Small-Scale Experiments of In-Situ Smouldering Combustion for the Remediation of Contaminated Land

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Abstract

In situ remediation by smouldering combustion is an innovative approach that has significant potential for sites contaminated with organic compounds. Many common industrial are flammable and contain substantial energy, releasing significant amounts of heat when oxidizes. Combustion of an organic phase contained within a porous medium involves an exothermic reaction, during which heat is transmitted from the burning to the pore space and the solid matrix. Contaminant destruction in such applications is dominated by smouldering (as opposed to flaming) combustion. Smouldering experiments have been conducted in a small beaker for fifteen different fuels (Coal tar, Vegetable oil, Explosive, grease, TCE, Dodecane, Peat, Oil Sands) with different inert. The results are upscale using a new non-dimensional number (smouldering propagation potential, S) which characterizes well the smouldering behaviour of all different fuels. Proof-of-concept research has been conducted at the small scale, with the initial results indicating that in situ smouldering remediation is viable across a considerable range of porous media types, contaminants, and subsurface conditions. Further experiments are being conducted at bench- and field- scales.

1 In-situ Smouldering

Common examples of smouldering combustion are the initiation of fires on upholstered furniture by weak heat sources (*e.g.* a cigarette, a short-circuited wire) [1], and the persistent combustion of biomass behind the flaming front of wildland fires. The characteristics of smouldering fires make them a threat taking the form of colossal underground fires or silent fire safety risks.

However, smouldering combustion has also a few beneficial applications, like in wildland fire management, the recycling of tires and in-situ combustion oil extraction [2]. We report here a new technological application of smouldering to be added to this list: smouldering combustion as a novel remediation technology for contaminated land.

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In situ remediation by smouldering combustion is an innovative approach that has significant potential for sites contaminated with nonaqueous (liquid, solid, or gaseous) phase organic compounds. Many common industrial pollutants (*e.g.*, liquids: solvents, coal tar, petrochemicals; solids: coal gasification purifier waste, residual explosives) are flammable and contain substantial energy, releasing significant amounts of heat when burned.

Combustion of an organic phase contained within a porous medium involves an exothermic reaction, during which heat is transmitted from the burning fuel (*e.g.*, nonaqueous phase liquid (NAPL)) to the pore space and the solid matrix. Often, the presence of a porous media matrix benefits combustion by storing and recirculating energy, resulting in an efficient, self-sustaining process for conditions that otherwise lead to extinction. Applications of NAPL combustion for ex situ incineration and enhanced oil recovery indicate significant potential, but the concept has yet to be applied in the context of subsurface remediation. Contaminant destruction in such applications is dominated by smouldering (as opposed to flaming) combustion (*e.g.*, a burning cigarette); very little research exists on the smouldering combustion of liquids.

3 Small Scale Experimental Results

The smouldering experiments have been conducted in a small beaker of 10 cm diameter and 15 cm high. The ignition was induced using an electrical coil as a heat source. Forced air flow was approximately 20 mL/min. Different fuels have been tested (Coal tar, Vegetable oil, Explosive, grease, TCE, Dodecane, Peat, Oil Sands) with different inert media (course and fine sands) and mixtures of the fuels. Fifteen successful ignitions were obtained. Fig. 1 shows a successful smouldering ignition in the beaker and the comparison of pre- and post-combustion soils. Fig 2 shows the thermocouple traces of one experiment with coal tar (and the comparison with an inert experiment with the same conditions).

Figure 1. (Left): .(Right top) Fine and coarse sands contaminated with coal tar; (Right middle) remediated fine and coarse sands from within smouldering zone; and (Right bottom) resulting fine and coarse samples from outside smouldering zone.
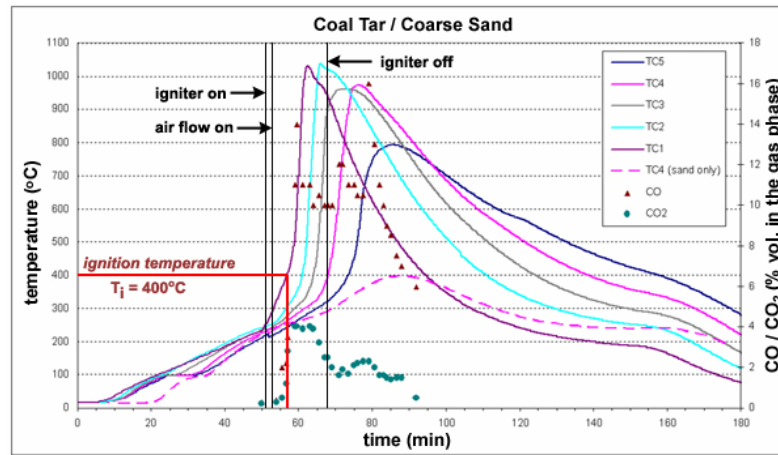
Figure 2. Temperature and CO/CO$_2$ profiles of in situ smouldering combustion of coal tar in coarse sand. TC4 dashed line is the temperature trace for the same experiment but without coal tar.

3 Scaling Analysis

Pirano et al. 2006 [3] suggested than a new non-dimensional number called the smouldering propagation potential (S) can be used to analyze the effect of scaling the sample size (D). This suggestion is developed further in this work and applied to the new experimental results. A simple energy balance at the smouldering front allows to resolve for the heat released and the heat lost. The smouldering propagation potential (S) is dictated by the heat losses through the periphery and the smouldering properties. Mathematical expressed this is:

$$S = \frac{\dot{Q}_{net}}{\dot{Q}_{total}} = \frac{\dot{Q}_{total} - \dot{Q}_{loss}}{\dot{Q}_{total}} = \frac{\pi/4\, D^2 \rho c \left(T_{max} - T_{ig}\right) - 2\pi D h \left(T_{max} - T_0\right)}{\pi/4\, D^2 \rho c \left(T_{max} - T_{ig}\right)} = \left(1 - \frac{h}{\rho c D}\frac{\left(T_{max} - T_0\right)}{\left(T_{max} - T_{ig}\right)}\right) \quad (1)$$

Thus, it is expected that as the size of the sample increases, the smouldering propagation potential increases. This means that the smouldering intensity observed in our small-scale experiments will be greater at a real site. Also, there exist a critical size below which smouldering is not possible (S=0). In the experiments, the smouldering potential can be calculated making used of an experimental parameter β as:

$$S = \left(1 - \frac{\beta_{exp}}{D}\frac{\left(T_{max} - T_0\right)}{\left(T_{max} - T_{ig}\right)}\right) \quad (2)$$

The results of applying Eq. (2) to the experimental results with the fifteen fuels is shown in Fig. 3, where a good value for β in the current setup has been empirically found to be 0.3.
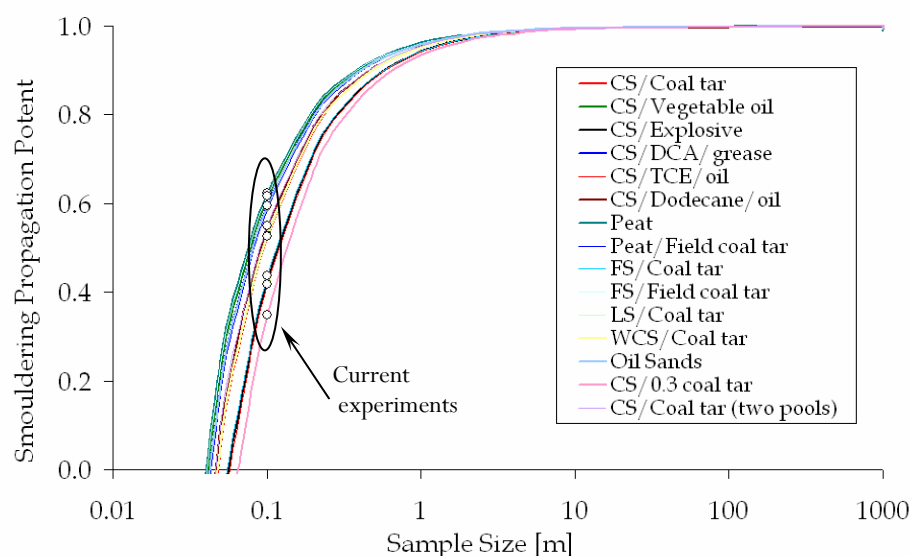
Figure 3. Trends of the smouldering potential with the sample size explaining the scaling of the current experimental results.

It is observed than the new non-dimensional number characterizes well the smouldering behaviour of all different fuels.

4 Conclusions

Initial proof-of-concept research [4] has been conducted at the small scale. Further experiments are being conducted at bench- and field- scales that explore sensitivity of the remediation process to a suite of in situ and operational parameters. Initial results indicate that in situ smouldering remediation is viable across a considerable range of porous media types, contaminants, and subsurface conditions. A controlled field experiment is planned. Numerical modelling is being employed to understand the detailed kinetic reactions occurring at the local scale and up-scaling the process to allow prediction of field scale behaviour. Field implementation would require that the NAPL be physically intersected in at least one location. However, once initiated, the ignition source may be removed (self-sustaining) and the combustion front may progress through NAPL pathways without knowledge of the NAPL distribution (self-targeting).

For dense NAPLs below the water table, water-filled porosity is expected to be a significant heat sink. However, provision of additional oxidant (e.g., air/oxygen) may help sustain combustion and operational costs should then be similar to air sparging. Furthermore, in relying on NAPL destruction, the technology should avoid some of the costs associated with flushing/recovery technologies. However, due to the early phase of the research, the answers to numerous scientific and technological questions are still being sought.

References

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