Analysis on the Actual Cooling Effect of the Standing Fan: A Comparative Study of Heat Loss and Thermal Comfort for Body Segments

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Abstract

To analyze the cooling effect of the standing fan, this study calculated the convective heat transfer coefficient (h_c) for each body segment and used the results to find the heat loss of the skin. This study derived h_c values through a thermal manikin test, and the results showed that the h_c value was the biggest for the head, hand, and arm segments. The h_c values were applied to the thermal balance equation to compute the skin's heat loss. The results were then compared to the user comfort survey that was conducted on the subjects. Thermal comfort zone of the subjects according to ASHRAE standards was -1.2~+0.5, extended in the negative direction. According to an analysis on the thermal comfort and heat loss sensitivity for body segments, the impact of the fan airflow change on the head was the biggest, and that for the left hand and forearm was smaller than for the lower body segments. This study will be useful for a detailed analysis of the standing fan's cooling effect. To this end, a further study should be conducted to factor in different positions of the fan and the amount of clothing.

Introduction

Unlike other cooling devices that control the temperature of the air, the standing fan creates a cooling effect by making an airflow to increase the amount of heat loss on the user's skin. In 2009, Schiavon and Arsen Krikor Melikov defined the cooling fan efficiency (CFE) of various cooling fans as the ratio between energy use and the cooling effect. Here, the cooling effect is the level of indoor temperature according to the reduction of skin temperature when the fan is running. The study made use of the thermal manikin under actual office environment to find the fan's CFE according to its speed and various temperatures. Using the CFE concept previously mentioned, Yang et al.(2015) presented a quantitative cooling effect data of brushless DC stand fan. With CFE extracted using the distance between the fan and the manikin as a variable, it was found that the dry-bulb air temperature, fan speed, and the fan-manikin distance influenced the cooling effect of the whole body while the fan-manikin orientation did not have an impact. Given that the above two studies used the thermal manikin as the test subjects, it only considered the decrease in skin temperature due to heat loss, leading to a difficulty in the broader application of its airflow and indoor temperature variables. Therefore, this study first seeks to examine the convective heat transfer coefficient on the human body surface that considers the airflow of the standing fan and indoor temperature. Then, this data was used to compute the skin's heat loss to examine the cooling effect.

The cooling effect of the standing fan, then, ultimately aims to enhance the user's thermal comfort. "Summer and Winter Comfort Zones" of ASHRAE Fundamental presents an airflow speed of less than 0.2 m/s as the premise. Likewise, measuring the thermal comfort improvement should be based on the indoor temperature reduction level, which is in an inverse relationship to the skin's heat loss. On the other hand, the thermal comfort analysis of ASHRAE is based on uniformly created airflows, but the airflow created by standing fan is non-uniform. Therefore, this study hypothesized that there would be a difference between actual thermal comfort and calculation-based thermal comfort.

This research derived skin's heat loss following the creation of airflow for 14 different body segments based on the thermal equilibrium of the human body. It also looked into the actual thermal comfort of users through participant surveys in order to analyze the cooling effect of the standing fan. Lastly, an analysis of heat loss and thermal comfort sensitivity was conducted to assess the real cooling effect of fans.

Methods

Specifications of the standing fan and experiment setting

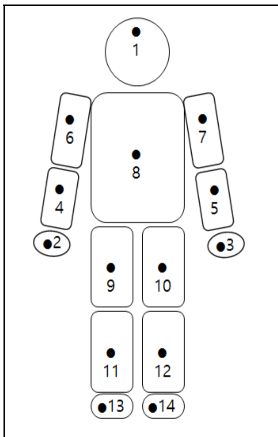
The standing fan that was used for this study had five 14" wings. There were three modes for the fan: low (1.48 m/s), medium (3.55 m/s), and high (4.73 m/s) at 0.6 m height. The distance from the fan that was determined through a preliminary measurement was 1.5m, and the height of the fan was 0.6 m. The airflow speed at the measurement point for each fan mode was 0.07 m/s at off, 0.48 m/s at low, 1.57 m/s at medium, and 1.98 m/s at high. The measurements were made at varied indoor temperatures between 22℃ to 30℃ with an increment of 2℃. The relative humidity was maintained at 40 ~ 60%.

Thermal manikin test

A thermal manikin test was conducted to derive the convective heat transfer coefficient (h_c) value. The environment chamber dimensions were 2.9 m*3.3 m*2.9 m(h), and its temperature and humidity were adjusted respectively between 22℃ ~ 30℃ (2℃ intervals) and 55%. Due to the limitations in space, an airflow generation outlet replaced a standing fan. The thermal manikin was dressed as can be seen in Figure 1.

Figure 1: Thermal manikin

Table 1: Body Segments for measurement points



i	segment
1	head
2	right hand
3	left hand
4	right forearm
5	left forearm
6	right upper arm
7	left upper arm
8	Torso
9	right thigh
10	left thigh
11	right calf
12	left calf
13	right foot
14	left foot

The outlet had three fans set up vertically, and the airflow creation area was 0.7 m*0.48 m. The airflow generation was on the left side of the manikin, and the distance from the outlet to the manikin was 1.0 m due to the size of the chamber. To make up for the change, the outlet airspeed was adjusted so that it would be similar at the heights of 0.1 m, 0.6 m, and 1.1 m to when the standing fan is used. Table 2 compares the airflow speed at 1.5m distance from the standing fan and at 1.0m distance from the outlet.

Table 2: A comparison of airflow speed from the standing fan and the outlet at different heights (m/s)

point	height	off	low	medium	high
1.5m from the fan	1.1m	0.04	0.16	0.27	0.32
	0.6m	0.07	0.48	1.57	1.98
	0.1m	0.05	0.1	0.22	0.24
1.0m from the manikin	1.1m	0.17	0.31	0.37	0.45
	0.6m	0.19	0.41	1.44	1.87
	0.1m	0.16	0.22	0.22	0.22

Yang et al.(2015) suggested that the height of 1.1 m—the height of the breathing line—was the most accurate for measuring the airflow speed. However, this height may cause unpleasant sensations due to dry eyes and other symptoms when the subject is exposed to a direct airflow for a long time. Given that this may affect individuals' activities, this study set the fan height at 0.6 m. 14 body segments as illustrated Table 1(head, right hand, left hand, right forearm, left forearm, right upper arm, left upper arm, torso, right thigh, left thigh, right calf, left calf, right foot, left foot) were distinguished for measurement. Equation (1) and (2) were used to calculate the h_c value. Equation (1) was applied to unclothed areas—head to left forearm; equation (2) was used for other body segments.

$$h_c = \frac{Q - h_r \times (t_{sk} - t_r)}{(t_{sk} - t_a)} \tag{1}$$

$$h_c = \frac{Q - f_{cl} \times h_r \times (t_{cl} - t_r)}{f_{cl} \times (t_{cl} - t_a)} \tag{2}$$

Heat balance equation

Heat loss on the skin surface based on thermal balance equation was derived using the process shown in Figure 2 in order to deduce the cooling effect of fan modes. Heat loss from the skin was divided into the sensible and the latent. First, the heat loss due to radiation and convection was calculated using Equations (3) and (4). Here, the applied clothing surface temperature was computed by repeated calculations until the value's difference from the assumed value was less than 0.001. Next, f_{cl} was calculated according to I_{cl} value. h_r was calculated using Equation (5), and the h_c value from the manikin test was applied. Latent heat loss on skin surface is due to evaporation heat loss from sweat, and was determined by the thermal signal. Evaporation heat loss was calculated by Equation (6). The heat balance equation was inputted through MATLAB and the key equations referred to ASHRAE Fundamental (2013).

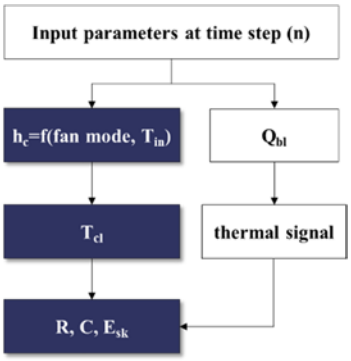


Figure 2: Heat loss calculation process

$$R = h_r f_{cl}(t_{cl} - t_r) \tag{3}$$

$$C = h_c f_{cl}(t_{cl} - t_a) \tag{4}$$

$$h_r = 0.72\sigma\varepsilon(4)\left(\frac{(t_{cl} + t_r)}{2} + 273.15\right)^3 \tag{5}$$

$$E_{sk} = wE_{max} \tag{6}$$

Questionnaire survey

To study the actual user comfort of different standing fan airflow speeds and indoor temperatures, an experiment shown in Figure 3 was conducted. Subjects were exposed to each fan mode for 15 minutes, with 5 minutes breaks between the fan mode changes. After the first set, the subjects took a break for 30 minutes at a different location and then participated in the next set. The subjects included 16 individuals around the age of 25. Their mean height was 167.6 cm, and their mean weight was 65.3kg. All subjects' clothing consisted of underwear, half-sleeve shirt, long cotton pants, socks, and slippers. Long hair was tied up so that it would not affect the result. Subject's activities were limited to simple ones including reading and writing. The survey items consisted of ASHARE 7-point scale thermal sensation, 4-point scale thermal comfort(uncomfortable, just uncomfortable, just comfortable, comfortable), and 4-point scale thermal acceptability(clearly unaceeptable, just unacceptable, just acceptable, clearly acceptable).

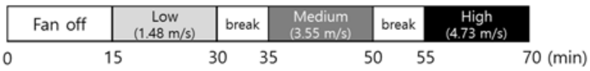


Figure 3: Questionnaire survey process.

Results

Convective heat transfer coefficient by fan mode

B and n values of the h_c value derived by the thermal manikin test, as well as the determination coefficient R^2 value are sorted into Table 3. According to an existing study, h_c value change based on airflow typically follow the form of Equation (7), with which h_c value was computed according to body segments and indoor temperatures.

$$h_c = B v^n \tag{7}$$

When it comes to specific body segments, the h_c value change for the hand according to airflow speed change was especially big. Head and the arms had next highest values. On the other hand, rise in airflow speed had relatively little effect on the h_c value for the lower body parts.

An interesting aspect of the result was that the body segments opposite to the airflow generation—the right side of the body in this study—had a very low R^2 value (shaded areas in table 3). That is, the h_c value on the opposite side of the airflow experienced little influence from the airflow speed, and it appeared that such body segment expanded as the indoor temperature increased. As can be seen in Table 3, body segments that did not have any correlation with the air speed at the target location (R^2<0.7) were the right forearm and upper arm at the indoor temperature of 22℃, but this was expanded to include the thigh, calf and foot when the indoor temperature was 30℃. The scope of value for the whole body was similar to that in existing studies, with a 0.5~0.6 range. B value increased as the indoor temperature rose.

Heat loss at different body segments

Heat loss analysis was conducted based on the subjects' body properties. At lower temperatures, heat loss increase according to air speed increase was bigger. Figure 4 shows the heat loss for each body segment at 22℃ , which was compared to h_c value-applied heat loss for body segments of de Dear et al.. The difference in the torso segment was small, and was excluded from the diagram.

The key variable in calculating the heat loss was the h_c and the clothing. As can be seen in Figure 4, the study also showed that the upper body areas, especially the unclothed areas, experienced bigger heat loss. This difference got bigger as the airflow speed increased.

Such difference may be due to the fact that h_c in de

Table 3: convective heat transfer coefficient for each body segment according to indoor temperature (Shaded cells imply little correlation between air speed increase and h_c (R^2<0.7)).

i	22℃			24℃			26℃			28℃			30℃		
	B	n	R^2	B	N	R^2	B	n	R^2	B	n	R^2	B	n	R^2
1	7.47	0.37	0.93	7.56	0.39	0.94	7.28	0.40	0.78	7.80	0.37	0.94	8.06	0.38	0.94
2	9.13	0.21	0.79	9.19	0.19	0.79	9.25	0.23	0.85	9.41	0.22	0.80	9.84	0.22	0.81
3	9.61	0.60	0.98	9.97	0.55	0.97	9.87	0.62	0.98	10.21	0.60	0.97	11.05	0.61	0.98
4	6.83	0.16	0.61	7.05	0.12	0.60	7.20	0.18	0.63	7.53	0.14	0.51	8.11	0.16	0.58
5	5.10	0.94	0.99	5.20	0.97	0.99	5.20	0.94	0.99	5.26	0.95	0.99	5.84	0.92	0.99
6	4.71	0.02	0.00	4.78	0.01	0.01	4.92	0.10	0.20	5.01	0.05	0.07	5.38	0.10	0.23
7	2.52	1.44	0.99	2.82	1.38	0.99	2.66	1.44	0.99	2.62	1.45	0.99	3.04	1.40	0.99
8	0.60	0.90	0.96	0.61	0.96	0.97	0.74	0.87	0.97	0.83	0.81	0.96	1.20	0.66	0.96
9	1.21	0.85	0.67	1.24	0.85	0.70	1.28	0.81	0.62	1.08	0.88	0.62	0.89	0.87	0.50
10	1.64	0.95	0.91	1.64	1.00	0.89	1.47	1.01	0.89	1.25	1.04	0.85	0.89	1.14	0.79
11	1.41	0.61	0.76	1.55	0.57	0.79	1.82	0.51	0.66	2.02	0.46	0.69	3.75	0.24	0.43
12	1.57	0.90	0.91	1.76	0.85	0.90	1.94	0.81	0.87	2.15	0.74	0.83	4.22	0.48	0.75
13	3.27	0.22	0.67	3.52	0.19	0.60	3.58	0.23	0.64	4.05	0.19	0.63	4.79	0.13	0.44
14	3.12	0.30	0.77	3.44	0.25	0.67	3.49	0.29	0.71	3.91	0.25	0.71	4.77	0.19	0.61
Avg.	2.68	0.62	0.92	2.77	0.62	0.93	2.83	0.62	0.91	2.95	0.59	0.91	3.49	0.54	0.90

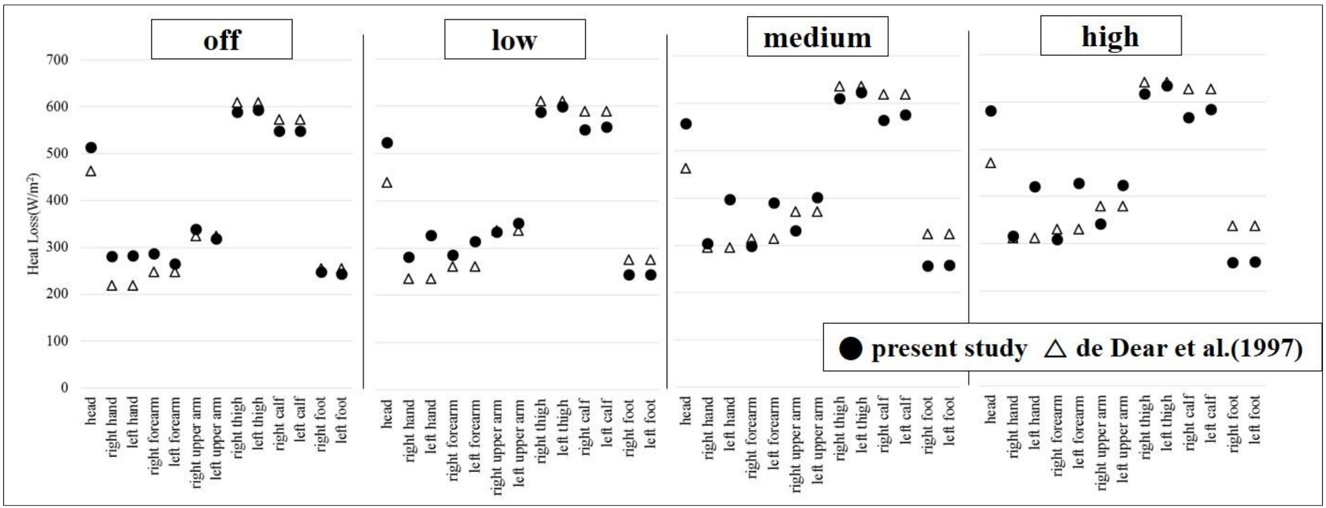


Figure 4: Heat loss at different body segments by fan modes

Table 4: Comparison of the Comfort Range According to Changes in the Indoor Temperature and Wind Speed

Temp [℃]	FSM	Survey				Elevated air speed model				
		TS	TC[%]	TA[%]	Comfort	SET[℃]	t_{adj}[℃]	CE[℃]	PMV	Comfort
30	Off	2	19	19		-	-	-	1.46	
	L	2	13	19		27.9	28.6	-1.4	0.93	
	M	1	50	50		26.6	27.5	-2.5	0.52	
	H	0	75	75	※	26.3	27.2	-2.8	0.41	※
28	Off	1	44	44		-	-	-	0.71	
	L	0	75	75	※	25.9	26.9	-1.1	0.3	※
	M	-1	100	100	※	24.7	25.7	-2.3	-0.15	※
	H	-1	94	100	※	24.3	25.4	-2.6	-0.26	※
26	Off	0	88	88	※	-	-	-	-0.04	※
	L	-1	88	94	※	23.7	24.8	-1.2	-0.49	※
	M	-1	100	100	※	22.4	23.6	-2.4	-0.93	
	H	-2	69	75		22.1	23.3	-2.7	-1.04	
24	Off	-1	100	100	※	-	-	-	-0.78	
	L	-1	81	81	※	21.6	22.8	-1.2	-1.23	
	M	-2	44	63		20.1	21.4	-2.6	-1.78	
	H	-3	19	31		19.7	21	-3	-1.93	
22	Off	-2	75	69		-	-	-	-1.54	
	L	-3	38	44		19.3	20.6	-1.4	-2.09	
	M	-3	6	13		17.7	19.1	-2.9	-2.67	
	H	-3	6	13		17.2	18.7	-3.3	-2.83	

Dear's study was extracted from a wind tunnel with near laminar air flow targeting an unclothed thermal manikin.

Also, this study assumed that the fan location to be on the left of the body, leading to the bigger heat loss for the left hand and the left arm.

On the other hand, the lower body parts had smaller heat loss compared to unclothed areas, and it also showed very little difference regardless of the change in airflow speed.

Comparison between survey result and calculations

The survey results are as sorted into Table 4. Responses on thermal sensation(TS), thermal comfort(TC), and thermal acceptability(TA) were accumulated to compute comfort zone. ASHRAE Standard suggests the range between -1 and +1 when TS is assessed using surveys.

However, a comparison of TS and TC showed about 93% of the subjects responded that an environment with the value of -2~+1 was comfortable. Therefore, this study regarded -2~+1 as the comfort zone.

Under this premise, this study considered it as being in the comfort zone if the TC and TA comfort was over 75% (shaded areas of table 4). Comfort standard, according to the survey, was determined as having the TS within the range of -2~+1, while TC and TA are over 75% respectively. The results showed that at the indoor temperature of 30℃, the subjects found it comfortable only when the fan mode was at high. At 28℃, all times when the fan was on was included in the comfort zone. When the temperature was lowered to 26℃, the subjects felt cold, and the thermal comfort was lower when the airflow speed was at high. At the indoor temperature of 24℃, the subjects responded that it was comfortable when the fan was either off or at low.

Next, comfort zones based on the results of the survey were compared to the PMV comfort zone presented by ASHRAE. "Elevated air speed model" of CBE Thermal Comfort Tool was used to calculate comfort. This model shifts the indoor temperature according to airflow speed, and the PMV is computed through the shifted indoor temperature. On the far right of Table 4 is the computed PMV. -0.5~+0.5 range was determined as the comfort zone standard. The analysis showed that high speed at 30℃, all speeds at 28℃, and low and off modes at 26℃ would be comfortable. Compared to results by the survey, actual comfort zone was expanded to include medium speed at 26℃ and off and low modes of 24℃.

This difference between the calculations and the survey results may have been caused by diverging effects of the airflow created by the standing fan on different body segments. While the results from the PMV with elevated air speed method evaluates a situation where there is uniform airflow around a human body, the airflow created by a standing fan impacts only parts of the human body. Also, summer being the primary time when standing fan is used may have factored into the comfort zone being expanded to the negative side.

Sensitivity analysis for body segments

This study found that a difference existed between the comfort zone extracted by survey and that by the elevated air speed model.

A sensitivity analysis to examine the differences in the thermal comfort zones for different body segments was conducted. Standardized Regression Coefficients (SRC) method was used as the analytical tool. This method is based on the linear relationship model between input (heat loss for body segments) and output (thermal comfort). Therefore, whether the heat loss for body segments and the R^2 value for the linear model was bigger than 0.7 was examined.

Figure 5 shows both the survey-based SRC and the calculation-based SRC. The closer the SRC value is to 1, the higher the correlation. A negative SRC value refers to a negative correlation while a positive value refers to a positive correlation. Since heat loss has a negative correlation with thermal comfort, SRC value for all body parts were negative numbers.

Sensitivity analysis based on the surveys showed that the correlation for the head was the highest with a value of -0.9, while the left hand and the left forearm were lower at -0.74 and -0.71 respectively. Coefficients for other areas had a mean of -0.82. That is, the head was the body segment that influenced the thermal comfort of subjects the most. On the other hand, the SRC derived by the CBE tool had a higher correlation than that by the survey overall. In this case, the left hand and the forearm had the highest correlation, followed by the left and right foot.

SRC comparison presents a difference between the assessments of the fan's influence based on the assumption that the airflow will influence the human body uniformly and how much thermal comfort the human body actually perceives from it.

The analysis showed that the fan's cooling effect as perceived by the subjects was the biggest at the head. In contrast, the left hand and left forearm, where the heat loss was the greatest, had the lowest actual cooling effect.

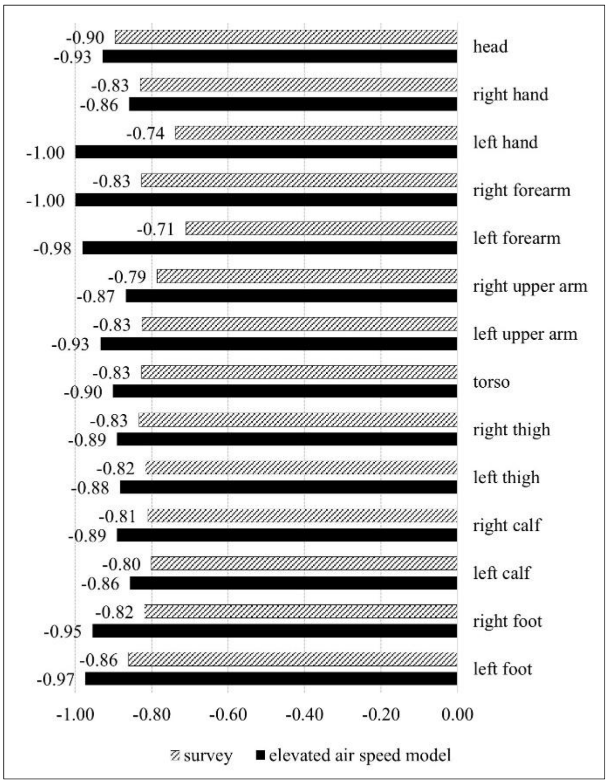


Figure 5: Standardized Regression Coefficients

Conclusion

To examine the cooling effect of the standing fan, this research derived the convective heat transfer coefficient (h_c) for different body segments and studied the heat loss from the skin. The derived values were then compared to the thermal comfort according to a survey. Key findings of this research are as follows:

- Convective heat transfer coefficient (h_c) for each body segment according to indoor temperature (Table 3) was derived. The results showed that the head, hands, and arms, which are unclothed areas, experienced the biggest change in h_c value as the airflow speed was changed.
- Heat loss, which was computed using the derived h_c value, was the biggest at the head segment. Whether there was clothing on the segment had a major influence in the computation of heat loss.
- A survey on the thermal comfort while using standing fan showed that the comfort zone was

expanded from the ASHRAE standard in the negative direction, from -1.2 to -0.5.

- An analysis of the studied thermal comfort from the survey and heat loss sensitivity showed that the influence of the head was the biggest, while left hand and left forearm had even lower influence than the lower body parts. The results of this study are significant in that it makes possible a detailed analysis of the standing fan's cooling effect. To this end, a further study will need to be conducted on the cooling effect based on different positions of the fan and changes in the amount of clothing.

Nomenclature

C	is the sensible heat loss by convection (W/m^2)
E	is the evaporative heat loss (W/m^2)
R	is the sensible heat loss by radiation (W/m^2)
Q	is the heat flux (W/m^2)
h_c,	is the convective Heat transfer coefficient (W/m^2K)
h_r	is the radiant heat transfer coefficient (W/m^2K)
t_{sk}	is the skin temperature (℃)
t_{cl}	is the clothed body surface temeprature (℃)
t_r	is the mean radiant temperature (℃)
t_a	is the air temperature (℃)
f_{cl}	is the fractional increase in body surface area
σ	is Stefan-Boltzman constant ($5.67*10^{-8} W/m^2K^4$)
ε	is the skin emissivity (0.97)
ω	is the total skin wettedness

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