ミストファンを使用し室内冷却するシステムの効果

EFFECTS OF AN INDOOR COOLING SYSTEM USING MIST FANS

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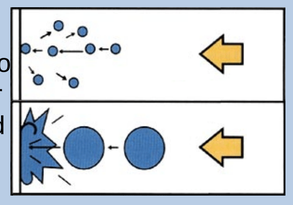
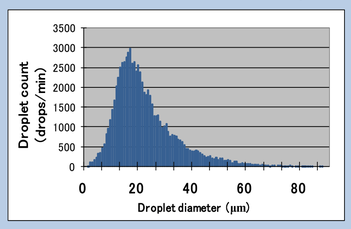
Water Mist for Evaporative Cooling

Micron-scale droplets tend to rebound rather than break and cause wetting



Hydraulic nozzles spraying average droplet diameters around 20-50μm



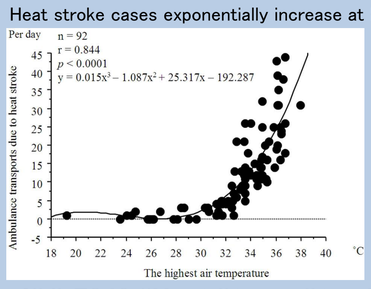
750W high-pressure water pump can spray 240liters/h from100 nozzles. Evaporative cooling of 164kW yields **COP>200**

However, temperature drop is limited to wet bulb depression (*In practice, about half that at most*).

In Japan, wet bulb depression is about 7K in summer, 10K on the hottest days

Problem: Risk of Heat Stroke in Factory

Heat stroke cases exponentially increase at higher temperature



Average ambulance transports per day for heat stroke in Osaka
Nobuyuki Miyatake et al.
Open Journal of Preventive Medicine Vol.2 No.1(2012)

Factory workers must wear lightweight uniform of long sleeves and cap (clo ≈ 0.8)
Light factory work ≈ 2met

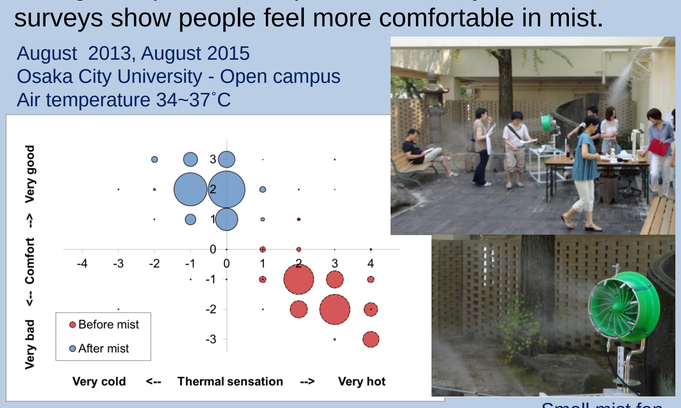
ISO 7243 “Heat Stress Standard”

- Limit heat-related illness for work and activity in hot environments , using Wet Bulb Globe Temperature (WBGT) as the standard
- WGBT calculation is weighted average of 70% wet bulb temperature, 30% globe temperature
- In evaporative cooling, wet bulb temperature does not change, WBGT standard does not work.

Comfort Surveys for Mist Fans

Though temperature drops are often only **1 – 3K**, surveys show people feel more comfortable in mist.

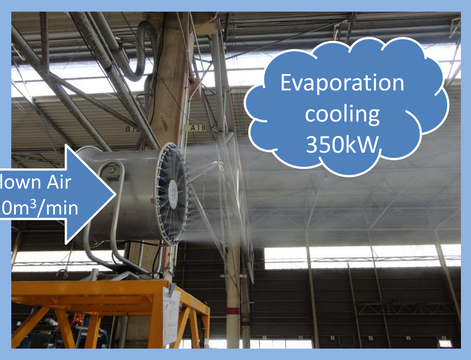
August 2013, August 2015
Osaka City University - Open campus
Air temperature 34~37˚C



Thermal sensation improved 3 steps on average among 141 surveyed people

Small mist fan
Spray volume 19ℓ/h
Blown air 80m³/min

Misting fan specifications



Droplet Sauter Mean Diameter　d_{32} = 25μm
Area of cooling with oscillation : Approx. 4000m²
Daily operating cost (6 fans, water + electric) : 3500yen

1 pump supplies 6 mist fans
Pressure = 6MPa
Spray volume = 510ℓ/h
Electric power = 750W

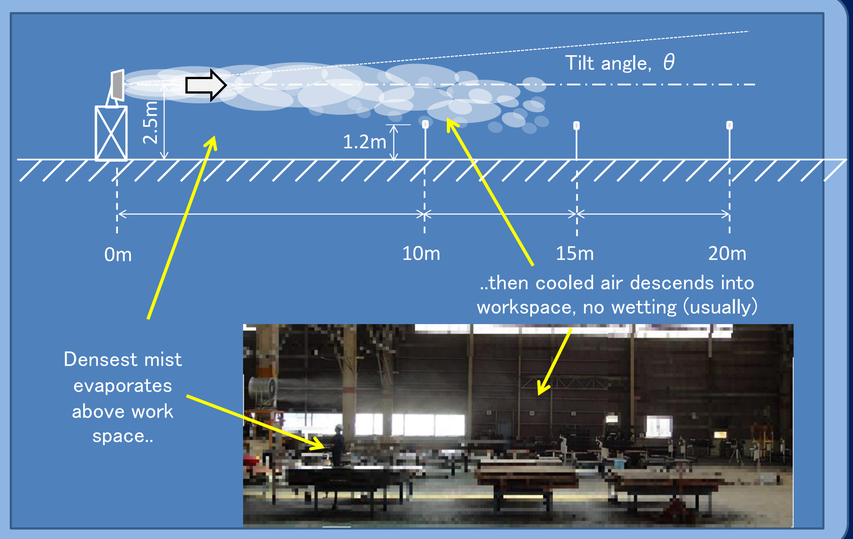
Experiment Conditions

September 21-22, 2014
Factory warehouse in Mie Prefecture, Japan

Weather:
Sunny
Air temperature 26~28˚C
Humidity 42-45%

Characteristics of the indoor space:

- 40,000m² floor space, 500,000m³ air volume
- Natural ventilation
- Open vehicle doors, windows on all sides
- No dividing walls
- Low worker density, mostly dry storage space



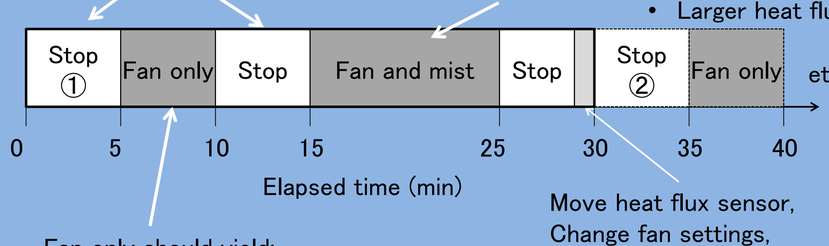
Experiment Procedure

No fan, no mist should yield:

- Natural convection baseline

Fan and Mist should yield:

- Temperature decrease / humidity increase
- Larger heat flux



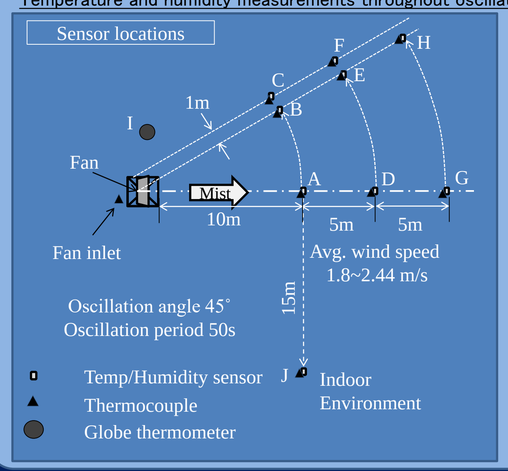
Fan only should yield:

- No temperature / humidity change
- Forced convection heat flux only

Move heat flux sensor,
Change fan settings,
Start next trial
Total of 16 trials over 2 days

Measurements : Temperature, Humidity, Surface Heat Flux

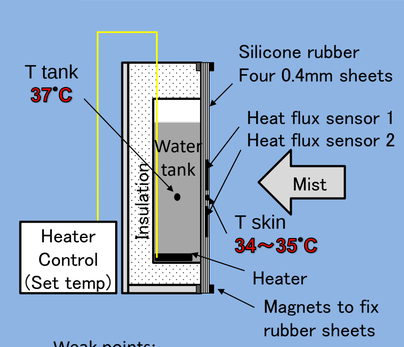
Temperature and humidity measurements throughout oscillation area



Temperature / Humidity (thermistor / capacitive)
Slow response
Record interval: 20s

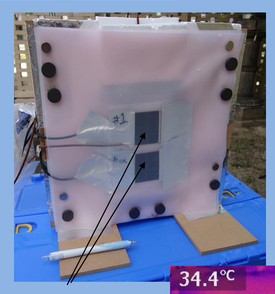
Temperature
Unshielded thermocouple (T-type)
Fast response
Record interval: 1s

Heated skin analogue to measure heat flux change due to mist

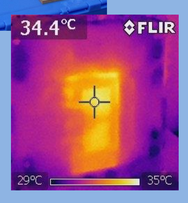


Weak points:

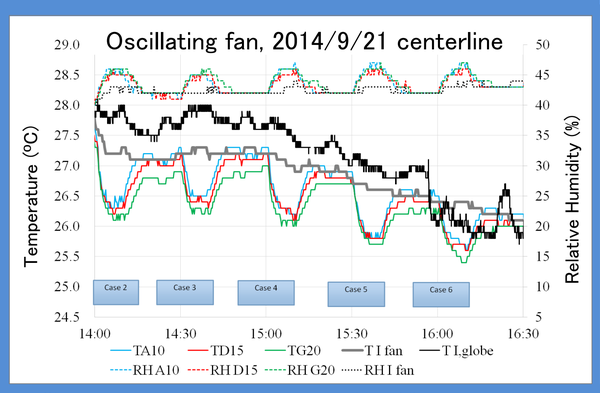
- No sweat on the “skin”
- No clothes



5cm X 5cm heat flux sensors embedded under 1 layer of silicone rubber (0.4mm)

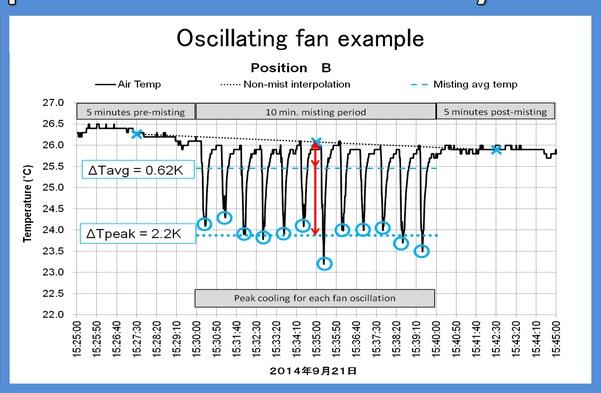


Results of Temperature and Humidity Measurements



Slow response sensor temperature and humidity measurements

- Average temperature drops about 1.0~1.5K
- Average humidity increase about +5%



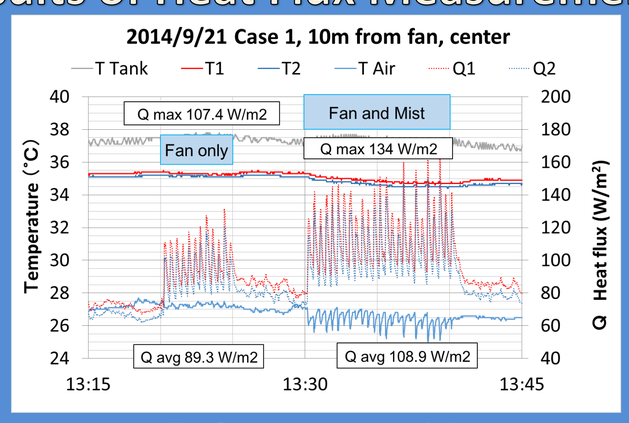
Fast response sensor temperature measurements example data

- Time-averaged temperature drops are small due to large periods with no mist during oscillation
- Peak temperature drops (as mist hits sensors) are much larger

Test runs			1 through 6		11 through 16	
Conditions			Osc. Tilt = 0˚		Osc. Tilt = -4˚	
Sensor point	Dist. (m)	Align	ΔT_{avg} (K)	ΔT_{peak} (K)	ΔT_{avg} (K)	ΔT_{peak} (K)
A	10	Ctr	0.5	1.9	0.5	3.0
B	10	Edge	0.6	2.2	0.5	2.5
C	10	Outer	0.0	1.0	0.2	1.8
D	15	Ctr	0.3	1.2	0.2	1.6
E	15	Edge	0.5	1.7	0.3	1.8
F	15	Outer	0.3	1.3	0.2	1.6
G	20	Ctr	0.4	1.1	0.2	1.2
H	20	Edge	0.5	1.5	0.4	1.5

- Average temperature drops about 0.5K due to large periods with no mist during oscillation
- Peak temperature drops (as mist hits sensors) about 1.0~2.2K

Results of Heat Flux Measurements



Heat flux measurements example data

- Heat flux with no fan, no mist is about 60~80W/m²
- Heat flux with fan increases, fluctuates as fan oscillates
- Heat flux with fan and mist is even higher

Heat Flux by Fan only vs. Fan + Mist

Conditions				Fan only			Fan and Mist			Fan effect		Fan and Mist effect	
Dist (m)	Align	Tilt (˚)	Osc/ Fixed	Heat flux (W/m²)			Heat flux (W/m²)			(W/m²)		(W/m²)	
				Before	Avg	Peak	Before	Avg	Peak	Avg	Peak	Avg	Peak
10	Ctr	0	Osc	67	93	112	80	109	134	+ 26	+ 45	+ 29	+ 54
10	Edge	0	Osc	75	99	135	76	110	166	+ 24	+ 60	+ 34	+ 90
15	Ctr	0	Osc	73	98	114	72	105	126	+ 25	+ 41	+ 33	+ 53
15	Edge	0	Osc	67	90	120	66	100	144	+ 23	+ 53	+ 33	+ 77
20	Ctr	0	Osc	73	96	106	77	108	127	+ 23	+ 33	+ 31	+ 49
20	Edge	0	Osc	73	97	117	75	105	138	+ 23	+ 44	+ 30	+ 63
15	Ctr	0	Fixed	89	161	176	87	179	189	+ 72	+ 87	+ 92	+ 102
20	Ctr	0	Fixed	80	131	143	75	144	155	+ 51	+ 64	+ 68	+ 80
15	Ctr	-4	Fixed	73	144	153	77	179	190	+ 70	+ 80	+ 102	+ 113
10	Ctr	-4	Fixed	74	155	174	73	237	262	+ 81	+ 100	+ 164	+ 189
10	Ctr	-4	Osc	73	104	152	65	108	171	+ 31	+ 78	+ 43	+ 107
10	Edge	-4	Osc	59	92	144	60	108	191	+ 33	+ 85	+ 48	+ 131
15	Ctr	-4	Osc	65	95	120	70	107	137	+ 30	+ 55	+ 37	+ 67
15	Edge	-4	Osc	66	95	135	68	109	169	+ 29	+ 69	+ 41	+ 101
20	Ctr	-4	Osc	75	105	118	76	114	133	+ 30	+ 43	+ 39	+ 57
20	Edge	-4	Osc	81	105	133	82	119	158	+ 24	+ 52	+ 37	+ 76
Avg.				**73**	**110**	**134**	**74**	**128**	**162**	**+ 37**	**+ 62**	**+ 54**	**+ 88**
							Added mist effect (above fan only)					**+18**	**+24**

- Forced convection from fan only yields increased cooling
  Time-averaged +37W/m² Average of peaks in oscillation +62W/m² This is fairly high due to the low air temperature (26~28˚C) relative to the skin temperature (34~35˚C)
- Mist effect above the fan only effect
  Time-averaged +18W/m² Average of peaks in oscillation +24W/m²

Would humidity rise be too high?

Mass balance of water vapor for ventilated room, assuming constant air density

$$M\frac{dY}{dt} = F + qY_o - qY$$

M, room air mass (assumed constant)
Y, water vapor mass fraction in air
Y_o, water vapor mass fraction of outdoor air
Ys, water vapor mass fraction as steady state is reached
F, mist spray flow
q, ventilation air flow
E, air exchanges (on a mass basis) E = q/M

Mass balance of water vapor as steady state is reached

$$Y_s = \frac{F}{EM} + Y_o$$

Assuming natural ventilation is a relatively small air exchange rate,, the average water vapor mass fraction reaches maximum at the steady-state value
Here, air mass M is this factory site 600,000kg, and spray rate is a 6 fan system 510kg/h

Air exchanges	Initial air conditions	Initial water vapor (g/kg)	Water vapor at steady-state (g/kg)	Rel. Humidity at steady-state
0.3	28˚C,45%	10.5	13.3	57%
1		10.5	11.4	48%
2		10.5	10.9	47%
0.3	35˚C,40%	13.9	16.8	48%
1		13.9	14.8	42%
2		13.9	14.4	41%

Even with very low air exchange, the humidity rise is on the order of +1~+12%, with smaller rise as temperatures are higher.

Conclusions

- Mist cooling can be used in a very large indoor space without worry of air saturation. Humidity will not significantly increase if there is minimal natural ventilation at 0.3 air exchanges
- Air temperature drops time-average to about 0.5K, but peaks during oscillation are up to 2.2K
- Mist fan cooling yields about 20W/m² more heat flux than a fan alone on a heated surface
  (But this surface does not account for sweat or clothing)
- Many more factors remain to be examined, including:
  - Clothing
  - Sweat
  - Human subjects

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