Effect of Wood Smoke Contamination on Water Droplet Evaporation and Surface Tension

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1 Introduction

In this paper, an experimental investigation was conducted on water droplet surface contaminated by smoke particles. Droplets were evaporated by external heating to show the effect on one of the primary four mechanisms of fire extinguishment. When water is sprayed over a fire plume, it serves to extinguish it by various mechanisms. Primary mechanisms are heat extraction and air displacement [1]. Heat is extracted from flames or the combustible surface by droplet evaporation. Evaporation leads to water vapour which in turn displaces air and reduces oxygen concentration. These mechanisms are all affected by the interaction of water spray and fire, which starts with water droplets passing through a smoke layer. Experimental investigations on water interaction with fire have been conducted in large scale setups, chambers, and real scale rooms. Experiments mainly focused on water suppressing efficiency [1, 2]. In practice, water spray is contaminated by smoke particles during fire quenching. The main aim of this paper is to show the significance of smoke contaminants can have on water droplet evolution and surface tension.

Smoke particles have been previously investigated in terms of their size distribution and composition. Studies were focused on both smoke from application-based burning and fire tests. Kleeman and others [3] found that smoke produced by wood contained not only carbon particles but also a variety of organic compounds and metal particles. Similar results were obtained when analysing boiler smoke [4]. Moreover, smouldering in masonry heaters produce fine smoke particles [5]. The studies mentioned above agreed that the produced smoke particles were below 1μm and peaks approximately at 100nm.

Experimental studies on smoke particles of wildfire and test fires were conducted and summarised in Table 1. It is noticeable that smoke analysed immediately after production showed a peak at 100 nm. While transported smoke, which tend to agglomerate, showed peaks at larger sizes. Furthermore, smoke particles vary in their chemical composition. This depends on their source, carbon soot is the main predominant agglomerate in wood combustion [3, 5, 6]. In addition, smoke contains metals such as potassium, iron, magnesium, sodium, and copper. Other materials can also be found such as silicon, phosphorus, and sulphates. Due to the size and composition of smoke particles, it is expected that surface contaminated droplets have different surface behaviour.

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Table 1: Comparisons of particles size distribution and peak values

Combustibles	Test environment	Test range(μm)	Peak value (nm)	Source
Wildfire	Transported smokes	0.01 – 10	300, 600	[6]
Timber harvest residues	Forest	0.010 – 43	150	[7]
Space vehicles materials	Microgravity on ISS	0.02 – 1	100-300	[8]
Buildings materials	Small cone calorimeter	0.04 – 10	No exact peak	[9]
Polymers	Small lab scale	1 – 10	2000	[10]
Woods	Medium Lab scale	0.006 – 0.5	10 – 100	[11]
Wildfire	Transported smokes	0.03 – 1	100, 500	[12]
Wildfire	Airborne	0.01 – 1	50 – 150	[13]
Wood	Small lab scale	0.02 – 10	20, 300	[14]

Rasid and Zhang [15] examined surface contamination in fuel and reported the influence of nanoparticles on thermo-physical properties, finding surface soot contamination significantly altered diesel droplet burning characteristics. They showed that evaporation and burning rate were reduced and stability critically affected. However, they focused on burning droplet behaviour only without further experiments on evaporation as an individual process.

Certainly, the problem is complex due to the variables of smoke content, particle size distribution, particle agglomeration, chemicals reaction with water, and the type of forces that arise between water and contamination. Considerable research has been conducted on smoke particles, the interaction between fire and water spray, and nanoparticle effect on fluids. However, so far, no experimental investigation into the fundamental properties of smoke particle contaminated water droplets has been conducted. Therefore, this experimental analysis aims to investigate the influence on evaporation rate and surface tension of water droplets. Water spray has a significantly larger surface area than that of a single droplet having a comparable mass. The possibility of contamination is much higher in real applications compared to a single droplet test. However, studying a single droplet system enables enhanced magnified imaging throughout the droplet lifetime.

2 Experimental Apparatus

Figure 1 shows the experimental setup. The setup was used in an average temperature and humidity condition of 23°C and 38% respectively. Water droplets were injected using 1 mL syringe and suspended on 100 μm silicon carbide fibre. The initial diameter of droplets was 1 ± 0.1 mm for all tests. The water used in this experiment was distilled water. To track the droplet lifetime, a Phantom SA4 was used with Nikon AF Micro 60 mm f/2.8 lens. In addition, backlighting of droplets was achieved by IDT LED intense illuminator and a diffuser.

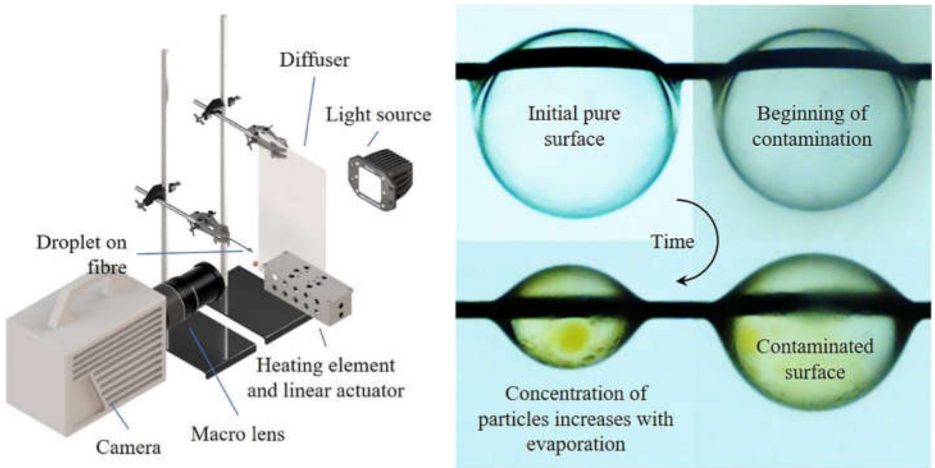


Figure 1. Left: Experimental apparatus for droplet evaporation using a heating element; Right: Time evolution of evaporating contaminated droplet

Two study cases were performed to show the effect of pine wood smoke particles on water droplet evaporation. The first case was to contaminate water droplets of 1mm in diameter using smoke from small wooden pieces as shown in Figure 2 (a) below. The initial droplet size was monitored by a live view to ensure that the size was within the allowable range. The droplets were then exposed to a heating element as can be seen in Figure 2 (b). Figure 2 (c) indicated how temperature was measured at the same location as the droplet suspension location. A K-type thermocouple was used with a Pico TC-08 Data Logger to record the temperature. Time evolution of temperature that is experienced by water droplets is shown on the right of Figure 2. Droplets were captured until complete evaporation. This was then compared to the distilled water droplet evaporation without applying smoke particles. Study case one gave an initial indication of how low amounts of contamination affected evaporation and surface tension.

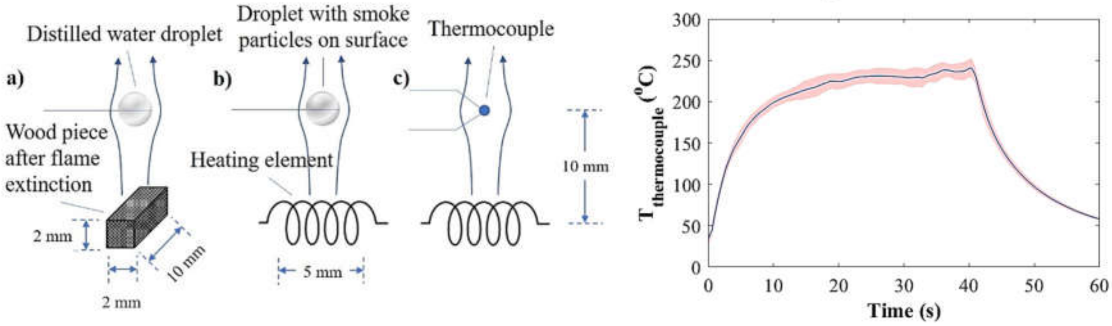


Figure 2. Study case one: a) Contaminating water surface; b) Droplet evaporation; c) Temperature measurements

In the second case, larger wooden pieces were used to apply smoke particles on droplets as indicated in Figure 3 (a). The second case was conducted to investigate whether contamination process had significant heat transfer contribution and increased initial droplet temperature. Droplets were evaporated by larger wood pieces. This was compared to uncontaminated droplets evaporated by a heating element. The heating element power settings were ensured to produce higher temperatures surrounding the droplet compared to the wood pieces. Temperature profiles with 80% confidence boundaries, which were measured by a thermocouple, are shown in Figure 3 (c). The temperate level approached by the heating element was higher than that of burnt wood pieces.

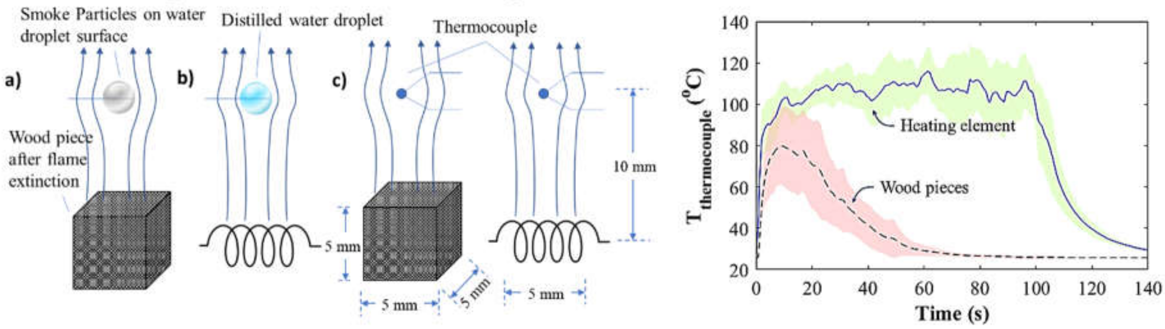


Figure 3. Study case two: a) Contaminating water surface process; b) Pure droplet evaporation; c) Temperature measurements

The droplets were evaporated using a constant power heating source. The source was designed to keep its power constant during each study case. In each test, the process started by supplying the same power to a stainless-steel heating element. The element was then allowed to reach a steady state. Then, the coil was moved under the droplet by a linear actuator. The actuator ensured the consistency of heating element placement under the droplet.

Droplet evolution images were processed using a MATLAB code. The algorithm used area segmentation methods to calculate droplet area, diameter, and centroid. In addition, droplets were assumed to be spherical based on the two-dimensional shape captured by the camera. Using this data, droplet normalised diameter reduction $(D/D_o)^2$ with time t/D_o^2 was evaluated according to D^2-law. The mass loss rate which leads to this law was used previously in several studies related to water evaporation. For example, droplet evaporation was investigated under different conditions such as hot air effect in fire extinguishment [16]. The law was used to illustrate the enhancement of fire suppressions by radiation attenuation [17]. In this paper, it is used to highlight the effect of smoke particles on water droplet surface.

3 Results and Discussion

Figure 4 (left) shows the results of the first study case. The results indicated three stages, starting with a heating period where the curve slope gradually increases. Then, a second stage where the slope is relatively steady. The second stage is followed by the final stage where there are disturbances to the shape of the droplet. Quantitative measurements were only made on the second stable stage. Evaporation rate was 0.0692, 0.0637 s/mm^2 for contaminated and pure surface respectively. Coefficients of variance were 4% and 9% respectively. Contaminated surface enhanced the evaporation rate by 8%. It was observed on this case study that the particles on the surface were not agglomerated but rather evenly distributed.

Figure 4 (right) presents the results of the second study case. Contaminated droplets showed a considerable increase in evaporation rate compared to pure surface droplets. The evaporation rate was 0.0152, 0.0286 s/mm^2 with coefficients of variance 10% and 6% for pure and contaminated respectively. The percentage increase in evaporation rate was 47%. It is noticeable that this effect is arising from surface contamination only, while the effect described in the literature was based on volume mixing of different particles and fluids. A similar effect has been reported in previous studies on nanoparticles [18]. The explanation was that enthalpy of vaporisation and surface tension were reduced when adding specific particles to a fluid. Hence, a higher evaporation rate.

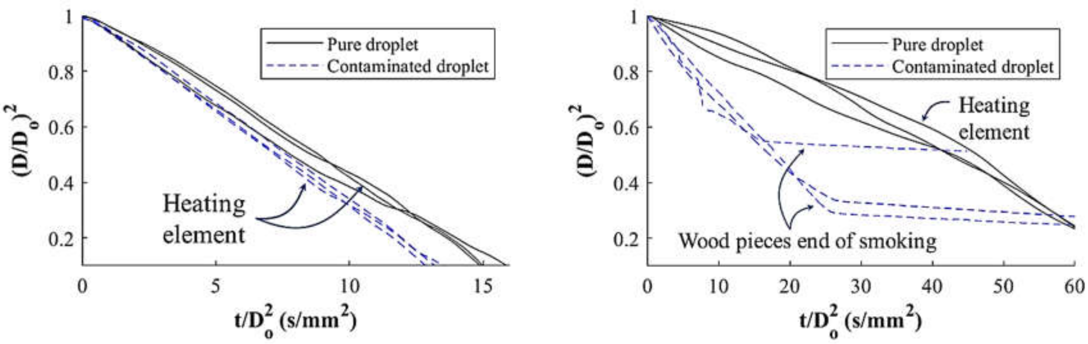
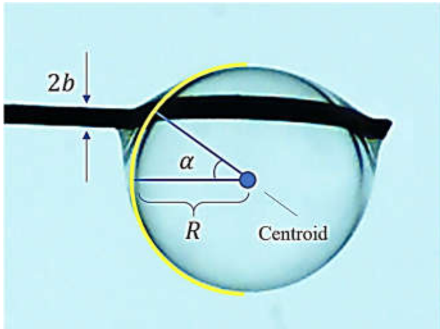


Figure 4. Left: Study case one evaporation results; Right: study case two evaporation results

Previous studies on nanoparticles on base fluids have shown enhancements of heat transfer. Xuan et al. [19] measured the increase in thermal conductivity with added copper nanoparticles up to 7.5% in volume concentration. In Kakac review of thermal conductivity enhancement with nanofluids [20], theoretical work was firstly conducted by Maxwell and then followed by other researchers with developed models. These models assume a discontinuous bulk phase. Furthermore, the review covered the theoretical and experimental work on the increase of convective heat transfer due to effective thermal conductivity and Brownian motion. Previous research deals with properties enhancement as it originates from the volume mixing of nanoparticles in a base fluid. Nevertheless, water used in fire extinguishment is surface contaminated with smoke particles rather than bulk mixed. Hence, it is expected that the surface behaviour of water droplets changes when it is contaminated. Although, the evaporation rate increase was relatively small in the first study case, low amount of contamination has a major impact on surface tension.

Radiation attenuation is indirect method by which water spray absorb radiant heat. Radiation absorption in water occurs as a volumetric phenomenon rather than a surface process only because water is semi-transparent [21]. In the case of this experiment, surface appearance was significantly altered, and this was an indication that properties such as emissivity were affected. Further experiments are required in order to understand the optical contaminated droplet properties and radiation contribution.

Surface tension influences liquid transport and heat transfer phenomena. It is generally understood that droplets on fibre take different shapes depending on characteristics of droplets, fibre, surrounding environment, and surface interaction between them. Examples of these shapes are barrel, clamshell, hanging by a triple line, and other configurations based on the stability of the droplet[22]. Moreover, a droplet on fibre configuration is affected by gravity and the droplet tend to be elongated. Elise et al. [23] have studied capturing droplets on thin horizontal fibres. Their analysis provides a method to measure surface tension for a barrel shaped droplet; the same configuration in this experiment. Figure 5 (right) is a plot of $\sin\alpha$ against $R^3$for pure and surface contaminated droplets; where α is the angle between the horizontal through the centroid and fibre first point of contact with droplet surface, R is droplet radius. The figure shows a linear relationship approximately. Assuming the bulk density of water is 997 $kg/m^3$and gravity acceleration is 9.81 m/s^2. Based on the linear regression of the data, it was found that surface tension values were 50.7 and 30.3 mN/m for pure droplets and contaminated droplets respectively. coefficients of variance were 4% for both cases. Interestingly, although the concentration of smoke particles increased with evaporation, the linear relation in Figure 5 remains constant. Surface tension is inversely proportional to Weber number which in turn influences spray characteristics. Changes to Weber number would influence the mechanism by which water droplets breakup in fire extinguishment systems.



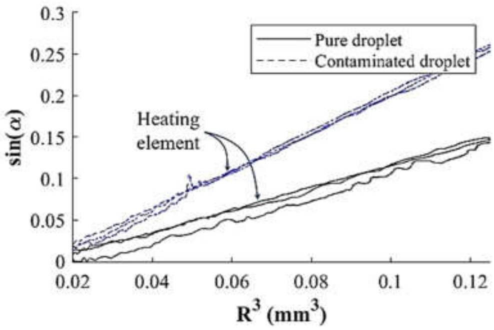


Figure 5. Left: droplet on fibre variables; Right: plot of $\sin\alpha$ versus cubed droplet radius

The trends in this study are consistant with the available research[24, 25]. A similar effect has been realised in evaporating pendant droplets [26], but some particles showed no effect on surface tension. On the other hand, it has been shown that surface tension can be increased when the concentration of nanoparticles increases [27]. On a molecular level, smoke particles could behave as hydrophobic nanoparticles. Wet hydrophobic particles adsorb at surfaces and lead to intermolecular separation of water molecules. The attraction of water molecules is lowered, leading to a reduction of surface tension [28]. Moreover, a closely related concept is the Marangoni effect which mass transfer along surfaces induced by surface tension gradient. Surface tension gradient usually induced by temperature variations and have a negligible effect on evaporation [29]. It can be suggested by observing contaminated droplet images that droplet surface become uneven in terms of smoke particles distribution. This unevenness would influence the surface tension gradient on the droplet surface and enhance surface circulation and Marangoni effect.

4 Conclusion

Water droplets evaporation has been shown to be affected by smoke particles contamination. In particular, the surface of water droplets was contaminated to simulate the effect of using water in fire extinguishment. Quantitative measurements on evaporating rate showed that contaminated droplets had a higher rate of evaporation. The results were consistent with available research on nanoparticle effect in fluids. However, previous experimental research investigates the properties changes by volume mixing while this study focused on surface contamination. Additionally, surface tension was found to be lower for surface contaminated droplets. Surface tension change can influence spray characteristics considerably in fire extinguishment systems.

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