Quantification of the Effect of Cooling Mists on Individual Thermal Comfort

Craig Farnham, Masaki Nakao, Masatoshi Nishioka, Minako Nabeshima
Dept. of Urban Engineering, Osaka City University, Osaka, Japan

Abstract
Fine water mists are being increasingly used as an efficient means to create "cool spots" in outdoor and semi-enclosed areas. Evaluation of the effectiveness of this cooling in humid urban areas has largely been limited to direct measurement of air temperature changes and thermal comfort surveys. A prototype analogue of a human arm is developed as an aid to quantifying the effect of mist on thermal comfort by measuring its effect on skin temperature. Using paraffin as a material and a thermal camera to record temperatures, the direct effect of fine mists on skin temperatures can be simulated. Reductions in skin temperature are 2 to 3 times expected air temperature reductions.

Key Words: water mist, thermal comfort, skin temperature

1. INTRODUCTION

Fog-like "dry" water mists are being increasingly used to create "cool spots" in semi-enclosed humid urban climates. Mists produced by hydraulic nozzles have a much higher COP than pneumatic nozzles, at the cost of producing larger diameter (SMD 20 microns) "semi-dry" mists. A balance must be maintained; with nozzles close enough to effectively cool, but far enough to reduce unpleasant wetting.
While direct measurement of the air with thermocouples has shown a limited cooling effect of around 1 - 2K in humid summer conditions (Yamada, et al., 2006), comfort surveys of passersby tend to show that the great majority report increased thermal comfort (Uchiyama, *et al.*, 2008). The direct effect of mist on the skin surface may account for this. Thermal comfort largely depends on the individual. According to ASHRAE (2005), the most important factor in the perception of comfort is skin temperature.
Previous surveys do not account for exposure time, mist density, distance from nozzles, etc. A survey incorporating these factors and including a wide range of people over a range of environmental conditions and mist characteristics would be challenging. Instead, an analogue of human skin was exposed to mists and the analogue skin temperature in relation to mist density and exposure time is determined.

2. APPARATUS AND PROCEDURE

Paraffin was chosen as an analogue for human skin. Its thermal properties and emissivity (Krupskii et al., 1965) nearly match human skin. It is inexpensive and simple to shape as desired through melting and simple molding. In this experiment a plaster mold of an author's left forearm was made. Two T-type thermocouples were installed during the molding process to monitor the deep core temperature. For surface temperature readings, a T-type thermocouple was held in place by applying melted paraffin in a thin layer, which then hardened. The sensor is still visible through the paraffin, less than 1mm below the surface. Paraffin is not suitable for general thermal mannequin usage, as it has a melting point around 53°C, it would not survive high heat or fire-related testing.

Table 1 – Thermal Properties of skin and paraffin

Material	Density (g/cm^3)	Heat Capacity (kJ/kg K)	Thermal conductivity (W/m K)	Emissivity
Human epidermis/dermis	1.2	3.2 - 3.6	0.21 - 0.32	0.98
Paraffin	0.93	3.26	0.26	0.95

To simulate body temperature, the paraffin arm was heated by placing it in a climate controlled box set at 39°C until the core temperature reached 38°C. The arm was then mounted at the misting site. When the core temperature fell to 37°C through natural convection, the surface temperature had fallen to values of 30 – 33°C (as was the skin temperature range of experimenters on site) and misting was started. This method only allows for one misting test, after which the arm is dried and heated again. The system is meant only to determine the immediate change in temperature of the surface layer, over the span of around 1 minute, where the core temperature does not have time to change in response to the cooling surface. This would coincide with studies that find mists applied locally to the skin can increase comfort, but do not affect the core temperature of subjects during exercise (Brisson et al., 1989). For future tests, a heating system will be installed in the arm.

Dept. of Urban Engineering, Regional Environmental Planning Laboratory
Osaka City University
3-3-138 Sugimoto Sumiyoshi-ku, Osaka-shi, 558-8585
JAPAN

Thermal imaging of the analogue arm side-by-side with a human arm showed that the exterior forearms qualitatively matched. The interior forearms were dissimilar, as the warmer blood vessels near the skin were clearly visible, while the analogue arm had a more uniform temperature. The temperature of fingers of the analogue arm was much lower than human fingers. Evaluation of surface temperatures was focused on the exterior forearm.

The arm was set in a cantilever-style mount atop a digital scale, accurate to 0.1g for weights up to 6kg. The mount allowed a waterproof sheet to cover the scale and mount, exposing only the arm. The scale was tared before misting. There was no detectable difference in weight after misting. Methods to better measure the amount of water adhering to the arm must be investigated.

The mount also ensured no movement of the arm, so the point temperatures in series of thermal images could be compared. The length of the arm was set perpendicular to the direction of the downward mist to maximize exposure of the exterior forearm.

The mist site was a concrete room, 3.5m X 4m with a height of 3.5m. The single window was blacked out. Average environment conditions at the times of testing are shown in Table 2. The low temperatures minimized the problem of thermal radiation from the background or reflections interfering with thermal camera measurements. Tests in hot conditions or outdoors will require more care on this point.

Table 2 Environment Conditions

Trial	Environment Conditions		
	Air Temp (°C)	Rel. Humidity	Wet Bulb Temp (°C)
1	21.0	42%	13.4
2	21.2	48%	14.5
3	20.7	49%	14.2

The mist in the experiment was produced with a single hydraulic nozzle which produces a nearly log-normal droplet distribution with an average diameter of about 20 μm and a flow rate of 36ml/min. The nozzle was mounted pointed downward on a separate rod and positioned at 1.0m, 1.5m and 2.0m above the arm. For misting periods, the nozzle was swung over the paraffin arm until the mist cone centered around the surface sensor. The nozzle was held stationary for the misting period, then swung away. Total misting times were 30 seconds.

The mist density is determined by an empirical relationship previously developed by the authors for this nozzle, based on the difference between the environment dry bulb and wet bulb temperatures and the distance from the nozzle (Farnham *et al.*, 2009). The relationship calculates the remaining unevaporated portion of the entire mist cross-section. These amounts are shown in Table 3.

3. RESULTS

3.1 Thermal Camera Sensitivity to Water Mist

Misting interferes with thermal camera readings. During the mist periods, thermal images showed lower temperatures than that of the surface layer thermocouple. Examples of this interference are shown in Figs. 1 and 2. Fine evaporating mist at typical atmospheric conditions consists of droplets at the wet bulb temperature (Pruppacher and Klett, 1997), so it is expected that thermal images through fine mists will trend toward the wet bulb temperature. After misting is stopped, the thermal camera values return to near the thermocouple temperatures.

Emissivity settings have a strong effect on the thermal camera readings. Point readings were taken with emissivity set at 0.95. For example, a change from 0.95 to 0.96 changes a point reading amongst the data here from 30.2°C to 29.8°C. Water droplets accumulating on the paraffin surface may influence emissivity settings. However, water itself has an emissivity of 0.95-0.96, the same as paraffin.

3.2 Temperature Reductions

In all cases, thermal camera readings of the surface showed greater temperature reductions than the embedded near-surface thermocouple. The thermal image values seem to have a closer relationship to the amount of remaining mist, whereas the thermocouple readings are nearly similar for trials 2 and 3, despite a 16% reduction in mist amount. Temperatures at the embedded thermocouple steadily decreased during the misting period, while camera readings showed a maximum drop during the misting, due to mist interference. The misting periods were short enough such that there was little to no effect on the core temperature.

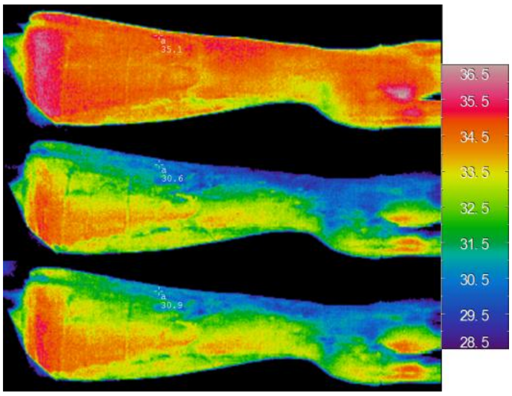

Fig. 1. Trial 2 thermal images. Top : before misting. Middle : during 30 sec. misting period. Bottom : 10 sec. after misting stopped.

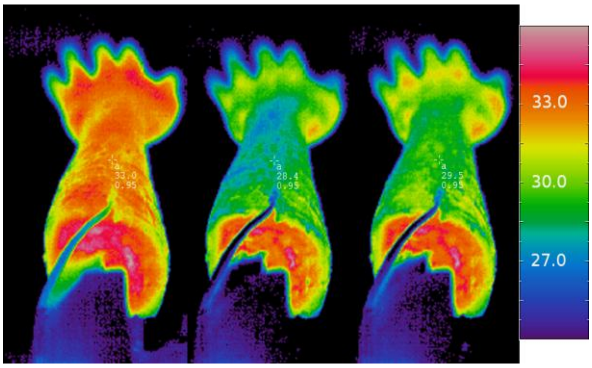

Fig. 2. Trial 3 thermal images. Left : before misting. Middle : during 30 sec. misting period. Right : 10 sec. after misting stopped.

Table 3 Mist amounts and temperature readings

Trial	Distance (m)	Remaining. mist flow (of 36ml/min)	Surface Temp (°C) (camera / thermocouple)			Surf. Temp. drop (K) (cam / tcpl)	Core Temp. drop (K)
			Before mist	During mist	10 sec after		
1	1.0	54%	32.8 / 33.2	25.3 / 28.9	26.9 / 27.5	6.3 / 5.3	0.2
2	1.5	46%	35.1 / 34.6	30.6 / 33.0	30.9 / 31.3	4.2 / 3.3	0.0
3	2.0	38%	33.0 / 32.8	28.4 / 30.2	29.5 / 29.4	3.5 / 3.4	0.1

4. CONCLUSIONS

The paraffin arm can be used as an inexpensive means to evaluate the effects of water mist cooling on human skin areas that have a fairly uniform temperature such as the exterior forearm. Surface temperatures fall quickly and remain low after misting is stopped, as the droplets that have adhered to the skin evaporate. Reductions in skin temperature were 2 to 3 times greater than typical air temperature reductions. Increasing amounts of mist increase the temperature drop. Future surveys of thermal comfort in mists should include skin temperature of human subjects on site as a more concrete value than opinion surveys.

Further study is needed to compare a range of human subjects' skin temperatures with the paraffin analogue. A method to determine the amount of water adhering to the skin is needed. More detailed research into the effects of the adhering water on surface reflectivity and emissivity and the effect on thermal camera readings is needed. These experiments will be continued in hot summer conditions.

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