temperatures and slow spread rates compared to other combustion processes (e.g., incineration) (Ohlemiller, 2008; Torero et al., 2020). These properties can lead to persistent, dangerous smouldering fires that are difficult to detect in porous solid fuels, e.g., home furniture (Rein, 2016), peatlands (Rein, 2013), coal fields (Song and Kuenzer, 2014), and stored biomass (Fernandez-Anez et al., 2020). However, smouldering may also be harnessed for engineered applications (Deng et al., 2020; Gerhard et al., 2020; Shi et al., 2017; Torero et al., 2020; Wyn et al., 2020; Yermán, 2016).

Emerging applications of smouldering use the energy embedded within otherwise problematic wastes to drive “self-sustaining” thermal treatment; that is, only a small amount of external energy is required for ignition, and then subsequent smouldering is sustained by the energy released by the exothermic reactions (Gerhard et al., 2020; Torero et al., 2020). Therefore, no external energy is required after ignition. The process is self-sustaining as long as the rate of heat released from smouldering exceeds the rate of heat lost near the reactions. To achieve these desirable “green” operating conditions, many applications mix the wastes within inert porous media, e.g., sand (Gianfelice et al., 2019; Pironi et al., 2009; Rashwan et al., 2016; Serrano et al., 2020; Yermán et al., 2015), soil (Sabadell et al., 2019; Sabadell et al., 2018; Salman et al., 2015), zirconium oxide beads (Saberi et al., 2020). These mixtures have been shown to foster self-sustaining
smouldering with high moisture content (MC, wet mass basis) wastes that are otherwise challenging to manage, e.g., > 70% MC faeces (Yermán, 2016; Yermán et al., 2015; Yermán et al., 2016), 80% MC sewage sludge (Rashwan et al., 2016), and 85% MC anaerobic digestate mixed with coco coir (fibre) (Serrano et al., 2020). There are multiple reasons to mix the fuel with inert porous media: (i) good airflow permeability can be achieved to deliver the oxidant to the reacting fuel surface and promote forward convective heat transfer, (ii) the exposed specific surface area of the fuel may be increased to promote high reactivity, and (iii) the heat evolved from smouldering may be recycled within the porous material (Pironi et al., 2009; Rashwan et al., 2016; Serrano et al., 2020; Torero et al., 2020) (much like a porous burner (Ellzey et al., 2019)), which provides a buffer against extinction and thereby improves the robustness of the smouldering system (Torero et al., 2020; Zanoni et al., 2019a, b).

The smouldering front, which propagates through space with a measurable velocity, is comprised of a series of zones, each of which are characterized by dominant physical and chemical processes (Fig. 1). When smouldering propagates in the direction of air flow (i.e., forward smouldering (Ohlemiller and Lucca, 1983; Williams, 1977)) the zones common to many smouldering systems are the: inert heating zone, reaction zone, and cooling zone. The inert heating zone is reactionless and characterized by endothermic physical processes like fuel preheating and phase changes (e.g., water boiling/evaporation). Exothermic reactions (primarily fuel oxidation) and endothermic reactions (primarily pyrolysis) compete within the reaction zone (Hadden et al., 2013; Zanoni et al., 2020a), though pyrolysis generally progresses ahead of oxidation in forward smouldering (Moussa et al., 1977; Williams, 1977). In most smouldering applications, the
reaction zone is quite thin, \([0 \text{ (0.001-0.01 m})]\) (Baud et al., 2015; Martins et al., 2010; Pozzobon et al., 2017; Zanoni et al., 2019a). Like the inert heating zone, the cooling zone is also reactionless and is characterized by convective cooling and perimeter heat losses to the environment. This is because most smouldering applications consume all fuel within the reaction zone and drive *fuel-limited propagation* (Fatehi and Kaviany, 1994; Rashwan, 2020; Torero et al., 2020). Heat transfer within the cooling zone fundamentally results from the exchange between the hot porous media and incoming cool air (i.e., local thermal non-equilibrium, LTNE) (Rashwan et al., 2021b; Zanoni et al., 2017, 2019c). In most smouldering applications using inert porous media, the cooling zone grows throughout propagation as much of the energy released from smouldering is stored here (Rashwan et al., 2021b; Zanoni et al., 2019a, b). Therefore, the cooling zone is much larger than the reaction zone \([> 0 \text{(0.1 m})]\) and highly susceptible to perimeter heat losses (Rashwan et al., 2021b). All three zones evolve with time, and therefore lead to a highly dynamic system (Torero et al., 2020).

Engineers are scaling up applied smouldering systems out of the laboratory to solve challenging environmental problems, primarily for land remediation and hazardous waste management (e.g., (Gerhard et al., 2020; Sabadell et al., 2019; Sabadell et al., 2018; Scholes et al., 2015; Solinger et al., 2020; Thomas et al., 2020)). However, like all novel technologies, there are new, previously unforeseen phenomena that emerge through scaling up. Though smouldering high MC biomass wastes like WWTP sewage sludge has shown strong promise in laboratory studies (e.g., (Feng et al., 2020; Rashwan et al., 2016; Serrano et al., 2020; Yermán et al., 2015)), only one study has smouldered these wastes in larger, prototype-sized reactors (Feng et al., 2021). These high MC wastes can
foster a weaker form of smouldering than most remediation or hazardous applications because of the large water fractions and lower calorific values (Torero et al., 2020). Therefore, smouldering systems for these high MC wastes need to be designed to operate robustly to avoid localized extinction that can negatively impact treatment success (Zanoni et al., 2019a, b, 2020b).

As the lateral length scale of the smouldering reactor increases, the influence of the perimeter heat losses on the global (i.e., whole system) energy balance decreases. Indeed, for smouldering granular activated carbon mixed in sand, the system energy efficiency increased from 65 ± 3% to 86 ± 5% when increasing reactor radius from 0.08 m to 0.3 m because of the improved heat retention (Rashwan et al., 2021b, c). This suggests that larger reactors may be ideal for encouraging more robust self-sustained smouldering conditions.

However, perimeter heat losses may also negatively influence the smouldering front by changing the distribution of air flux (i.e., temperature gradients in the cooling zone can lead to non-uniform air flux) (Rashwan et al., 2021a) and/or form an unreacted crust near the wall (i.e., temperature gradients in the reaction zone can lead to non-uniform reactions) (Pironi et al., 2009; Rashwan et al., 2021a; Zanoni et al., 2020b). These potential negative effects – and the balance between the positive and negative effects at scale – are not well understood. Prototype-sized experimental studies are therefore necessary to clarify how these effects may emerge and impact larger smouldering systems, particularly for high MC wastes like sewage sludge.

This study explores use of self-sustained smouldering for treating sewage sludge in large reactors beyond typical laboratory sizes towards more practical scales. A main objective
of this study is to integrate, synthesize, compare, and obtain trends and conclusions from a wide range of experiments with different conditions. In doing so, a robust treatment regime was identified. However, new challenges were uncovered that can occur due to perimeter heat losses. By combining detailed experimental analysis and analytical modelling, the potential for such heat losses to cause non-uniform air flux and non-uniform reactions in certain systems, and thereby impair overall performance, were demonstrated. This new understanding now provides insights that are critical to scaling up towards successful commercial applications. Altogether, this study provides new guidance for commercial scale waste-to-energy smouldering systems so that they can operate robustly for a wider range of wastes.
2. Methodology

20 forward smouldering experiments were conducted following published smouldering methods, including using a constant injected air flux in highly instrumented reactors (Table 1). While these experiments used varying methodologies (e.g., ignition procedures) over a wide range of operational conditions, the results targeted are quite general and unaffected by these methodology differences. Moreover, all experiments were self-sustaining and experienced good smouldering through the centre of the column; though, all high MC (> 70%) DRUM experiments exhibited slow smouldering velocities due to channelling around the unburned crust near the reactor wall (noted in Table 1 and explored in detail in Section 3). The reactors were either 0.08 m radius (LAB) or 0.3 m in radius (DRUM). These experiments included continuous measurement of axial and radial temperatures, mass loss, and emissions (CO, CO₂, and O₂). The instrumentation for every experiment is detailed in the Supplementary Materials, Section S.1. The fixed beds comprised of sewage sludge mechanically mixed with coarse grain sand lightly packed into the reactors. The dry fuel/sand fractions varied between 36 – 60 g dry fuel kg⁻¹sand in all experiments, which is a consistent range with similar studies (e.g., (Feng et al., 2021; Rashwan et al., 2016; Yermán et al., 2015)). After ignition at the base of the reactor, the heater was turned off and all experiments supported self-sustained smouldering propagation. All high MC experiments (> 70% MC) used virgin sludge directly from the WWTP. All low MC experiments (< 70% MC) dried the sludge to the desired MC and were used to better understand the sensitivity to MC. Additional details on the established experimental methods are available in (Pironi et al., 2011; Pironi et al., 2009; Rashwan et al., 2016; Rashwan et al., 2021a; Switzer et al., 2009; Switzer et al.,
and the experimental setups, sewage sludge properties, and methodologies used are further detailed in the Supplementary Materials, Section S.1.

Table 1 summarizes key experimental conditions and results. The experiments used varying fuel fractions, moisture content, and air fluxes, and therefore fostered a broad spectrum of robustness behaviour. The methodology from (Rashwan et al., 2021a) was used to analyze the heat transfer within the cooling zone affected by non-uniform air flux, where a summary of that methodology is included in the Supplementary Materials, Section S.2. Section S.2 also identifies the characteristic heat transfer time scales, which are discussed later in Section 3.2.
3. Results and discussion

3.1. Experimental results highlighting the effects of perimeter heat losses on applied smouldering performance

Figure 2 presents the centreline and wall temperature histories from DRUM S7. The centreline results show characteristic smouldering temperatures that indicate the reaction is self-sustaining there (Rashwan et al., 2016; Torero et al., 2020; Yermán et al., 2015). Conversely, the wall temperatures show smouldering did not occur there as the temperatures were well below 200°C. This behaviour was characteristic of all sewage sludge DRUM experiments with ≥ 72% MC at the same air flux (i.e., DRUM S6-S9, see the Supplementary Materials, Figs. S.5 and S.8).

Figure 3 presents the centreline temperature histories from DRUM S9 and S10, which decreased the sand dilution by increasing the fuel concentration to 222 from 153 g\text{fuel kg}\text{-1 sand} used in DRUM S7 (see Table 1). Like Fig. 2(a), the centreline results in Fig. 3 show characteristic smouldering temperatures that indicate the reaction was self-sustaining. However, by decreasing the sand dilution, DRUM S9 and S10 became more sensitive to non-uniform air flux. This sensitivity to sand dilution is observed in multiple applied smouldering studies and is a combination of factors affecting the local energy balance near the smouldering reactions (e.g., surface area for combustion, local air velocities) and global energy balance around the whole system (e.g., physical integrity of the mixture, heat and mass transfer surrounding combustion) (Gianfelice et al., 2019; Rashwan et al., 2016; Serrano et al., 2020; Torero et al., 2020; Yermán et al., 2015).
Figure 3 shows severe air channeling in both DRUM S9 and S10; this is observed by centreline TCs in the air above the fuel bed (i.e., TCs 8-11 at 0.6-0.9 m) heating before the front reached the top of the fuel bed (just above TC 5 at 0.5 m). This shows that hot air short-circuited the smouldering region in the centre of the reactor, flowing instead near the wall. Air channelling was most pronounced in DRUM S9 and S10; only minor air channeling was observed in DRUM S4-S8 (Figs. 2 and S.5). Moreover, air channelling was more severe in DRUM S10 (Fig. 3(b)) than in DRUM S9 (Fig. 3(a)), as the hot air exited the reactor approximately 150 and 75 minutes before the smouldering front reached 0.5 m, respectively.

However, unlike DRUM S6-S9, DRUM S10 experienced combustion near the walls and exhibited a thinner crust formation (see the Supplementary Materials, Fig. S.9). This thin crust resulted because the effect of non-uniform reactions was minimized in DRUM S10 with the high applied air flux (which supported sufficiently robust smouldering near the wall to resist extinction), but the effect of non-uniform air flux was maximized. Therefore, even though DRUM S10 experienced more robust combustion near the walls, the temperatures near the walls were still cooler than the centre because of perimeter heat losses in the cooling zone. This lateral temperature difference and high air flux facilitated more severe non-uniform air flux that caused a highly distorted smouldering front (further discussed below in Section 3.2). Therefore, air channeling in DRUM S10 primarily occurred after the highly distorted smouldering front reached the top of fuel bed near the wall ~40 min after turning off the heater (~150 min in Fig. 3, when the air temperatures above the fuel bed, TCs 8-11, began to rise). See an expanded discussion on DRUM S10 in the Supplementary Materials, Figs. S.9 and S.10.
Figure 4 collects the centreline temperatures behind the smouldering front (i.e., in the cooling zone, Fig. 1) measured near the end of propagation (when the last TC in the fuel bed peaked) from select DRUM experiments with relatively short ignition periods. The following analysis targets the key evidence that most clearly shows the presence of non-uniform air flux in the reaction-less cooling zone, following the methodology developed by Rashwan et al. (2021a) (see extra details in the Supplementary Materials, Section S.2).

The experimental results in Fig. 4 are compared to modelled curves using Eqs. (S.11-S.13) with the values from Tables 1 and S.1. Figure 4 shows the results from two modelled curves per experiment that used either (i) the injected air flux ($\bar{m}_{g,\text{inj}}''$), which assumed non-uniform air flux did not occur, and (ii) the fitted effective air flux ($\bar{m}_{g,\text{fit}}''$), which assumed non-uniform air flux did occur. The $\bar{m}_{g,\text{fit}}''$ fitting minimized the difference between the modelled curve (ii) and experimental data at the beginning of the cooling front from 0 to 0.1 m in DRUM S5-S9 and 0 to 0.2 m in DRUM S10 (because the cooling front travelled further in DRUM S10 with the higher applied air flux, see Table 1).

Figure 4 shows that flow divergences due to non-uniform air flux lowered the effective axial convection along the reactor centreline. This is because the centreline was the hottest region in the reactor and had the greatest resistance to flow (with the highest air densities and lowest air viscosities) (Lutsenko, 2018; Rashwan et al., 2021a; Zanoni et al., 2021). This is shown by comparing the black and grey curves in Fig. 4, which show the effective axial mass fluxes were less than the applied air fluxes in all frames. Furthermore, the $\bar{m}_{g,\text{fit}}''/\bar{m}_{g,\text{inj}}''$ values in Fig. 4 show that cooling in DRUM S5-S9 was similarly impacted by non-uniform air flux as all values are between 0.462-0.565. These
results align with the findings from Rashwan et al. (2021a), who showed a similar degree of non-uniform air flux in experiments with sand and granular activated carbon in the same DRUM experimental setup and similar applied air fluxes. However, DRUM S10 exhibited the slowest cooling along the centreline with a very high applied air flux, resulting in \( \dot{m}_{g,fit}/\dot{m}_{g,inj} = 0.270 \) (which aligns with the discussion around Fig. 3 and below in Section 3.2). Furthermore, the grey line in Fig. 4(f) shows that, by assuming \( \dot{m}_{g,inj}'' \), cooling along the centreline was so fast that the whole domain was predicted to cool to ambient temperatures by the end of propagation. This comparison is the strongest contrast in Fig. 4, as the observed cooling shown in the data points in Fig. 4(f) was much slower. Altogether, Fig. 4 visualizes the effects of non-uniform air flux on the cooling zone, which impacted all experiments compared (DRUM S5-S10). However, the extent of flow non-uniformity was sensitive to the applied air flux, as it was highest in DRUM S10 with the highest applied air flux.

Figure 5 collects the mean centreline smouldering velocities from all sewage sludge experiments with an injected air flux less than 10 cm s\(^{-1}\) and highlights their key trends within the context of other applied smouldering results. Like many other studies (e.g., (Baud et al., 2015; Pironi et al., 2009; Rein, 2016; Switzer et al., 2014; Yermán et al., 2015; Yermán et al., 2016; Yermán et al., 2017; Zanoni et al., 2019a)), Fig. 5 shows the linear relationship between \( \nu_{oxid} \) and injected air flux, which signals that increased air flow increased forward heat transfer and oxygen supply and promoted faster smouldering propagation. As seen in Fig. 5, the propagation velocity in all DRUM experiments with sewage sludge were characteristically lower than all other examples. The reasons governing this behaviour are discussed below.
Robust smouldering velocities from experiments mixing coarse grain sand with: (i) sewage sludge in the LAB reactor (by Rashwan et al. (2016) and new experiments detailed in Table 1), (ii) coal tar in multiple sized reactors by Switzer et al. (2014), and (iii) granular activated carbon in the LAB reactor by Duchesne et al. (2020) all illustrate the harmonized behaviour of robust smouldering under a range of experimental conditions (e.g., fuel type, fuel concentrations, fuel MC, reactor size/type, ignition procedure). These robust experiments scatter around the linear best fit line from (Rashwan et al., 2016) and indicate similar, approximately one-dimensional, fuel-limited smouldering propagation (Torero et al., 2020). In other words, the injected air flux governed the smouldering propagation velocity under these robust conditions.

Weak smouldering velocities are also highlighted in Fig. 5, which scatter around the linear best line from (Rashwan et al., 2016). The smouldering velocities in LAB experiments were lowered as water boiling/evaporation interacted with the reaction zone, either due high MC (i.e., 79%) sewage sludge (Rashwan et al., 2016) or because of poor mixing (LAB S5(2)). In both cases, smouldering robustness decreased from a diminished local energy balance. This is because high MC fuel did not dry completely ahead of smouldering and poorly mixed wet fuel/sand had: (i) a lower surface area available for smouldering and (ii) a slower drying rate due to more water being bound in large, unmixed fuel particles, which also may have not completely dried ahead of smouldering (see a picture of the LAB S5(2) mixture and discussion in the Supplementary Materials, Fig. S.4). Therefore, both high MC fuel and poorly mixed wet fuel/sand are expected to decrease smouldering robustness by dropping the effective heat of smouldering, resulting in lower peak temperatures and propagation velocities (Rashwan et al., 2016). If either effect is
sufficiently severe, extinction will occur. Yermán et al. (2017) provides detailed discussion and results on this type of transition to non-robust smouldering due to increasing MC, which aligns with many other experimental studies (e.g., (Rashwan et al., 2016; Serrano et al., 2020; Wyn et al., 2020; Yermán et al., 2015; Yermán et al., 2016)).

Most importantly, Fig. 5 shows the smouldering velocities in all DRUM sewage sludge experiments were characteristically slow (roughly 50% of robust smouldering at the same injected air flux). These results align with the findings from Feng et al. (2021). Unlike the cooling characteristics in Fig. 4, Fig. 5 shows the unburned crust had a strong impact on the smouldering velocities. These slow velocities in experiments using high MC sewage sludge (> 70% in DRUM S1-S3 and S6-S9) are hypothesized because air channelled through the unburned crust (formed from non-uniform reactions, seen in the photos in Fig. 5). The crust was roughly 0.01-0.1 m thick and contained ~1-6% of the smoulderable sludge mass. This shows the combination of non-uniform air flux and non-uniform reactions severely slowing smouldering propagation. This phenomenon is similar to differences in permeabilities leading to airflow distortions and air channelling in other combustion systems using porous media (e.g., (Glazov et al., 2017; Solinger et al., 2020; Taira, 2020; Wang et al., 2021)). However, the air channelling here is expected to be driven by differences in air thermophysical properties. This is hypothesized because some LAB experiments experienced a similar crust formation as those seen in the DRUM experiments in Fig. 5, but did not experience the same severe drop in propagation velocities as the DRUM experiments (examples are shown in the Supplementary Materials, Fig. S.3 and discussed in Section S.3).
As seen in the photos from Fig. 5, the low MC DRUM experiments (i.e., DRUM S4 and S5 with 3.2% and 40% MC, respectively) did not develop a significant crust like in the high MC DRUM experiments (i.e., ≥72% MC in DRUM S6-S9). As the sewage sludge MC increased in the DRUM experiments, the resulting velocities significantly decreased below the weak smouldering velocities from (Rashwan et al., 2016) (highlighted on Fig. 5 with the downward arrow showing the transition from the low MC experiments [DRUM S4 and S5] to high MC experiments [DRUM S6-S9]). These lower velocities in the DRUM experiments also coincided with decreased centreline peak temperatures and heating rates, which did not occur in the LAB experiments at the same experimental conditions (Supplementary Materials, Figs. S.6 and S.7). Therefore, these results show the smouldering robustness of DRUM experiments were more susceptible than the LAB experiments to the channelling from non-uniform reactions and non-uniform air flux. The other high MC DRUM experiments in Fig. 5 (DRUM S1-S3) show the persistence of channelling at low injected air fluxes (< 5 cm s⁻¹).

From another perspective, the effect of air channelling on smouldering controllability is highlighted in the non-dimensional mass loss rates in Fig. 6 from select experiments with minimal initial experimental effects and physical perturbations. The mass was made non-dimensional with the combustible mass in the system and the time was made non-dimensional with the ignition time (identified from the inflection in the mass loss curve) and end of propagation time assuming robust propagation (identified from dividing the pack height by the expected robust smouldering velocity empirical equation from (Rashwan et al., 2016) at the applied air flux). See additional details on this methodology in the Supplementary Materials, Section S.4.
Figure 6 isolates the consequence of non-uniform air flux on mass loss behaviour. No mass loss curve in Fig. 6 extends completely to -1, as some sewage sludge remained unburned along the edges in all experiments (common to many smouldering systems, e.g., (Pironi, 2009; Pironi et al., 2009; Rashwan, 2015; Zanoni et al., 2020b)). However, Fig. 6 shows that LAB S7 and S8 were least affected by non-uniform air flux and air channelling as ~96% and ~95% of the mass was lost steadily from the reactor, respectively, as the smouldering front propagated nearly uniformly up the reactor and concluded abruptly near non-dimensional time (NDT) = 1 (where the minimum masses in LAB S7 and S8 are plotted at NDT = 1.2 and 1.4, respectively). This aligns with their robust smouldering behaviour observed in Fig. 5. However, DRUM S9 and S10 were both strongly affected by non-uniform air flux, as their mass loss curves plateaued far beyond NDT = 1 (i.e., their minimum masses were reached at NDT = 4.6 and 7.4, respectively). In the context of applied smouldering, these tailing mass loss curves represent a process inefficiency, as it lengthens the overall processing time. Agreeing with the hot air breakthroughs observed in Fig. 3, this inefficiency grew the most in DRUM S10, which took the longest to finish propagating relative to its applied air flux.

3.2. The fundamental drivers of non-uniform air flux: A hypothesis to harmonize results

Figures 2-6 highlight the complicated behaviour observed in the DRUM experiments due to perimeter heat losses, which is hypothesized to have resulted from the combined effects of non-uniform air flux and non-uniform reactions. These interacting phenomena are shown in Fig. 7, which summarizes new insights from the experiments presented in this manuscript. The problem is simplified in Fig. 7, as radial flow vectors in the cooling
zone will ultimately lead to non-uniform air flux in the cooling zone (Lutsenko, 2018; Rashwan, 2020; Rashwan et al., 2021a). Figure 7 shows the key impact of non-uniform air flux on the axial component of the air vectors driving concave front distortions on both the smouldering and cooling fronts when the system is: adiabatic (Fig. 7(a)), non-adiabatic and affected by non-uniform air flux but minimally affected by non-uniform reactions – as robust smouldering occurs across the whole cross section (Fig. 7(b)), and affected by both non-uniform reactions and non-uniform air flux (Fig. 7(c)). As described above, non-uniform reactions may lead to the formation of an unburned crust near the reactor walls (Fig. 7(c)). These unburned sections effectively reduce the net energy generated at the smouldering front. Moreover, these unburned edges may be much cooler than the smouldered region (as seen in Fig. 2) and provide a preferential conduit for air flow. Therefore, the effect of non-uniform air flux may be exacerbated and lead to air channelling through the unreactive crust, which will reduce the air flux into the reaction zone driving smouldering in Fig. 7. In other words, air bypasses smouldering reactions entirely along the cooler, unreactive regions near the wall in Fig. 7(c). However, non-uniform air flux still outcompetes non-uniform reactions within the smouldering region and drives a concave distortion in the centre of the reactor (which aligns with observations and theory from Rashwan et al. (2021a) and experiments here using multi-point TCs that are discussed in the Supplementary Materials, Fig. S.2). Altogether, these unburned edges can reduce the oxygen supply to the reaction zone, inhibit forward heat transfer, and lower the net energy generated at the front. Figure 7(c) shows decreased smouldering robustness, which will manifest as slower smouldering velocities (as seen in
Fig. 5), lower peak temperatures and heating rates (as seen in Figs. S.6 and S.7), and in critical cases lead to non-self-sustaining smouldering.

Figures 5 and 6 show that the effects of non-uniform air flux driving air channelling were more severe in the DRUM experiments than the LAB experiments (though both showed crust formations from non-uniform reactions). Therefore, the extra sensitivity observed in the DRUM experiments is hypothesized to result from scale-related differences in the radial and axial heat transfer. In other words, the radial temperature differences in the cooling zone, which led to non-uniform air flux and air channelling, persisted longer in the DRUM than LAB experiments. This is because radial temperature differences in the cooling zone, and associated air thermophysical differences, dissipate primarily from radial diffusion out of the reactor (Pozzobon et al., 2017; Rashwan et al., 2021b). As the reactor radius increased, so did the characteristic radial heat transfer time

\[ t_{c,r} = \left( \rho C_p \right)_{bulk} \frac{r_o^2}{k_{bulk}}. \]

However, the characteristic bulk axial heat transfer time

\[ t_{c,x} = \left( \rho C_p \right)_{bulk} \frac{k_{bulk}}{\left( \dot{m}_{g,inj}'' C_{pg} \right)^2} \]

was unaffected by reactor radius (see Eqs. (S.8) and (S.10), where the injected mass flux, \( \dot{m}_{g,inj}'' \), governs bulk axial heat transfer). It is hypothesized that the degree of non-uniform air flux scales qualitatively with the ratio of these time scales, i.e., non-uniform air flux increases with \( t_{c,r}/t_{c,x} = \left( \frac{r_o \dot{m}_{g,inj}'' C_{pg}}{k_{bulk}} \right)^2 \).

This ratio appears to explain many of the results reported in this work and the results from Rashwan et al. (2021a). This includes the differences observed between the LAB and DRUM experiments’ smouldering velocities, and the increasing severity of non-uniform air flux from DRUM S9 to S10 also qualitatively scales with \( t_{c,r}/t_{c,x} \), as \( t_{c,r}/t_{c,x} \) also
increases with applied air flux. Therefore, the high injected air flux in DRUM S10 led to a large $t_{c,r}/t_{c,x}$, which drove an extremely distorted smouldering front, like in Fig. 7(b).

While there have so far been few efforts to minimize or even understand the challenges associated with lateral heat losses on applied smouldering systems, the hypothesis above provides some novel insight in overcoming these challenges. That is, because lateral temperature differences in the cooling zone led to flow divergences and channelling through the unreacted crust, it would be best to dissipate these temperatures quickly throughout the cooling zone by minimizing $t_{c,r}/t_{c,x}$. However, the full complexity of this problem is not yet understood; therefore, a multi-dimensional numerical model would be highly beneficial towards understanding the interactions between non-uniform reactions and non-uniform air flux. Here, novel experimental evidence, analyses, and hypotheses are provided to guide that future work.
4. Conclusions

Though applied smouldering has been shown to be a viable waste-to-energy strategy for high moisture content wastes like wastewater sewage sludge, nearly all research has focused on laboratory experiments. However, the systems needed to manage these wastes will need to be much larger. This study addressed this knowledge gap by conducting a series of sewage sludge smouldering experiments in oil-drum sized reactors. Though smouldering reactors with increased footprints benefit from improved heat retention, they can suffer from other challenges due to the combined impacts of non-uniform air flux and non-uniform reactions, both from perimeter heat losses. These challenges were studied in detail across a wide range of experimental conditions and the new understanding provides insights to overcome them. Altogether, this study provides novel guidance towards designing future waste-to-energy smouldering systems that can operate robustly using a wider range of wastes.

Heat losses within the cooling zone was shown to lead to non-uniform air flux (observed as slow cooling along the reactor centreline) and heat loses within the reaction zone led to non-uniform reactions (observed as a significant crust formation in high MC experiments). The combination of these two phenomena lead to a problematic scenario, as air channelled through the cooler unburned sections and reduced both (i) the forward heat transfer in the smouldering region and (ii) the oxygen supply to the reaction zone. As a result, smouldering systems most impacted by the combination of these two phenomena resulted in less robust smouldering with cooler peak temperatures, lower heating rates, slower propagation velocities, and reduced controllability. Moreover, increased air flux exacerbated this problem, as the smouldering front became highly
distorted and facilitated severe air channeling without a significant crust formation. Non-uniform air flux, leading to air channelling, was hypothesized to roughly scale with the ratio of the characteristic radial and axial heat transfer times. In qualitative agreement with this hypothesis, channelling was shown most severe in sewage sludge experiments in the large (oil-drum sized) reactor with high air flux.

Though simplified analyses have been used here to highlight the effect of perimeter heat losses on smouldering sewage sludge, the full complexity of this problem has not been resolved. A multi-dimensional numerical model would therefore be highly valuable in better understanding the interactions between non-uniform reactions and non-uniform air flux to confidently predict smouldering performance at a commercial scale. Here, unique experimental evidence (especially beyond the laboratory scale) and integrated analyses are provided to inform that future work.
5. Acknowledgements

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6. References


Fig. 1. The characteristic temperature profile in a forward smouldering system, highlighting the 3 key zones: Inert Heating Zone, Reaction Zone, and Cooling Zone. The smouldering and cooling velocities ($v_{cool}$ and $v_{oxid}$, respectively) approximately bound these zones and the $|dT/dx|$ profiles (dashed grey lines) highlight the temperature changes at ends of the smouldering temperature profile. Like in most applied smouldering systems, the fuel is completely consumed in the reaction zone; therefore, only ash and inert porous media (IPM) remain in the cooling zone. Example photos show (a) sewage sludge and sand mixture (DRUM S6) (b) remaining sand and ash (DRUM S7).
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<th>Experimental Conditions</th>
<th>Smouldering Results</th>
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<td><strong>Experimental Conditions</strong></td>
<td><strong>Smouldering Results</strong></td>
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<tr>
<td><strong>1</strong> Experiment</td>
<td><strong>2 Fuel/Sand [g fuel kg⁻¹]</strong>&lt;br&gt;LAB ± 0.3%&lt;br&gt;DRUM ± 2%&lt;br&gt;<strong>MC ± 0.1%</strong>, <strong>ash ± 0.1%</strong></td>
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Experimental Conditions’ errors are estimates of experimental equipment error. Smouldering Front Results’ errors estimate experimental variability as the normalized standard deviations from three DRUM and LAB repeat experiments. These errors align with similar experimental studies (Duchesne et al., 2020; Kinsman et al., 2017; Rashwan et al., 2016; Salman et al., 2015; Wang et al., 2021; Zanoni et al., 2019c).

1 The results represent averages after the heater was turned off to avoid capturing initial effects (when the front was ≥ 0.1 m from the heater) until the last TC in the fuel bed peaked (which approximately indicated the end of propagation, when the smouldering front was ≥ 0.01 m from the end of the fuel bed).

2 The total fuel mass to sand is presented, though the MC% and ash% (EPA Method 1684) varied between each sewage sludge experiment.

3 At standard temperature and pressure (21.1°C at 1 atm).

4 The percentages represent vol.% values.

5 Briefly turned off the air to collect grab samples, so the time-averaged air flux is presented; DRUM S3 used a manual rotameter to control low air flow (0-0.010 m³ s⁻¹, King Instrument Company).

6 The median propagation velocity is presented, as it is most representative of overall propagation in this experiment due to abnormal centreline behaviour.

7 Mass balance results were spurious because the instrumentation caused erratic physical vibrations.

8 Weak smouldering resulted from mixture heterogeneity due to poor mixing to investigate the sensitivity to mixture quality.

9 The centreline results were approximated from TCs that were 0.003 m offset from the centre.

10 The propagation velocity was estimated with centreline and half-radius TCs and captured minor ignition effects.

a The ash content was not measured.

b CEMS-DRUM/LAB was not operational.
Fig. 2: The (a) centreline and (b) wall temperature histories from DRUM S7. Note that $P_{1_{\text{air}}}$ and $P_{2_{\text{air}}}$ indicate plenum temperatures from the thermocouples (TCs) in the air space below the fuel bed, see Fig. S.1.
Fig. 3: Centreline temperature histories from (a) DRUM S9 and (b) DRUM S10 with similar MC and fuel concentrations and air fluxes of 5.0 and 15 cm s\(^{-1}\), respectively (further detailed in Table 1). The legend is common to (a) and (b) and the onset of hot air channelling out of the reactor is approximately noted by stars and the thermocouples (TCs) in the air above the fuel bed are bolded. Note that P\(_{1\text{air}}\) and P\(_{2\text{air}}\) indicate plenum temperatures from the thermocouples (TCs) in the air space below the fuel bed, see Fig. S.1.
Fig. 4. Centreline temperature data from (a-f) DRUM S5-S10, respectively, showing axial cooling behind the smouldering front at the end of propagation compared to the modelled sand and air temperatures from Eqs. (S.11- S.13) using either the fitted air flux ($\bar{m}_g^{''\text{fit}}$, black) or the injected air flux ($\bar{m}_g^{''\text{inj}}$, grey). The modelled temperatures consider the cooling time after the heater was turned off, which modelled the cooling after (a) 4 366 s, (b) 8 824 s, (c) 8 881 s, (d) 9 717 s, (e) 14 180 s, and (f) 12 578 s. The numbers beside the frame letter indicate $\bar{m}_g^{''\text{fit}}/\bar{m}_g^{''\text{inj}}$. The plenum air temperature measured 0.05 m below the fuel bed was used as the 0 m temperature (see the experimental setup in Fig S.1).
Fig. 5: Smouldering velocity as a function of air flux in various smouldering systems using a range of fuels mixed with coarse grain sand. The error bars represent the 95% confidence interval from three repeats from (Rashwan et al., 2016). The numbered pictures show the unburned crust after excavating select sewage sludge experiments (DRUM S4-S9) and the numbers and percentages near the markers note the sewage sludge experiment number and sewage sludge moisture content (MC), respectively, where the bolded labels indicate DRUM experiments. The downward arrow highlights the decreased velocity with increased MC in the DRUM experiments. All experimental conditions are detailed in Table 1 (adapted from (Solinger, 2016)).
Fig. 6: Comparing non-dimensional mass loss curves between LAB S7, LAB S8, DRUM S9, and DRUM S10 sewage sludge experiments.
Fig. 7. Conceptual model of the smouldering front shape: (a) flat without perimeter heat losses, (b) concaved because of non-uniform air flux, and (c) concaved because of non-uniform air flux but also slower and cooler because of air channelling through unburned sections near the wall because of non-uniform reactions. The approximate cooling front distortions are shown in blue below the smouldering front. The (i) Inert Heating Zone, (ii) Reaction Zone, and (iii) Cooling Zone are highlighted. Common pressure and temperature results are highlighted from constant air mass flux smouldering experiments.