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12th Annual Conference on Liquid Atomization and Spray Systems

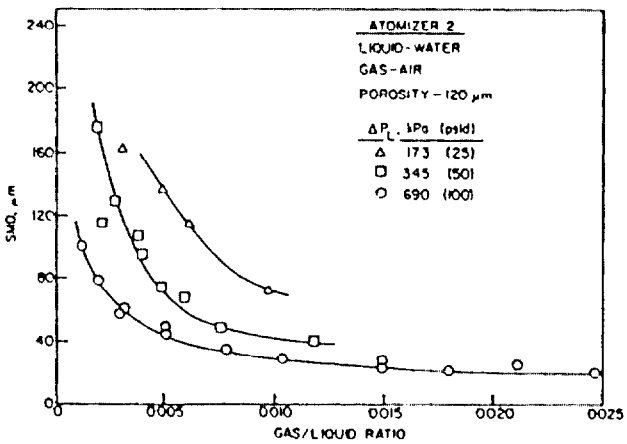

Fig. 8. Influence of pressure on mean drop size

From: T.C. Roesler and A.H. Lefebvre, "Studies on Aerated-Liquid Atomization," Int'l Journal of Turbo & Jet Engines, vol.6, pp. 221-229, 1989.

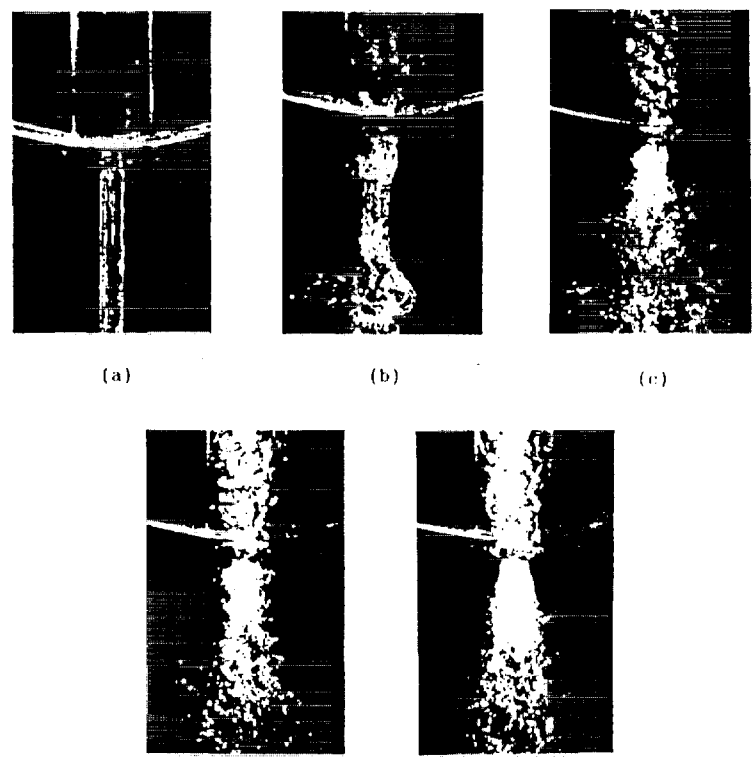

Figure 4.1 Aerated Liquid Atomizer Spray Photographs (137 kPa)

16 –19 May 1999
The Radisson City Centre
Indianapolis, Indiana

Extended Abstracts

On The Interaction Between Evaporating Sprays and Heated Surfaces

by

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Abstract

An experimental study mapping the size and velocity history of water droplets in a polydispersed spray as they approach a heated surface was conducted. A Phase Doppler Particle Analyzer (PDPA) was used to record the size and velocity histories. Different mass flow rates were applied to study the effect of both buoyancy and evaporation on droplet trajectory. The initial surface temperature was about 600°C. Surface temperature profiles were recorded to study the influence of water mass flow rate and drop size distribution on the hot surface temperature profile. The influence of water mass flow rate and drop size distribution on the hot surface temperature profile, and on the variation of size and velocity distribution, are presented and discussed.

The long term objective is to produce experimental data that can be used to validate submodels for four key physical phenomena involved in the interaction of sprays with burning surfaces: (1) the effect of buoyancy (caused by hot combustion products) on the trajectory of a single droplet; (2) the effect of evaporation on the trajectory of a single droplet; (3) the cessation of reaction and reduction in flame spread caused by the droplets on flaming surface combustion; and (4) the reduction in surface temperature caused by the effect of drop impingement, spreading and evaporation on surface combustion.

Introduction

Impingement of spray droplets onto a wall/target surface is widely used in fire safety, and the interaction between water spray droplets and heated/burning surfaces has been studied for almost four decades (Braidech et al., 1955; Rasbash et al., 1960; Pedersen, 1969; Lugar, 1979; Mawhinney et al., 1994). Braidech et al. (1955) have concluded correctly that in most cases the efficacy of a water spray is predominantly due to the oxygen displacement effect of the water evaporating, rather than thermal cooling. Pedersen (1969) showed that approach velocity is the dominant variable affecting droplet heat transfer and that surface temperature has little effect on heat transfer in the non-wetting regime. However, there are no detailed models describing the size reduction and evaporation of droplets.

A recent study by Hicks and Senser (1995) shows that spray-target interactions can be described by dividing the process into a near-nozzle flow-development (NNFD) region and a target-interaction (TI) region. Key features of the NNFD region include spray formation, atomization, and entrainment of surrounding air. The TI region is characterized by two-way coupling between gas and liquid phase momenta where the spray can no longer be considered dilute, i.e. in the boundary layer near the target itself. Key features are deposition of some drops, depending on their sizes (big drops are more likely to impact the surface due to their larger momentum-to-aerodynamic drag ratios), and the formation and growth of a boundary layer which makes it difficult for drops to deposit as one moves further from the spray centerline. The most important conclusion they obtained is that spray deposition on a target is dependent on the drop size distribution. Since all of their experiments were done for unheated surfaces, spatially revolved measurements of droplet sizes and velocities are still necessary for flames/heated surfaces, whose flow physics are different.

Many studies have been performed that quantify the vaporization process of both single and multiple droplet arrays impacting on hot surfaces (DiMarzo and Evans, 1986; DiMarzo et al., 1989). DiMarzo and

Tinker (1996) investigated the cooling effect of a sparse spray impinging on a semi-infinite solid by monitoring the surface temperature. All of these studies have identified the need for spatial and temporally resolved data describing the droplet trajectory as it approaches a hot surface (including buoyancy effects) as well as the temperature distribution of the surface material. The present work is aimed at providing experimental data that describe the interactions of water sprays with flaming and non-flaming surface combustion.

Experimental Apparatus

The experimental apparatus consists of the spray nozzle and the associated feeding systems, the heated surface and its associate power supply, a Phase Doppler Particle Analyzer to measure the spray size and velocity distributions, and thermocouples and the associated data processing system. This configuration is shown in Figure 1.

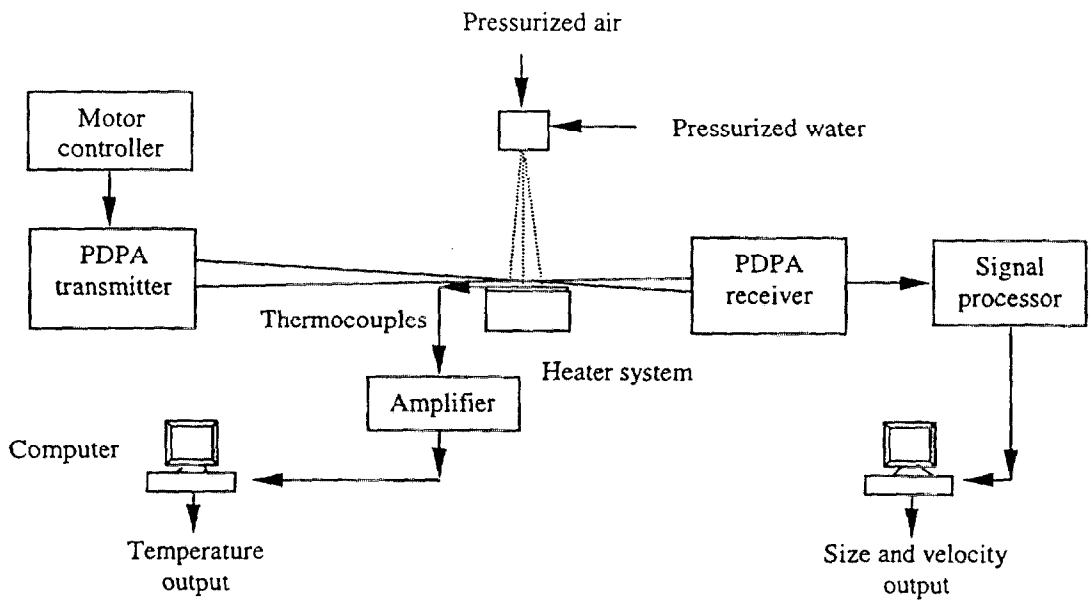

Figure 1: Experimental apparatus.

The spray nozzle is an effervescent design. A metered flow rate of air is injected into a known flow rate of liquid such that bubbles are formed inside the nozzle body. The resulting two-phase flow exits the final orifice in the annular flow regime. The rapidly moving air core causes the slower moving liquid to break up into ligaments, with the ligaments then breaking up into drops.

The heated surface is a cylindrical copper disk nominally 20 cm in diameter and 5 mm thick. It's positioned 254 mm beneath the nozzle, and placed on a spiral wound resistance heater whose power is supplied by a pair of Variacs and a transformer. The thermocouple arrangement on the surface is illustrated in Figure 2.

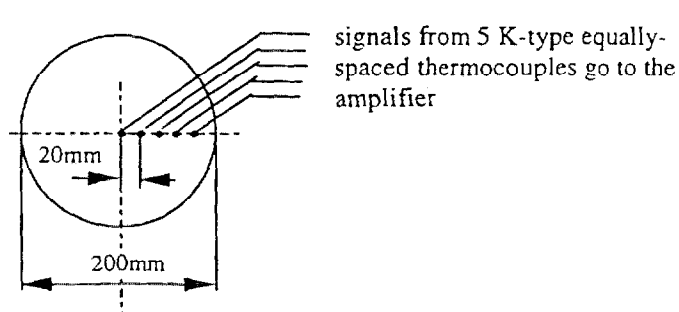

Figure 2: The structure of the heated surface with the thermocouples.

A Phase Doppler Particle Analyzer (PDPA) was used to obtain the size and velocity histories of the sprays. The scattered light was collected at a forward angle of 30°, and the velocity component measured was normal to the heated surface. The transmitter was equipped with a 160 mm focal length beam expander and a 1000 mm focusing lens. The receiver was configured with a 495 mm focal length lens and a 100 μm wide slit.

Results and Discussion

By changing the air and water pressures and flow rates, different droplet size and velocity distributions were obtained and used to study the interaction between the spray and the heated surface. Steady state temperature, droplet size and velocity profiles were measured.

(a) Temperature history

The initial steady state copper surface temperatureis about 600 °C for each experiment. The average temperature distribution is shown in Table 1.

Table 1: Average temperature profile before spray

Radial distance (mm)	0	20	40	60	80
Temperature (°C)	598.7	600.2	602.4	605.9	597.5

The average temperature is 600.9 °C and the standard variation is 2.9 °C. Five fine K-type thermocouples were used; their expected accuracy is ±2.2 °C. At each radial location, 32 samples were collected at a frequency of 1 MHz.

(1) The influence of flow rate

Three sprays with similar size distributions were obtained to investigate the influence of flow rate by changing the water and air mass flow rates. See Figure 3. The water mass flow rates used were 0.160, 0.385 and 0.600 g/s respectively. For the 0.160 g/s case, the droplets approached the plate with relatively smaller diameters, since the finest droplets vanish before they hit the surface and most of the coarse droplets have partly evaporated. Furthermore, there was no water deposition at the lowest mass flow rate case, with occasional droplets observed to bounce from the plate and evaporate quickly. Consequently the surface temperature is much more uniform than for the higher mass flow rate cases, where water deposition was observed in the center of the plate. See Figure 4. Generally speaking, the temperature is lowest in the center, then increases as the radial distance increases. For higher flow rates, the temperature difference between the center and the edge is much more prominent.

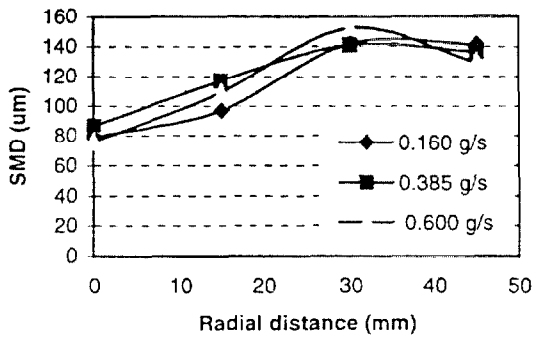

Figure 3: Size distributions at three different flow rates.

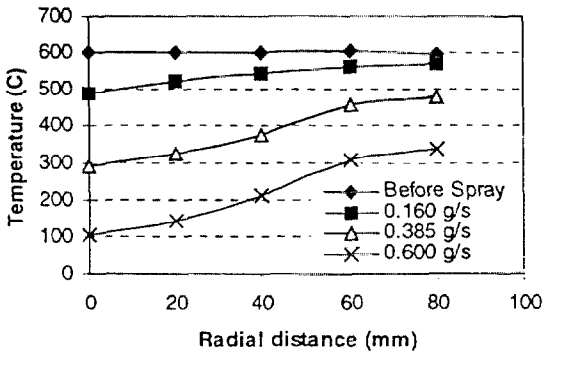

Figure 4: The steady state surface temperature distribution for the three flow rates shown in Figure 3.

(2) **The influence of initial size distribution and velocity**

Setting the flow rate constant at 0.385 g/s and changing the size distribution by varying the pressure and flow rate of the air resulted in three sprays with different size and velocity distributions. See Figure 5. Since the flow rates are the same, a higher velocity is associated with a finer spray. Figure 6 shows that the temperature profile for the finest spray, size 1, is higher than for the other two cases, and that the radial temperature profile decreases most strongly for the size 3 spray. The larger decrease is due to more large drops in the coarse spray, which are more easily deposited on the surface and then evaporated. In contrast for the fine spray, the velocity is higher and it's easier for large drops to bounce back from the plate. Hence, the total thermal energy transferred from the plate to the fine spray is less than the amount transferred to the coarse spray.

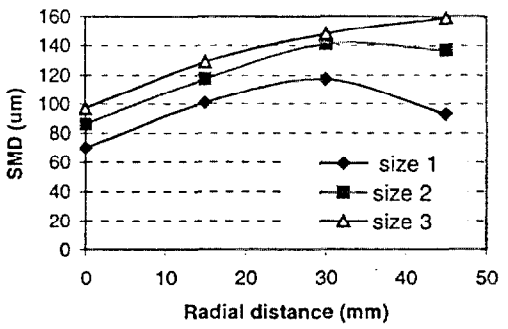

Figure 5: The initial size distributions for the three sprays at 0.385 g/s.

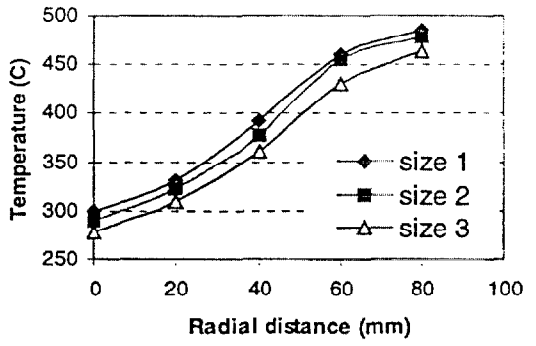

Figure 6: The steady state surface temperature profile for the three 0.385 g/s size distributions.

(b) Size distribution history

(1) **Influence of the water mass flow rate**

By applying sprays of similar size distribution, as shown in Figure 3, the influence of water flow rate was be investigated. Figure 7 shows the size distribution of the spray measured 250 mm downstream from the nozzle. Note that the SMD increases from the center of the heated surface to a maximum at some radial distance then decreases again. The spray is a solid cone, and the drop size at the center is lower because of the migration of very fine droplets from the outer

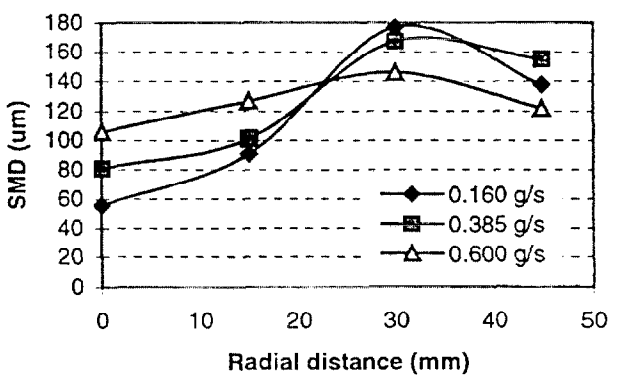

Figure 7: Size distribution of the spray in steady state, measured 250 mm downstream from the nozzle, and 4 mm above the heated plate.

part of the spray. Figure 7 shows the size distribution measured at the same location, but 4 mm above the heated plate, after reaching the steady state. We see that the size distribution has been narrowed after the spray interacts with the heated surface for the largest flow rate, while it's widened in the lowest flow rate case.

(2) **Size profiles at different heights**

For the three 0.385 g/s sprays shown in Figure 5, it's helpful to look at the size distributions at different heights, so this data was obtained at 64 and 4 mm above the heated surface respectively, as shown in Figure 8 and Figure 9. We see that the mean sizes are higher at the location closer to the surface. The simple explanation is that the number of the small drops has been reduced through evaporation, so SMD increases. This is supported by the diameter history as recorded by the PDPA, which indicates that the number of small droplets decreases dramatically. The number of the big drops is also declining, indicating that they have partly evaporated too.

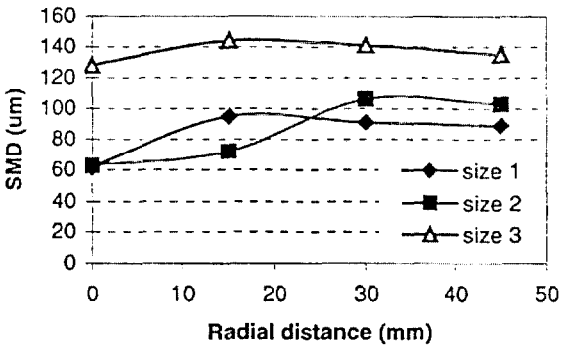

Figure 8: Size distribution of the spray in steady state at 0.385 g/s, measured 190 mm downstream from the nozzle.

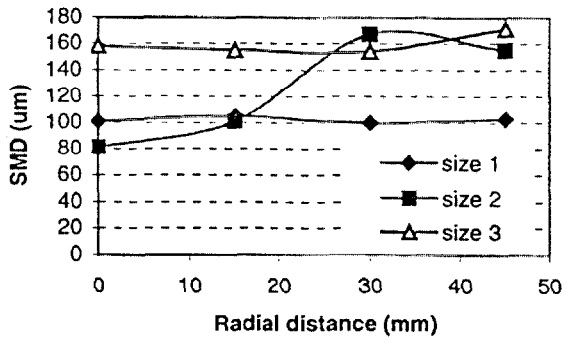

Figure 9: Size distributions of the spray in steady state at 0.385 g/s, measured 250 mm downstream from the nozzle.

(c) Velocity history

Figure 10 shows the velocity distribution for the 0.385 g/s spray (size distribution 2 shown in Fig. 5). Comparison between the two sprays at the same height before and after the spray's interaction with the heated surface shows results which at first seem surprising, because the average velocities increase after droplets have evaporated and been acted on by aerodynamic drag for some time. However, it must be kept in mind that these are polydisperse sprays containing large droplets with correspondingly higher velocities.

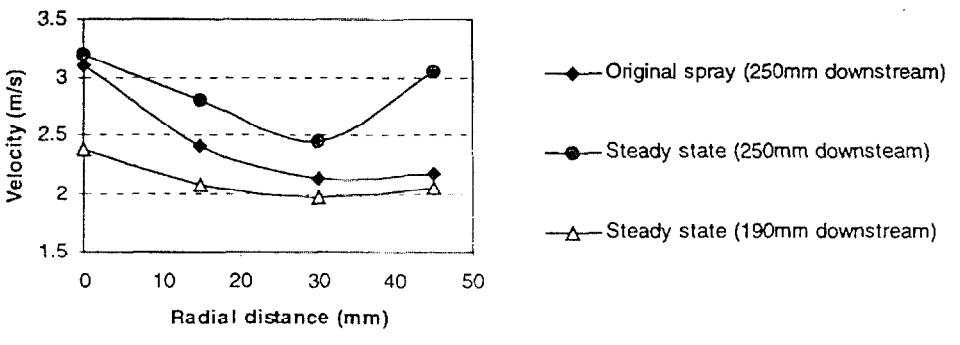

Figure 10: Velocity distributions of 0.385 g/s spray (size distribution 2), before and after the interaction at different locations.

Since the velocity distributions usually have a wide range, the contribution toward the mean value due to the larger droplets is dominant when drops approach the plate because the small droplets have evaporated. This is confirmed by the velocity histories and count numbers as recorded by the PDPA.

Summary

The current experiments considered the interaction between a heated surface and a spray, as illustrated by the surface temperature and size-velocity distribution profiles. Evaporation, obviously, played a most important role in reducing the surface temperature, changing the size and velocity. Buoyancy, which acts via the upward air stream above the heated surface, also enhances drop evaporation by lengthening the evaporation time. At the same time, the turbulence generated by the rising hot air and the downward spray also enhances the evaporation rate (Sirignano (1983) discussed such an effect by revising the d^2 law for constant properties).

Since the spray is polydisperse, it is difficult to quantitatively analyze the drop sizes and trajectories. In addition, convection, conduction and radiation were present, making it challenging to calculate how much energy was consumed by evaporation. Our next step will be to use a monodisperse spray to develop a model for droplet size and velocity in an evaporating spray.

Acknowledgement

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