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Case Study: Thermal Comfort in a Water Mist on Hot Summer Days

Craig Farnham and Kazuo Emura

Osaka City University, Dept. of Housing and Environmental Design, Osaka-shi Sumiyoshi-ku, Sugimoto 3-3-138, Japan 588-8585

Abstract:

In a case study on outdoor mist cooling, 141 people attending an open campus event were surveyed over 2 hot summer days. Nozzles mounted on an oscillating fan sprayed about 18L/h of mist with average droplet diameter of 25μm. Subjects stood in the misting area where they wished. Time spent in the misting area was recorded. Skin temperature of the forearm and face were taken with IR surface thermometers before entering and after leaving the misted area. Each participant was surveyed for "thermal sensation" on a 9-level scale, and "general comfort" and "feeling of wettedness" on 7-level scales. "Feeling of wettedness" included an additional qualitative parameter of "unpleasant", "pleasant" or "neither".

Misting will increase wettedness, but it can feel pleasant. On average, thermal sensation dropped from +2.7 (very hot) to -1.4 (slightly cool) and comfort increased from -1.4 to +1.8. Though wettedness increased from +0.8 to +1.6, the qualitative wettedness parameter changed from 75% unpleasant to 75% pleasant. Skin temperatures dropped an average of 1.1˚C on the forearm, and 1.0˚C on the face.

Key Words: water mist, evaporative cooling, thermal comfort, fan cooling

1 Introduction

Use of mist evaporative cooling for thermal comfort in outdoor and semi-enclosed spaces is increasing in Japan, yielding temperature reductions on the order of 2 – 3K on hot summer days (Yamada et al. 2006). Simple surveys of comfort and wettedness showed that about 77% of people experienced increased comfort in a misted area (Uchiyama et al. 2008). Evaluation of the cooling effect of a mist is difficult as results often include readings that indicate that sensors near or within the mist tend to read at the wet bulb temperature (Hayashi et al. 1998, Miura et al. 2008, Suzuki et al.2009).

Most of the evaporative mist sprays in the literature in Japan consist of droplets of average diameter on the order of 10 - 30 microns. The smallest droplets are generated by pneumatic nozzles driven by high pressure air, while 20 micron droplets can be generated by hydraulic nozzles driven by high-pressure water pumps. The energy consumed by hydraulic spray nozzles is usually lower than air-driven, but at the cost of larger droplets which evaporate more slowly, making wetting of surfaces more likely.

In addition to improved thermal comfort, evaporative cooling mists could be a preventive measure against heat-related illness. Water mists are recognized as a valid emergency medical treatment for heat stroke (Biddinger, 2002). Yet spraying a localized cooling water mist only on the face for comfort has been found to yield no change in core body temperature (Brisson et al., 1989).

The above misting experiments in Japan all involved free falling mist from nozzles set above the target area to be cooled. Placement and control of the spray is designed to limit wetting of the ground and surfaces. However, this results in relatively thin mist such that the measured temperature drops in the zone of human activity may be only 1 – 3K. If the mist is more dense, wetting of surfaces will more likely occur and could be unpleasant. Combination of a fan with mist nozzles could improve thermal comfort on hot days better than either method on its own. The forced convection of the fan that helps cool people will also help speed evaporation of mist droplets that have adhered to skin and clothing. A detailed investigation of a fan and mist cooling system for thermal comfort on hot summer days is needed. A model for thermal comfort improvement due to use of mist fans is also needed to aid in system design and use.

2 Theory

Small mist droplets cool rapidly from the source temperature to about the wet bulb temperature and an individual droplet evaporation rate can be expressed as directly proportionate to the wet bulb depression. (Pruppacher, 1997) In the case of 25 micron scale droplets in typical atmospheric conditions, the change takes a few milliseconds, while the droplets decelerate almost instantly to near zero relative velocity to surrounding air, taking about 50 milliseconds as determined by iterative calculations outlined by Chaker (2002) and Holtermann (2003).

The mist "cone" as a whole will evaporate away in proportion to the time, and therefore distance, traveled. Finely sprayed mist, such as used here, were found to evaporate in proportion to the wet bulb depression in earlier research (Farnham, 2009). During the experiments here, the wet bulb depression was about 8K, as calculated using approximations from the HASP/ALCD (JAMBEE,1992).

2.1 Thermal comfort

Thermal comfort and means to calculate indices such as PMV and PPD are explained in detail in the ASHRAE Handbook – Fundamentals. Key concepts important to the use of mist evaporation include:

- The theoretical cooling limit of sweating at maximum sweat rate with good evaporation conditions is about 675W/m^2. (Compare this to the potential evaporative cooling of impacting mist, which with this misting fan may exceed 1000W/m^2 if the mist can evaporate completely)
- "Skin temperature is the best single index of thermal comfort."
- When in a state of thermal discomfort, any move away from thermal stress is perceived as pleasant during the transition.

Mist cooling has the potential to cool the body much more effectively than even the maximum possible natural sweat rate. A difficulty with the ASHRAE standard models is the version in the 2005 handbook is designed only for air velocities much lower than from this fan. Equations for the convection heat transfer coefficients are only offered for velocity up to 4.0m/s. Values of clothing permeability offered are only valid for air velocity under 0.2m/s.

3 Experiment

A mist cooling system with a fan was set up outdoors in an area partially shaded by buildings and trees at our university during an open campus event for high school students and their families. The mist was directed to an area well shaded by trees usually used as a resting area with benches and chairs available.

The main experiment measured both the change in skin temperature and the perception of thermal comfort of the subjects before and after entering the mist area. However, as the subject were volunteers recruited “on the street”, a rigid experiment protocol with multiple trials per subject was not practical. Secondary experiments measuring skin temperature of a small number of subject in a more regular manner were also done, however, with repeated trials on a small number of people, a thermal comfort survey was not done.

3.1 Experiment apparatus for main trials on thermal comfort perception

The mist cooling system consists of a hydraulic pump, hoses, a ring header and 8 nozzles. The nozzles are mounted around the edge of an oscillating fan with a diameter of 35cm and a flow straightener cowling. The pump pressurizes the water to 6MPa, producing a mist from the nozzles with droplets of Sauter Mean Diameter of 25 microns. The flow rate of each nozzle averages to 0.67ml/s, yielding a total mist flow of 5.35ml/s, or about 19L/h at the nozzle outlets. During the trials, the mist was seen to completely evaporate within about 5m of the fan.

The airspeed immediately in front of the fan was 7m/s as measured with a hot-wire anemometer with the nozzle spray off. The fan has an oscillation period of 30 seconds, swinging over a 90 degree arc, but it was kept in a fixed position for most experiments excepting brief periods during the trial in which participants asked to see the oscillation in action. Most participants stood directly in the line of the fan, with a maximum of 3 participants at one time, such that all could experience the mist cooling. Some participants chose to sit on a bench located 4m from the fan. The velocity profile along the centerline of the fan at set distances is given in Table 1.

Additional misting was produced from 8 more nozzles of the same type and flow rate from stationary headers. One placed near a bench at a height of 50cm spraying diagonally upward, and one mounted to the building wall at 3m height spraying diagonally downward to help cool the area as well as some of the air entrained into the fan. Most participants would choose to stand near in front of the fan. It should be noted that the air velocity near the fan exceeds the limits on locally controlled air velocity in the ASHRAE Thermal Comfort Tool based on ASHRAE 55-2010 as supported on the UC Berkeley Center for the Built Environment web tool. (Tyler et al. 2013)

Air temperature and humidity were measured with data recorders equipped with temperature/humidity sensors. Skin temperature of the test subjects was measured on the face and forearm with two non-contact infrared thermometers designed for medical use, accurate to 0.2˚C. A box was designed to assure repeatability in measuring the same location of the arm with a hole to insert the arm, a hand grip to keep the arm in place, and a second smaller hole through which to read the skin temperature. A similar rig was attempted for the head with a cradle for the chin and a mounted non-contact thermometer, but proved impractical during testing and was not used. Two thermo-cameras were used to take images of each subject. Six stopwatches were used to record the time each person spent in the mist. Globe thermometers were used to measure the mean radiant temperature of the test space.

The testing area was in a shaded area near the entryway for the buildings of the department. Students and families visiting the department would first encounter the mist testing setup. Most families had walked approximately 5 minutes from the nearby train station along a brick walkway, partially shaded by trees. Some arrived after visiting other departments on campus. A small number tried the mist when leaving the building. It is assumed the metabolic rate of all subjects is that for slow walking.

Table 1: Velocity profile of the mist fan with mist off

Distance from fan (m)	Air velocity (m/s)
0.0	7.0 - 7.2
1.0	6.3 - 6.7
2.0	5.3 - 5.7
3.0	3.2 – 3.5
4.0	2.6 – 2.8
5.0	1.8 – 2.0
6.0	1.5 – 1.8

Figure 1: Left: Photo of the test area. Right: Staff and test subjects during testing.

To estimate the amount of mist impacting per unit area, some trials with mist collectors set at 3m and 4m from the fan along the centerline were done in a 8m X 5m X 3.5m room, such that the room quickly became saturated, retarding evaporation of the mist and evaporation of collected mist from the collector itself. This should yield a maximum possible mist impact per unit area. With this fan, the value was $1.75x10^{-4}g/cm^2s$ at 3m and $4.6x10^{-4}g/cm^2s$ at 4m. In actual use the amount is much lower due to evaporation. Given a heat of evaporation of 2450kJ/kg for water. The potential cooling from evaporation of the $0.014g/cm^2s$ is over $1000W/m^2$.

3.2 Procedure for main trials on thermal comfort perception

Experiment subjects were recruited from the visitors to the university on the weekend of the Osaka City University open campus event, August 10 -11, 2013. Approximately 10% of those visiting the department took part in the experiment. There may be some selection bias as people who may expect the mist to be unpleasant would choose not to participate.

The weather on each day was sunny and among the hottest days of the year, the nearest meteorological station at Sakai (about 5km from the test site) recorded a high temperature of 36.9˚C on August 10 and 37.6˚C on August 11, making it the second hottest day of that year. Due to safety and accuracy concerns with the globe thermometer stands, the globe thermometer measurements were done on the following weekend, under similar weather conditions, sunny and hot (36.3˚C at Sakai). Globe temperature in the shaded area when not using mist was found to match the air temperature.

As each person approached the area a staff asked if the person would like to take part in an experiment with mist for “about 5 minutes”. If the person accepted, the following steps were taken.

1. Staff asks the personal data questions (age, sex, etc.) on the survey form or asks the subject to fill those items in.
2. Staff quickly checks off boxes on the “clothing worn” chart. The system may be confusing and not left to the subjects.
3. Staff measures temperature of the right cheek under the eye with the IR thermometer and notes it on the form.
4. Staff asks subject to put the right arm in box and grip the handle, then measures the forearm temperature with an IR thermometer.
5. Staff takes images of the face and forearm with the thermo-camera.
6. Staff quickly explains the thermal sensation, comfort and wettedness ranks and asks the person to make their votes before entering the mist.
7. Staff also explains the special item on perception of wettedness.
8. Staff starts a stopwatch, gives it to the subject and notes the time on the form.
9. Staff tells subject to enjoy the mist for as long as desired, to stand or sit if desired, and to return to the survey table when done.
10. When done, the stopwatch is collected and total time spent in the mist noted.
11. Arm and face IR temperature and thermo-camera images are done again.
12. The subject is asked to vote on thermal sensation, comfort and wettedness feelings he/she felt while in the mist.
13. Subject is asked to write any additional comments as desired and thanked for his/her time.

The procedure was not followed in exact order when the number of subjects exceeded the number of staff taking measurements. At times, there were delays of up to 1 minute between exiting the mist and temperature measurements.

A total of 141 subjects completed the survey forms. There were some omissions in a handful of cases. However there was a large number of omissions on the “perception of wettedness” item, which was only completed correctly by 59 people. Though 17 more only answered the after mist item, omitting the before mist item.

3.3 Survey questions

The survey form included the following items.

Personal data: age, sex, home prefecture (state), wearing sunblock? wearing makeup?

Clothing worn: A simple diagram of a body with check boxes for shirt, half sleeve, long sleeve, shorts, knee length shorts, pants, socks, hat, gloves, sandals, skirt, stockings/leggings. Due to the hot weather, each check box is later correlated with the lightest weight article from the clothing insulation chart in the ASHRAE Handbook (ASHRAE, 2005). All subjects were assumed to be wearing the lightest weight clothing possible on the hottest week of the year, which proved true.

Skin temperature: Arm and face (cheek). Before mist and after mist.

Thermal sensation: 9 level scale starting at Extremely cold (-4), very cold, cold, cool, mild, warm, hot very hot, extremely hot (+4)

Overall comfort: 7 level scale starting at Very uncomfortable (-3), uncomfortable, slightly uncomfortable, neither, slightly comfortable, comfortable, very comfortable (+3)

Skin wettedness sensation: 7 level scale starting at Very dry (-3), dry, slightly dry, neither, slightly wet, wet, very wet

Wettedness impression: The subject was asked, if feeling wettedness, “Is the wet feeling pleasant, unpleasant, or neither?” If the subject did not understand the concept, it was explained “For example, if you are damp from sweating, does that feel unpleasant?” Some staff forgot to ask subjects about this item.

Comments: Free comment section.

3.4 Results of main trials on thermal comfort perception

Survey form data was entered into a spreadsheet. The averages of all 141 cases are shown in the tables below. The skin temperature change averaged a drop of 1.1˚C at the arm, and 1.0˚C at the face. The thermal sensation started at an average of +2.7 (hot) before misting and dropped to -1.41 (slightly cool) after misting. Wettedness sensation increased, but as shown in the pie charts below, 75% of wettedness after misting was rated as pleasant, where wettedness had been rated as 75% unpleasant before misting.

Table 2: Measured skin temperatures before and after misting

	Measured point	Average (˚C)	Std. Dev. (˚C)
Before mist	Arm	34.0	0.92
	Face	34.9	0.87
After mist	Arm	32.9	1.49
	Face	33.9	1.20
Temperature change	Arm	-1.1	1.24
	Face	-1.0	1.06

Table 3: Results of thermal comfort votes from before and after misting

		Average	Std. Dev.
Before mist	thermal sensation	+ 2.71	0.93
	comfort sensation	- 1.41	1.04
	wettedness sensation	+ 0.82	1.21
After mist	thermal sensation	- 0.35	0.95
	comfort sensation	+ 1.82	1.01
	wettedness sensation	+ 1.56	0.86
Comfort level change	thermal sensation	- 3.06	1.33
	comfort sensation	+ 3.23	1.27

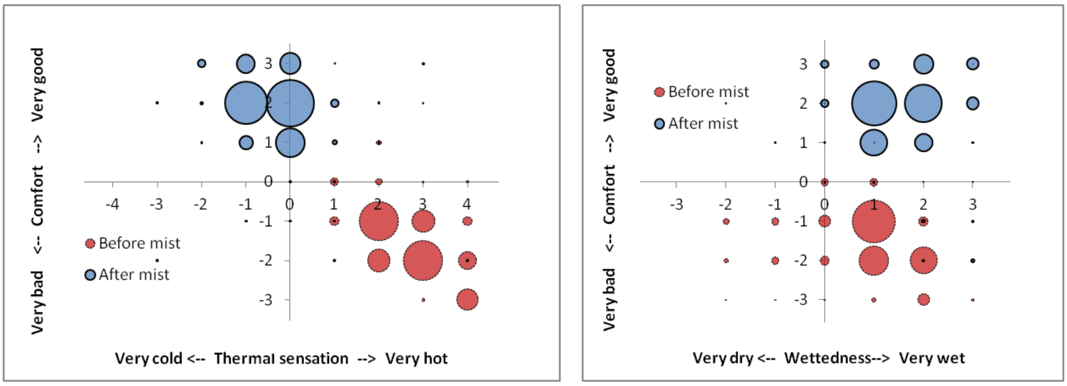

Figure 2: Left: Plot of thermal sensation votes vs. comfort votes with bubble size proportional to number of people. Total 141 people. Right: Plot of wettedness votes vs. comfort votes.

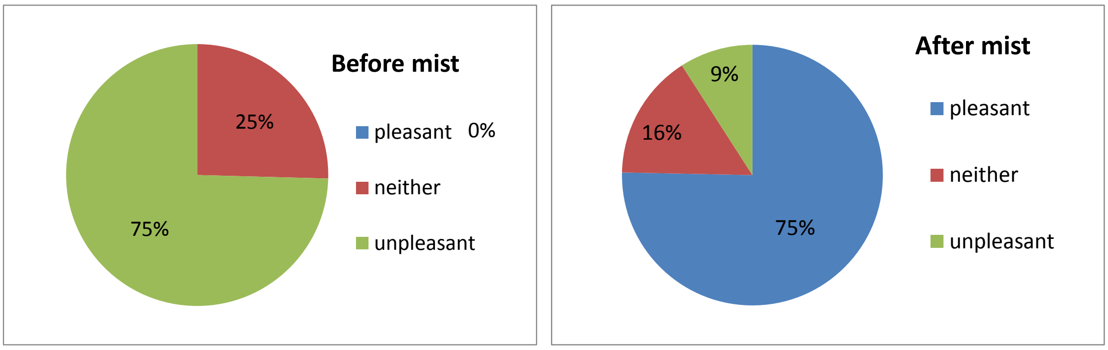

Figure 3: Perception of skin wittedness before and after entering mist.

The change in temperature of each case, and the change in the vote are plotted against the total time spent in the mist in the figures below. There is no clear trend in any case.

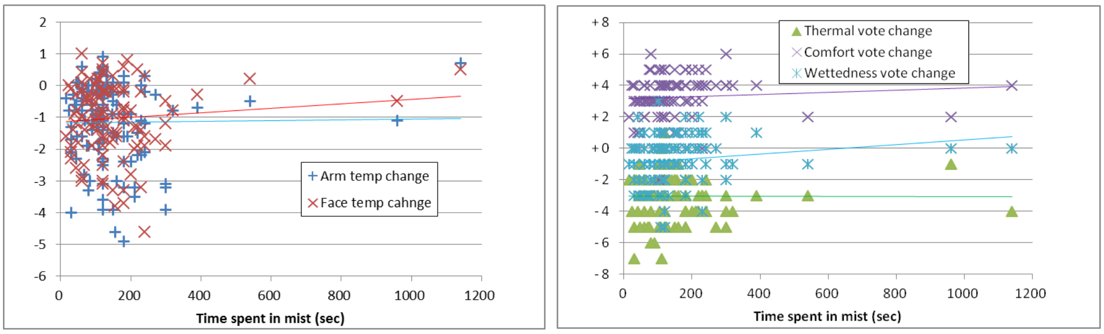

Figure 4: Difference in results before and after mist plotted against time spent in mist. Left: temperature changes. Right: thermal vote changes

No correlations could be developed from clo values, as the clo value of most subjects was nearly the same. The average was 0.37clo, with a standard deviation of only 0.08clo. Most people were wearing their lightest clothing for the hot summer day. For example, only 11% of subjects wore long sleeves of any kind. Only 40% wore pants or skirts of ankle-length. The results showed that skin temperatures dropped by about 1 degree, and comfort nearly universally improved.

3.5 Procedure for transient measurement of skin temperature

During preparatory experiments and during the trial itself, it became clear that skin temperatures changed noticeably and rapidly, if not instantly, when exposed to the misting fan. A more controlled set of experiments was done with the 4 staff to measure the change in skin temperature over time. Each staff subject stood at a set distance from the fan between 3 – 6m with one arm relaxed but extended outward at the elbow, parallel to the ground, exposing the inner side of the forearm to the mist. The inner side was chosen due to there being less body hair to interfere with the result. (In the author's personal experience, body hair can act as a mist droplet trap.)

An IR thermometer was held in the other hand, moved to a single spot on the arm, the measurement trigger pulled, then the thermometer is removed to the side to avoid blocking mist. In the first set of trials, this was repeated every 30 seconds, remaining in the mist for 120 seconds. In the later trials this is repeated every 5 seconds without leaving the mist. The measurements were first done about 4 times to establish a baseline, then the subject walked into the misted area and performed the measurement. The test was also repeated with only the fan running and no mist. The details of the trials are shown in the table below. Air temperature ranged from 30.3 – 30.4C, with relative humidity at 50% and a wet bulb depression of 7.8K

Table 4: Transient skin temperature measurement conditions for long measurement period trials

Case	Meas.period (s)	Dist. From fan (m)	Mist?	Init skin temp (˚C)
A	30	6	Yes	31.5
B	30	4	Yes	33.4
C	30	4	Yes	33.9
D	30	4	**No**	33.9
E	30	4	**No**	31.4
F	30	4	Yes	31.3
G	30	6	Yes	33.4
1	5	6	Yes	32.1
2	5	4	Yes	31.7
3	5	5	Yes	31.8
4	5	4	Yes	33.9
5	5	4	Yes	31.9
6	5	3	**No**	31.1
7	5	3.5	Yes	34.2
8	5	3	Yes	32.4
9	5	3	Yes	31.8
10	5	4	Yes	34.7
11	5	4	**No**	31.8
12	5	4	**No**	34.1

3.6 Results for transient measurement of skin temperature

Plotting the change in temperature over time, with the base temperature as the average of the 4 measurements before entering the mist shows drops in most misting cases, but no significant change in the fan only cases with no mist. Stronger drops tend to happen at closer distance. Longer trials at 30 second intervals showed the time to recovery after leaving the mist (at 120s) could be 2 minutes or up to 7 minutes. The arm had become significantly wet in these cases.

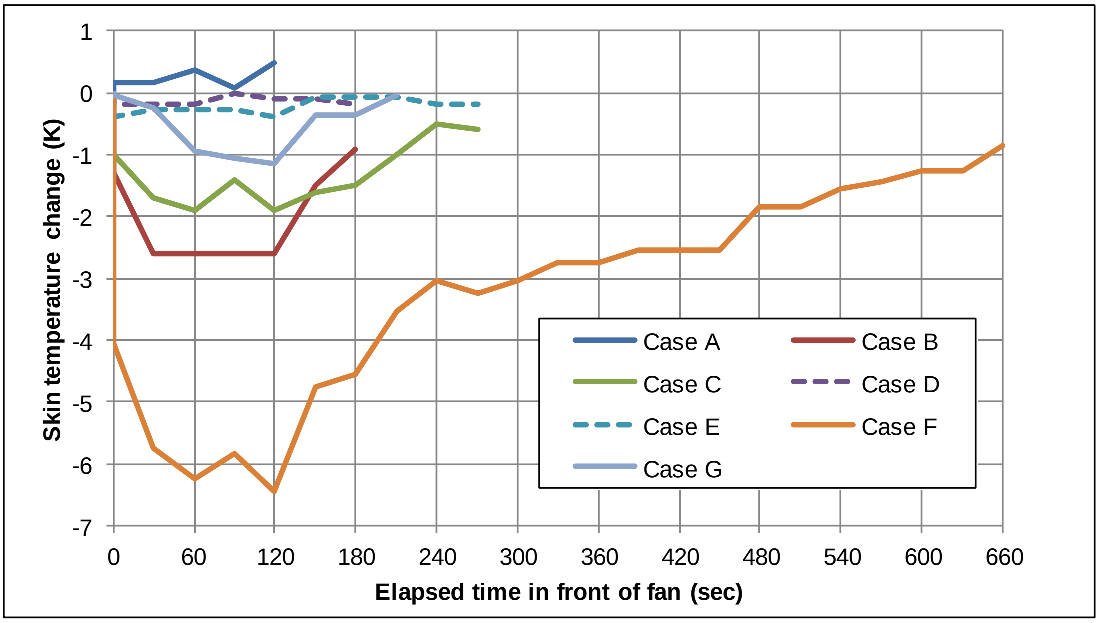

Figure 5: Change in skin temperature and after entering mist, remaining for 120 seconds, then leaving.

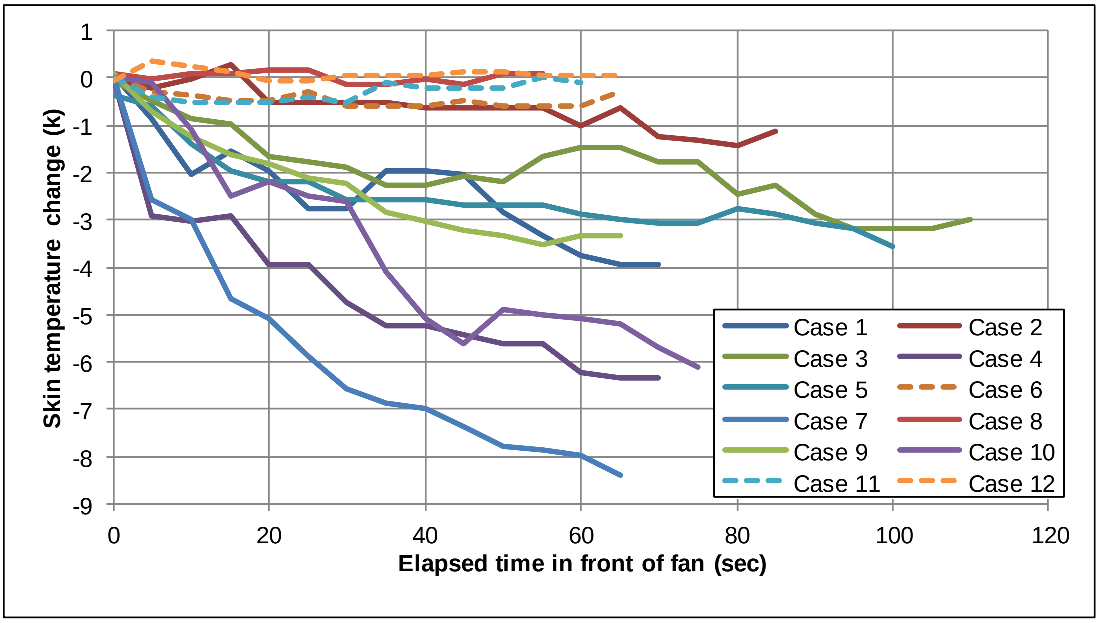

Figure 6: Change in skin temperature measured every 5 seconds and after entering mist.

Skin temperatures drop quite rapidly even in sparse mists, often 2 degrees in the time it takes to get the first measurement. The fan alone in these cases yields little or no drop in skin temperature. Mist seems to provide instant relief from the heat. With continuing drops over time and lingering effects after the skin becomes wet.

4 Conclusions and Discussion

Mist nozzles combined with a fan can yield great relief to thermal discomfort on hot summer days even in a relatively humid climate such as in Japan. Skin temperatures were measured as 1 degree cooler even after leaving the mist. Measurements taken inside the mist showed that exposed skin temperatures could drop 2 degrees within 5 seconds with light wetting. The density of the mist in the misting fan used here could easily exceed the maximum potential cooling due to sweat evaporation alone.

This effect is likely the result of skin wetting and subsequent evaporation. Although wet skin is typically assumed to be unpleasant, in this case the test subjects were asked if the wet sensation felt pleasant or unpleasant. 75% of respondents said the wettedness from the mist was pleasant, while 75% of respondents had claimed their state of wettedness before entering the mist (due to their own sweating) was unpleasant.

No correlation could be found between time spent in mist and degree of effect. This was likely due to allowing the subjects to freely choose their location in the misted area. The visible nature of misting may help people better control their own experience. Mist evaporates away at greater distance from the fan, so subjects seeking more cooling may choose to stand in the visibly dense mist, while those worried about wetting may choose to stand beyond the visible mist cloud.

Research will continue towards quantifying the effects and developing a model of mist cooling comfort.

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