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This technical note outlines an initial assessment of the feasibility of using water sprays to intercept and extinguish airborne embers, as a means to protect buildings during wildfires. An analytical model was developed to calculate the probability of inter-particle collisions within two intersecting streams of particles, and was then applied to a range of test cases involving embers and water droplets. Results from this simplified analysis indicated that water sprays could effectively protect buildings from 'ember attack' in this manner, but only when either: i) large water flow rates were used (in the order of 1 L s^{-1} per metre of building perimeter to be protected), or ii) the sprays were comprised of very small (~0.1 mm) droplets at moderate water flow rates (~0.1 L s^{-1} m^{-1}). It is likely that the quantity of water required to satisfy (i) would not be available in many circumstances, and further investigation is required to determine whether sprays of ~0.1 mm droplets could operate effectively in the conditions of a wildfire. The analysis presented herein would be a suitable basis for further investigation into these spray systems, and for quantitative comparison with other types of wildfire sprinkler systems.

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On the use of sprays to intercept airborne embers during wildfires

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Abstract

This technical note outlines an initial assessment of the feasibility of using water sprays to intercept and extinguish airborne embers, as a means to protect buildings during wildfires. An analytical model was developed to calculate the probability of inter-particle collisions within two intersecting streams of particles, and was then applied to a range of test cases involving embers and water droplets. Results from this simplified analysis indicated that water sprays could effectively protect buildings from 'ember attack' in this manner, but only when either: i) large water flow rates were used (in the order of 1 L s^{-1} per metre of building perimeter to be protected), or ii) the sprays were comprised of very small (~0.1 mm) droplets at moderate water flow rates (~0.1 L s^{-1} m^{-1}). It is likely that the quantity of water required to satisfy (i) would not be available in many circumstances, and further investigation is required to determine whether sprays of ~0.1 mm droplets could operate effectively in the conditions of a wildfire. The analysis presented herein would be a suitable basis for further investigation into these spray systems, and for quantitative comparison with other types of wildfire sprinkler systems.

Keywords: Wildfire; Bushfire; WUI; Interface; Resilience; Sprinkler; Firebrand; Ember; Particle; Collision.

Introduction

The risk posed by wildfires to human lives and property is significant, and increasing due to urban expansion into forested areas and changes in climate [1–5]. Engineering measures to improve the wildfire resilience of buildings at the wildland-urban interface have consistently been identified as a necessary component of attempts to minimise this risk [2,6–9]. Establishment of 'defensible space' (i.e. separation between wildland fuels and at-risk buildings) is a widely recommended measure, which can significantly reduce the intensity of radiant heat fluxes incident on buildings [10,11]. However, the primary cause of building ignition during wildfires is the deposition of burning embers (or 'firebrands'), and defensible space typically does not pose an effective barrier to wind-blown embers [12–14]. This issue is identified in literature where both defensible space and prevention of home ignition were identified as key components of preventing home loss. See, for example, [15]

External water spray systems may be an effective, easily retrofitted means to protect buildings from wildfire [16–18]. However, such 'wildfire sprinkler systems' have been subject to very little scientific investigation. Water sprays could prevent the ignition of building components by several mechanisms, e.g. *via* the direct cooling of surfaces or the attenuation of radiant heat by airborne droplets, but no evidence appears to exist which quantitatively compares the effectiveness of these mechanisms in the conditions of a wildfire.

In the present work, a relatively simple geometric model was derived to assess the feasibility of using water sprays to intercept airborne embers. The model has been applied to several test scenarios, to provide a 'reality check' as to whether wildfire sprinkler systems could effectively defend buildings from wind-blown embers by such a mechanism. The model derivation, test scenarios, and results have been reported in Sections 2, 3 and 4, respectively.

Collision Model

Collision probability for an isolated ember traversing a stream of droplets

First, consider a single spherical ember, radius r_E (m), travelling at constant velocity S_E (m s^{-1}), through a stream of spherical droplets, each with the same radius r_D (m), travelling at constant velocity S_D (m s^{-1}). The stream of droplets is infinite and uniform in the dimension normal to the droplet and ember velocity vectors. The droplet stream has a depth L_D (m) normal to the droplet velocity vector in the plane of the droplet and ember velocity vectors. The number flux of droplets in the stream per unit area is $\ddot{n}_D$ (m^{-2} s^{-1}). Fig. 1(a) depicts the problem considered.

For convenience and without loss of generality we consider the problem rotated, such that droplets travel straight down. The ember traverses the stream of droplets between times t_1 and t_2 at an angle β. All droplets that will collide with the ember are contained in a cylinder that travels with the stream of droplets (referred to hereafter as the collision cylinder). The collision cylinder has a radius equal to the sum of the ember and droplet radii, and travels downstream with velocity S_D such that the collision cylinder centreline intersects the ember trajectory at the ember location at all times during the ember traverse. The collision cylinder is shown in Fig. 1(b) and 1(c), bounded by dotted lines and with its centreline marked by a dot-dashed line.

The number of droplets that will strike a given ember is equal to the number of droplets in the collision cylinder. At any point in time, the number of droplets in the collision cylinder will be the spatial droplet 'density' (i.e. number of droplets per unit volume) multiplied by the volume of the cylinder.

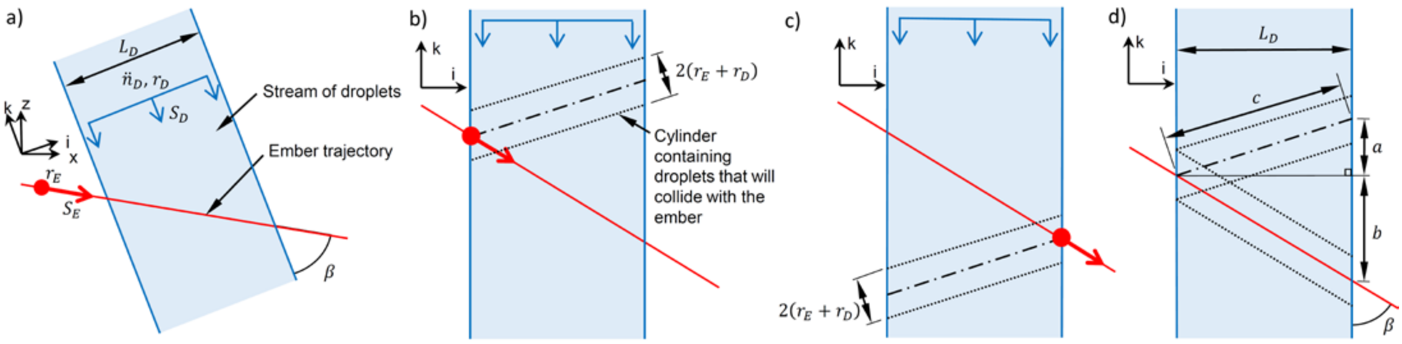

Figure 1. Schematic diagrams showing the idealised case of a single ember (radius r_E, speed S_E) traversing a stream of droplets (with uniform radii r_D and speed S_E; stream depth L_D and uniform droplet number flux within the stream $\ddot{n}_D$). (a) The problem being considered. (b) The rotated system and collision cylinder at time t_1, when the ember enters the droplet stream. (c) The rotated system and collision cylinder at time t_2, when the ember leaves the stream. (d) Definition of the dimensions a, b and c, which were used to find the volume of the collision cylinder.

The time taken for the ember to traverse the stream is given by

$$t_2 - t_1 = \frac{L_D}{S_E \sin\beta}. \quad (1)$$

During this time the collision cylinder falls with the droplet velocity a distance

$$a + b = (t_2 - t_1)S_D. \quad (2)$$

From the geometry shown in Fig. 2(d) the distance b is given by

$$b = \frac{L_D}{\tan\beta}. \quad (3)$$

Therefore,

$$c = \sqrt{a^2 + {L_D}^2} = \sqrt{\left(\frac{L_D S_D}{S_E \sin\beta} - \frac{L_D}{\tan\beta}\right)^2 + {L_D}^2} \quad (4)$$

and the collision cylinder volume, V (m^3), is given by

$$V = \pi(r_E + r_D)^2 L_D \sqrt{\left(\frac{S_D}{S_E \sin\beta} - \frac{1}{\tan\beta}\right)^2 + 1}. \quad (5)$$

For a constant flux of droplets, the number flux (droplets passing through a unit area per unit time) $\ddot{n}_D$ is the product of the spatial number density of droplets C_D (droplets per unit volume) and the droplet velocity, i.e.

$$\ddot{n}_D = C_D S_D. \quad (6)$$

The number of collisions between the ember and droplets is given by the product of the collision cylinder volume and the number density of droplets (C_D) in the stream:

$$N = V\left(\frac{\ddot{n}_D}{S_D}\right) \quad (7)$$

Substituting (5) into (7) leads to

$$N = \left(\frac{\ddot{n}_D \pi L_D (r_E + r_D)^2}{S_D}\right)\sqrt{\left(\frac{S_D}{S_E \sin\beta} - \frac{1}{\tan\beta}\right)^2 + 1} \quad (8)$$

or

$$N = \eta(1 + \varrho)^2 \Gamma \quad (9)$$

where

$$\Gamma = \frac{1}{\tan\beta}\left(\tan^2\beta\,(1 + \varphi^2) + \varphi^2 - 2\varphi\sqrt{\tan^2\beta + 1} + 1\right)^{1/2} \quad (10)$$

is a geometric parameter and

$$\eta = \frac{\ddot{n}_D L_D \pi r_E^2}{S_D}, \quad \varrho = r_D/r_E, \quad \text{and} \quad \varphi = S_D/S_E. \quad (11)$$

are the dimensionless droplet number flux, droplet-to-ember radius ratio, and droplet-to-ember velocity ratio, respectively.

Collision probability for a stream of embers traversing a stream of droplets

In general, however, there will be multiple embers with an initial number flux of $\ddot{n}_{E0}$ (m^{-2} s^{-1}) spread across an ember stream of width L_E (m). See Fig. 2 for a schematic of this problem. The probability of collision can be influenced by other, previous collisions in this case. Therefore, assumptions must be made regarding the effect of a collision on each ember trajectory. Two simple cases are considered below, in which the inertia of each ember is assumed to be either much larger or much smaller than that of each droplet, respectively.

Embers with relatively small inertia

In cases where the inertia of each ember is much less than that of each droplet, the result of a collision can be approximated by removing the ember from consideration and letting the droplet continue with an unchanged trajectory. The stream of droplets is unaffected by the embers in this case, and each ember is unaffected by the other embers. Therefore, the collision probability relevant to each ember is given by Equations (9), (10) and (11), above.

Embers with relatively large inertia

Alternatively, consider a steady system in which embers have significantly greater inertia than droplets, such that a collision between an ember and a droplet will eliminate the droplet and have a negligible impact on the trajectory of the ember, regardless of the number of droplets that strike it. In this case, embers near the top of the stream will intercept droplets, reducing the number flux $\ddot{n}_D$ that can collide with embers lower down. Equations (5) and (7) are still valid for any given ember in the stream. However, in this case, the number density of droplets in a given collision cylinder will decay as it passes through the stream of embers. The number flux of embers will remain uniform and equal to the initial flux, $\ddot{n}_{E0}$.

First, we define a coordinate, q (m), which is the distance through the stream of embers, normal to the ember trajectories. For a given q, the flux of droplets will be uniform and steady. Fig. 2 gives a schematic representation of the problem and defines the coordinate q.

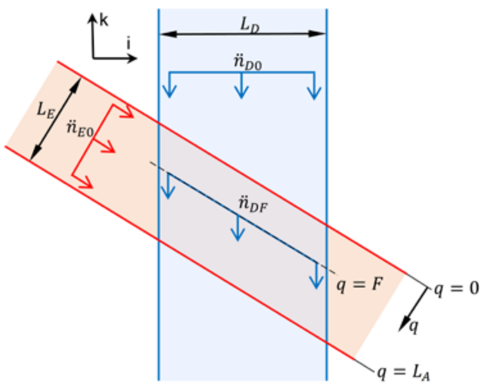

Figure 2. Schematic diagram showing the coordinate q normal to the ember stream, relevant to cases where the inertia of each ember is much greater than that of each droplet.

For a control volume of unit width normal to the two particle streams and of thickness dq the number of collisions per second is the number of embers entering the control volume per second multiplied by the number of collisions per ember, N. That is, the number of collisions per second is $N\ddot{n}_{E0}dq$, where N is given in (7). For each collision, one droplet is lost from the stream. Therefore, there is a reduction in the number flux of droplets of $d(L_D\ddot{n}_D)$ which is equal to the number of collisions with embers. As L_D is a constant, we can write

$$\frac{d\ddot{n}_D}{dq} = -\frac{\ddot{n}_E N}{L_D}. \tag{12}$$

Substituting (7) into (12) gives

$$\frac{d\ddot{n}_D}{dq} = -\ddot{n}_D \frac{\ddot{n}_E V}{L_D S_D} \tag{13}$$

in which all the terms on the right hand side are constant except $\ddot{n}_D$. Therefore, (13) can be integrated to give

$$\ddot{n}_D(q) = \ddot{n}_{D0} \exp\left(\frac{-V\ddot{n}_E q}{L_D S_D}\right). \tag{14}$$

By substituting (14) into (7), the number of collisions per ember can be calculated as a function of q as

$$N(q) = \frac{\ddot{n}_{D0} V}{S_D} \exp\left(\frac{-V\ddot{n}_E q}{L_D S_D}\right) \tag{15}$$

or, by incorporating (10) and (11), as

$$N(\vartheta) = \eta\Gamma(1+\varrho)^2 \exp\left(\frac{-\eta}{\omega\tau}\Gamma(1+\varrho)^2\vartheta\right) \tag{16}$$

where

$$\vartheta = q/L_E, \quad \tau = L_D/L_E \quad \text{and} \quad \omega = \ddot{n}_{D0}/\ddot{n}_E \tag{17}$$

are the fractional distance across the ember stream, droplet-to-ember stream width ratio, and initial droplet-to-ember number flux ratio respectively.

The mean number of droplets likely to collide with each ember in the stream can be calculated by integrating (16) across the width of the ember stream:

$$\bar{N} = \int_0^1 \eta\Gamma(1+\varrho)^2 \exp\left(\frac{-\eta}{\omega\tau}\Gamma(1+\varrho)^2\vartheta\right) d\vartheta \tag{18}$$

which yields the following expression:

$$\bar{N} = \omega\tau\left(1 - \exp\left(\frac{-\eta}{\omega\tau}\Gamma(1+\varrho)^2\right)\right). \tag{19}$$

Application to test scenarios

Scenarios were investigated in which a $L_E = 3$m-thick stream of embers traverses a droplet stream at an angle of $\beta = 60°$, representing a stream of embers that could otherwise impinge on the wall of a building. Nine sprays were modelled by varying the flow rate of water per horizontal metre of wall, such that $L_D\ddot{n}_D = \{0.01, 0.1, 1\}$ L s^{-1} m^{-1}, and the droplet diameter, such that $2r_D = \{0.1, 0.32, 1\}$ mm. Droplets were assumed to be travelling at terminal velocity (i.e. 0.27, 1.25 and 4.03 m s^{-1} for 0.1, 0.32 and 1 mm droplets, respectively [19]), and ember velocities were assumed to be dictated more strongly by the wind speed, so were set at 5 m s^{-1}. Fundamental characteristics of ember streams that buildings are exposed to during wildfires (e.g. typical size distributions and mass fluxes) are still poorly understood and subject to ongoing investigation [6,20]. For this reason, wide ranges of ember sizes and number fluxes have been investigated in the present work.

Equations (10), (11), (17) and (19) were used to estimate the mean probability of collision for embers in each scenario, under the assumption that the inertia of individual embers was much greater than that of each droplet. To ensure that this assumption was reasonably valid, results were disregarded from cases in which the mass of individual embers was less than ten times that of individual droplets, based on an assumed ember density of 300 kg m^{-3}, which is commensurate with measured values from experiments [21], and lies between typical values for charcoal and wood.

In order to estimate the net effect of the droplet-ember collisions on each ember stream, the quantity of heat that each droplet could absorb as it rises to 100°C and then evaporates: $Q_D = m_D(C_{PD}(100 - T_{D0}) + h_{eD})$, and the quantity of heat that must be removed to reduce the ember temperature to 100°C: $Q_E = m_E C_{PE}(T_{E0} - 100)$, were calculated. Here, m_D and m_E are the droplet and ember masses respectively (kg), $C_{PD} = 4.186$ and $C_{PE} = 1.5$ are the specific heat capacities of water and embers respectively (kJ kg^{-1} K^{-1}), $T_{D0} = 25$ and T_{E0} are the initial temperatures of droplets and embers respectively (°C), and $h_{eD} = 2256$ is the latent heat of vaporisation of water (kJ kg^{-1}). Thus, the fraction of heat (expressed as a percentage) that could hypothetically be removed from an ember by $\bar{N}$ collisions could be calculated as

$$\Delta = \min(100\bar{N}\, Q_D/Q_E,\ 100). \tag{20}$$

Two cases were considered for the temperature distribution within the ember. In case 1 the ember is assumed to have a surface temperature of $T_{E0} = 800$°C (based on surface temperature measurements of burning wood products in [22]) that extends throughout the outer 2 mm of the ember, with the remainder of the ember being at $T_{E0} = 450$°C. For case 2, the ember is assumed to have an initially uniform temperature throughout the ember of $T_{E0} = 930$°C, based on the average of ember surface temperature measurements in [23]. Cases 1 and 2 were considered to represent 'best' and 'worst' case scenarios, respectively, in terms of the quantity of heat to be removed by the spray. In all cases it was assumed that the cooling process is instantaneous. That is, the water evaporates on contact with an ember and the temperature distribution in the ember is uniformly reduced by this energy exchange.

Results and Discussion

The calculated fraction of heat removed from the ember streams (Δ) varied from 0.29% to 100% in the scenarios investigated (see Fig. 3). Within the ranges of variables considered, Δ was approximately proportional to the water flow rate, and increased strongly with decreased droplet diameter. Sprinkler effectiveness was of a similar order of magnitude in the two cases with different assumed ember temperatures; up to 18% more of the embers heat was removed in case 1 (the 'best' case, with colder embers).

Large fluxes (>100 m^{-2} s^{-1}) of small (<5 mm) embers could be extinguished effectively by spray flow rates in the order of 0.1 L s^{-1} per metre of building perimeter, when implemented as a fine spray of 0.1 mm droplets. The superior performance of fine sprays was due to the low terminal velocity of small droplets, which resulted in a greater mass of airborne droplets for a given spray flow rate. However, further investigation would be required to determine whether streams of such small droplets could be maintained around a building, given the strong winds that typically occur during wildfires [24].

If streams of very small (~0.1 mm) droplets cannot be established around a building in the conditions of a wildfire, it appears that water flow rates in the order of 1 L s^{-1} would be required per metre of the building perimeter that is to be protected, in order to extinguish the majority of embers while airborne. To protect the perimeter of a relatively small (8 × 15 m) building for 3 h, this would amount to ~500,000 L (500 m^3). It is likely that such large volumes of water would not be available in many cases.

Larger embers collided with more droplets in the test scenarios, but due to their large mass (which scales with r_E^3) they were not cooled as effectively. The number flux of embers had relatively little effect on the fraction of heat removed from the ember streams, which indicates that the inferior performance of sprays with low flow rates was primarily caused by the more widely spaced fields of droplets that they produced, leading to fewer collisions with embers, rather than the water being 'used up' due to collisions with embers.

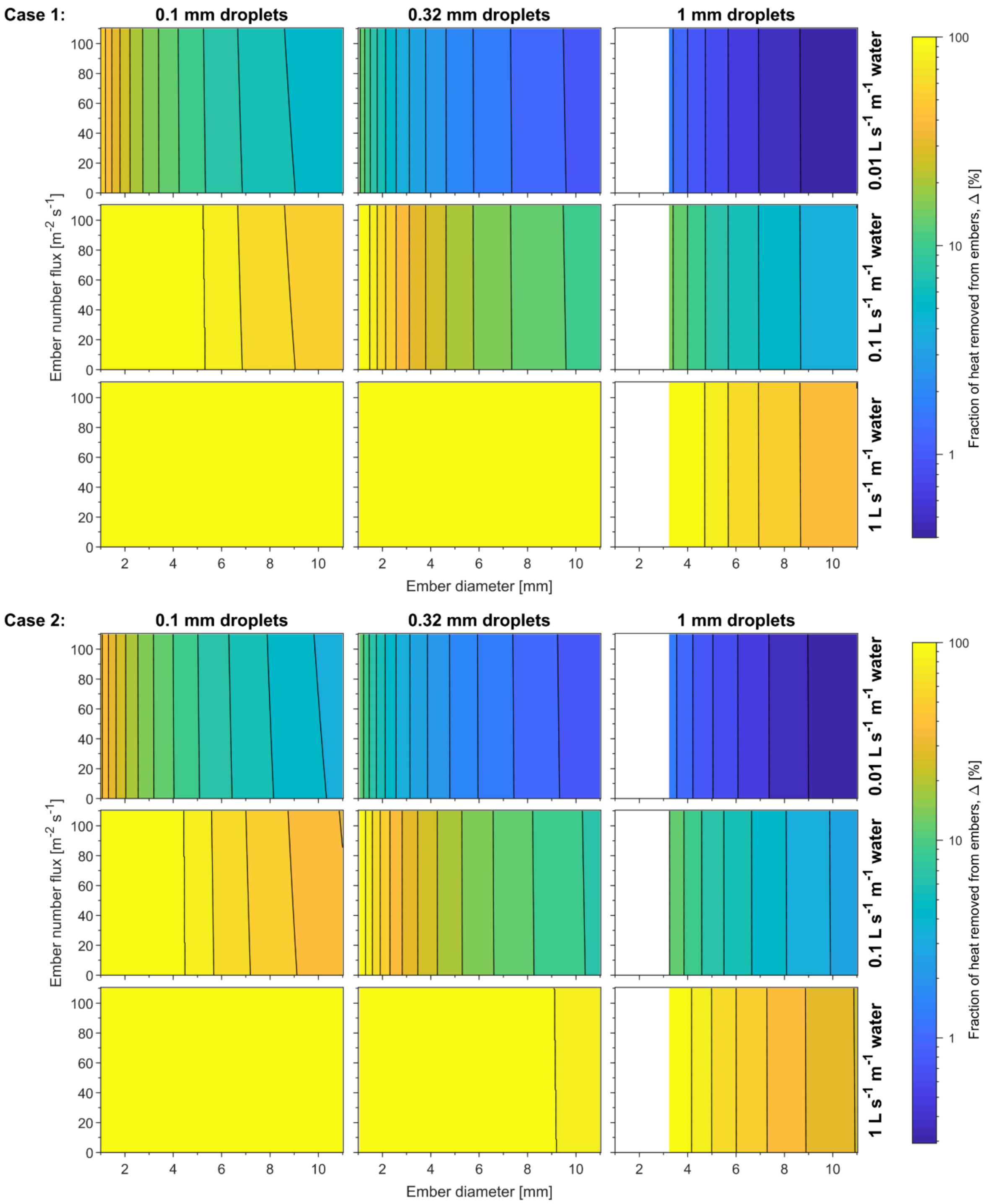

Figure 3: Percentage heat removal from streams of airborne embers by water sprays, due to mid-air collisions. Results are presented for sprays with three uniform droplet diameters (0.1, 0.32 and 1 mm), three water flow rates per unit length of the building perimeter (0.01, 0.1 and 1 L s^{-1} m^{-1}), and two cases with different assumed ember initial temperature distributions (embers in case 1 had an outer 2 mm-thick layer of material at 800°C surrounding a core at 450°C, in case 2 embers were isothermal at 930°C). Yellow regions represent high percentage heat removal and, therefore, effective ember suppression. Blue regions indicate low heat removal and incomplete suppression. Regions of the plots where the mass of one droplet would be more than one tenth of the mass of one ember have been left blank, since the collision model may not apply to such cases.

Conclusion

The effectiveness of water sprays at intercepting and extinguishing streams of airborne embers has been estimated, to assess whether external sprinkler systems could feasibly protect buildings from wildfires by such a mechanism. A simple analytical model was developed to predict the collision probability of two intersecting streams of particles. Application of this idealised model to ember-droplet collisions revealed that such spray systems could only be effective if they dispense water at high flow rates (on the order of 1 L s^{-1} per metre of the building perimeter) or if they produce very small (0.1 mm) droplets at moderate flow rates (on the order of 0.1 L s^{-1} m^{-1}). Further investigation is required to determine whether such fine sprays could be maintained around buildings in the hot, dry, windy conditions of a wildfire. If they cannot, it appears that the suitability of such a sprinkler system is likely to be limited to buildings near large independent water sources (e.g. lakes).

The approach taken in the present work was highly simplified, so should be considered to be an ‘order of magnitude’ estimate, rather than an exact calculation. Important aspects of the physical process that were not considered include: (1) droplet splashing, bouncing etc. during collisions; (2) the effects of turbulence on particle trajectories; (3) non-parallel droplet or ember trajectories; (4) polydisperse ember and droplet streams; (5) non-spherical embers; (6) mechanisms of extinguishment other than cooling (e.g. oxygen exclusion); and (7) heat production due to combustion within the region of intersecting particle streams (i.e. ember ‘burn back’). Experiments or three-dimensional computational fluid dynamics simulations that capture the flow field around the building would be required to obtain predictions much more accurate than those presented here.

Despite the simple approach that was taken, the analysis presented herein does provide a useful indication of the quantity of water and size of droplet that would be required to effectively protect buildings from ‘ember attack’, if sprays were used to intercept and extinguish airborne embers. Quantitative comparison with other mechanisms of operation (e.g. the direct cooling of building surfaces, or pre-wetting of buildings and surrounding fuels prior to the passage of a fire front) could reveal the most effective method to protect buildings from wildfires using water sprays, which could ultimately save human lives and property.

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Appendix A

Table 1. Parameter values used in the model example calculations.

Parameter	Value
Flow rate per unit width of building ($L_D \dddot{n}_D$)	0.01, 0.1, & 1.0 L s^{-1} m^{-1}
Droplet Diameter ($2r_D$)	0.1, 0.32, & 1.0 mm
Droplet velocity (u_D)	0.27, 1.25 & 4.03 m s^{-1}
Ember velocity (u_E)	5 m s^{-1}
Ember density (ρ_E)	300 kg m^{-3}
Droplet specific heat (C_{PD})	4.186 kJ kg^{-1} K^{-1}
Ember specific heat (C_{PE})	1.5 kJ kg^{-1} K^{-1}
Latent heat of vaporization (h_{eD})	2,256 kJ kg^{-1}
Droplet initial temperature (T_{D0})	25 ºC
Ember initial Temperature (T_{E0})	800–450 & 930 ºC