Prediction of Skin Temperature and Examination of Cooling Effect according to Speed of Electric Standing Fan

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ABSTRACT
In this study, the cooling effect of the non-uniform airflow generated from a standing fan flowing around parts of the human body was examined. For this purpose, a thermal manikin was used for the test conducted to derive the values of the convective heat transfer coefficient (h_c) on each part of the human body. The derived coefficients were then used for the formulation of an equation expressing h_c. The derived coefficients were then employed in an algorithm for human body temperature prediction based on the 'Pierce two-node model' to predict the temperature in 14 areas of human body. The established algorithm was verified by comparing the results with the measurements of skin temperature obtained under a stabilized condition at an indoor temperature of 30℃. The time required for body temperature stabilization had little influence on the results. The results of the analysis showed that the cooling effect on the upper half of the body was greater than that on the lower half of the body. Additionally, the cooling effect of the fan appeared to decrease in accordance with increases in the indoor temperature.

KEYWORDS
Standing fan, Skin temperature, Pierce two-node model, Convective heat transfer coefficient

INTRODUCTION
Air movement in warm conditions is a cooling method that improves the comfort of humans while simultaneously reducing the consumption of energy. Natural or artificial air movement in a building can be created by the occupants through opening a window or with fans. Natural ventilation employed to cool the inside of a building can be assumed to create a uniform airflow around the human. On the contrary, the effects on human from airflow created by a cooling fan vary depending on the position and distance of the fan to the human body.

The purpose of this study is to examine the cooling effect of non-uniform airflow on parts of the human body. For this purpose, a thermal manikin test was carried out to collect the measurements of the convective heat transfer coefficient (h_c). The regression equation yielding h_c was then derived from these measurements. The derived regression

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equation was applied to the skin temperature prediction algorithm based on the Pierce two-node model, and the cooling effect of the airflow from the standing fan on parts of the human body was then examined.

LITERATURE REVIEW

Yang et al. (2015) used the concept of Cooling Fan Efficiency (CFE) presented by Stefano Schiavon and Arsen Krikor Melikov in 2009 and introduced the quantitative cooling effect of the brushless DC standing fan based on the manikin test. The results showed that the dry-bulb air temperature, the fan speed, and the distance between the fan and the manikin influenced the degree of cooling, whereas the orientation of the fan appeared to be less significant. They also formulated an expression for the cooling effect of a cooling fan using the fan speed as a parameter. The cooling effect of the fan used for the CFE index solely reflects the sensible heat loss. It is therefore estimated that the resulting cooling effect might differ from that actually experienced by the human body. The manikin test is required in the presented method to calculate the cooling effect; however, the test might not be able to reflect the effects of changing indoor temperature. In this study, the prediction of the skin temperature at various parts of the human body was employed to compensate this limitation, and the quantification of the cooling effect of non-uniform airflow generated by a standing fan was then examined.

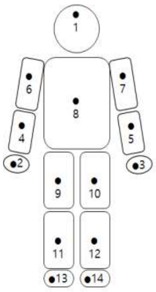
The two-node model by Pierce was employed in this study for the prediction of the skin temperature of the human body. Ehab and Kai (2011) predicted the skin temperature for 11 parts of the human body by modifying the calculation of the h_c and the heat transfer from core to skin based on the Pierce two-node model. Indoor temperatures of 30.2℃ and 15.3℃ were used for respective measurements and simulations, with corresponding stabilization times of 1 hour, 2 hours, and 4 hours. The results obtained from the study showed less difference in skin temperatures corresponding to each stabilization time at the indoor temperature of 30.2℃. However, with the indoor temperature of 15.3℃, the skin on the hand, thigh, leg, and foot of the human body required stabilization times of more than 2 hours. Based on the duration of stabilization times for the respective parts of the human body as presented by these studies, a test was carried out to verify the skin temperature prediction algorithm used in this study.

PREDICTION OF SKIN TEMPERATURE BY FAN MODE

Convective heat transfer coefficient by fan speed

In this study, the value of h_c obtained from a thermal manikin test conducted in the environmental chamber (2.9m×3.3m×2.9m(h)) was used. The temperature of the chamber was varied from 22℃ to 30℃ with an increment of 2℃, and the airflow speed had 4 stages of Off, Low (1.48 m/s), Medium (3.55 m/s), and High (4.73 m/s), yielding a total of 20 cases. The relative humidity was kept constant at 55%, and the distance between the airflow generation unit and the manikin was 1m, with the height of the fan set at 0.6m for the most prominent airflow variation around the human body according to each fan speed mode. Yang et al. (2015) reported a height of 1.1m for the fan (the height of the breathing line) as the height with the most prominent difference. However, a height of 1.1m may affect individuals exposed to the fan for a long time with unpleasant sensations such as dry eyes that might disrupt their activities. Therefore, the height was set at 0.6m in this study. The 14 segments illustrated in Table 1 were distinguished for the measurement. The segments from No. 1 to No. 5 represent the unclothed areas of the skin. The regression equation for h_c was additionally established based on the results obtained from the chamber test.

Table 1. *Regression values of convective heat transfer coefficient by body segments*

i		*segments*	*gradient*				*intercept*			
			off	*L*	*M*	*H*	*off*	*L*	*M*	*H*
	1	head	0.07	0.10	0.09	0.12	6.20	6.38	9.39	10.61
	2	right hand	0.09	0.10	0.15	0.17	7.55	7.41	8.20	8.69
	3	left hand	0.18	0.23	0.37	0.53	5.74	8.30	10.90	9.37
	4	right forearm	0.17	0.15	0.17	0.23	3.34	3.59	4.18	3.81
	5	left forearm	0.08	0.14	0.19	0.11	3.45	6.15	11.35	16.20
	6	right upper arm	0.08	0.13	0.14	0.20	3.14	1.54	1.11	1.03
	7	left upper arm	0.04	0.11	0.26	0.26	1.81	4.14	7.87	11.69
	8	torso	0.08	0.10	0.09	0.11	-1.22	-1.25	-0.26	-0.32
	9	right thigh	-0.04	-0.08	-0.07	-0.11	2.35	3.11	5.38	7.10
	10	left thigh	-0.09	-0.16	-0.18	-0.25	3.94	6.01	9.36	12.55
	11	right calf	0.28	0.21	0.26	0.22	-4.92	-3.15	-2.79	-1.53
	12	left calf	0.33	0.24	0.31	0.35	-5.98	-3.30	-2.48	-2.27
	13	right foot	0.19	0.16	0.16	0.16	-0.71	-0.34	0.75	1.12
	14	left foot	0.21	0.18	0.19	0.20	-1.48	-0.71	0.28	0.37

Prediction of skin temperature for different body parts

The skin temperature was predicted to derive the cooling effect of the respective conditions for the operation of the fan. The prediction assumed the change of the h_c for each part of the human body exposed to the airflow created by the standing fan to reflect the change in the prediction of skin temperature. By assuming fast thermal transference of the human body, the skin temperature at a certain point (time step n+1) can be calculated from thermal balance equations for the human body (equations 1 and 2).

$$T_{co}^{n+1} = T_{co}^{n} + \frac{A_D}{m_{co}c}\left(M - W - \left(C_{res} + E_{res}\right) - H_{c-s}\right) \tag{1}$$

$$T_{sk}^{n+1} = T_{sk}^{n} + \frac{A_D}{m_{sk}c}\left(H_{c-s} - \left(C + R + E_{sk}\right)\right) \tag{2}$$

where,

T is the temperature (℃),
m is the mass (kg)
c is the body heat capacity (J/kg℃)
A_D is the body surface area (m^2)
M is the metabolic rate (W/m^2)
W is the rate of mechanical work (W/m^2)
C is the convective heat loss (W/m^2)
E is the evaporative heat loss (W/m^2)
R is the heat loss by radiation (W/m^2)
H_{c-s} is the heat transfer from core to skin (W/m^2)
n is the time increment
res is the respiration
co is the body core
sk is the skin compartment

The values of the respective parts of the human body used for the prediction of skin temperature are as presented in Table 2. The surface areas (A_D) of the parts of the human body were derived from the equation by DuBois, and the mass of the core and skin were calculated by applying a fraction of the total body mass (the effective shell thickness). Figure 1 illustrates the simplified process for skin temperature prediction conducted in this study, in which the calculation of h_c from the process proposed by Ehab and Kai (2011) was modified.

Table 2. *Input parameters*

i	$T_{sk(set)}$	$T_{co(set)}$	A_D	I_{cl}	f_{cl}	i	$T_{sk(set)}$	$T_{co(set)}$	A_D	I_{cl}	f_{cl}
unit	℃	℃	m^2	clo	-	unit	℃	℃	m^2	clo	-
1	34.88	36.75	0.14	0	1.00	8	33.00	37.30	0.59	0.17	1.03
2	34.05	35.85	0.05	0	1.00	9	32.16	37.35	0.15	0.24	1.05
3	34.05	35.85	0.05	0	1.00	10	32.16	37.35	0.15	0.24	1.05
4	33.95	36.90	0.06	0	1.00	11	32.18	37.35	0.14	0.24	1.05
5	33.95	36.90	0.06	0	1.00	12	32.18	37.35	0.14	0.24	1.05
6	32.93	37.20	0.08	0.17	1.03	13	33.54	36.75	0.06	0.04	1.01
7	32.93	37.20	0.08	0.17	1.03	14	33.54	36.75	0.06	0.04	1.01

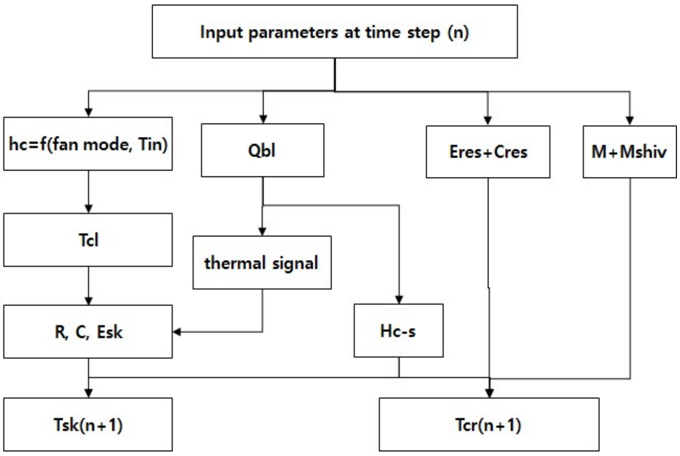


Figure 1. *Flow for skin temperature prediction*

In the algorithm for skin temperature prediction, the h_c is reflected in two separate parts. These are the parts for the calculation of heat loss due to the sensible (convection and radiation) and latent (evaporation) heat. Before calculating the heat loss in the human body, the h_c is considered for the calculation of the temperature of the surface of clothing T_{cl}. In this study, the thermal balance equation was implemented in MATLAB to predict the skin temperature. The 2013ASHRAE Handbook, Fundamentals, was used to determine the essential formulas that need to be used which are associated with the thermal balance equation.

Verification with experiment

The prediction of skin temperature based on the Pierce two-node model was verified through the test below conducted in this study. In the center of the space prepared for the test, a thermo-hygrometer was installed at the heights of 0.1, 0.6, and 1.1m, together with an Electric Heat Pump (EHP) run to maintain the set temperature and humidity.

The indoor temperature was kept at 30 ℃ to reduce the time required for the stabilization, and the relative humidity was kept in the range of 40% to 60%. The standing fan was placed 1.5m (the wind speed at the position of the occupant was the same as that applied in the manikin test) from the subject, as in the case of the test to derive the h_c. The physical characteristics of the subjects are as shown in Table 3. The subject was assimilated to the indoor temperature for 15 minutes before the beginning of the test, with 5 minutes allowed for rest at the point when the mode of operation for the fan was changed. The skin temperature was measured from 10 sites, except for parts 6, 7, 13, and 14, with an interval of 10 seconds.

Table 3. *Physical characteristics of the participants*

subject	*age*	*height (cm)*	*body mass (kg)*	*$A_D(m^2)$*	*body fat (%)*
A	24	159	51	42.58	30.7
B	27	174	87	57.04	25.2
C	30	170	79	53.83	23.6

Figure 2 presents the predictions and measurements of skin temperature at different parts of the human body which are less influenced by the time required for the stabilization of skin temperature at each fan speed. The predictions and measurements of skin temperature for different parts of the human body appeared to have similar trends except for those of the torso. The measured skin temperatures for subjects B and C were lower in the torso, deviating from the trend observed at low speed and with turned off. These results were attributed to a possible error in the measurement process.

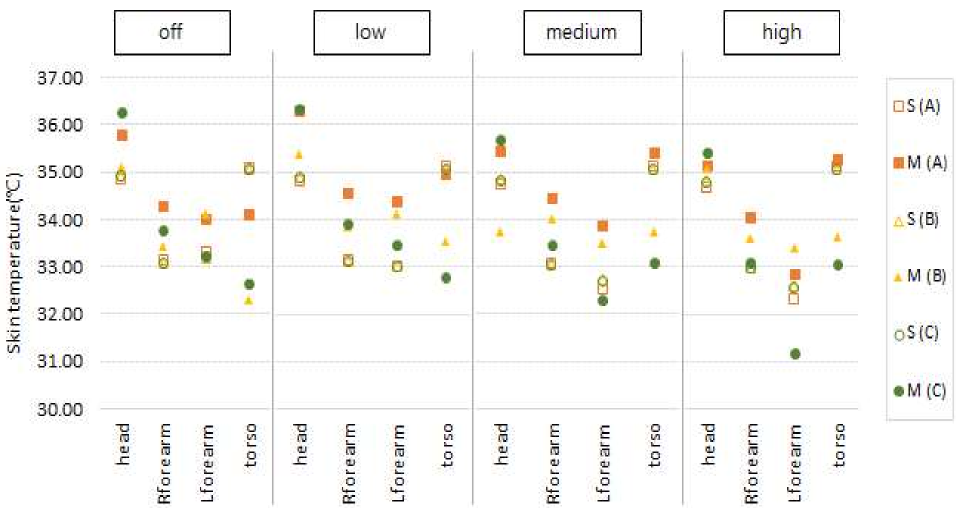


Figure 2. *Predictions (S) and Measurements (M) of skin temperature by fan mode*

Table 4. *Temperature difference (simulation-measurement) by fan mode*

i	off	low	medium	high	average
1	0.82	1.14	0.90	0.45	0.83
4	0.74	0.99	0.93	0.61	0.82
5	0.56	0.99	0.84	0.90	0.82
8	2.06	1.31	1.20	1.20	1.44
average	1.04	1.11	0.97	0.79	0.98

The differences between the prediction and measurement of skin temperature are as shown in Table 4. The difference between the prediction and measurement values tended to decrease in accordance with the increase in the fan speed. The torso showed the largest difference (1.44℃) between the predicted and measured values among all parts of the human body, while the head and arms had similar values with a difference of approximately 0.82℃. In particular, the predicted and measured values on forearms appeared to be similar. This indicated that the values of h_c, which vary according to the fan speed, were correctly reflected in the prediction of skin temperature. The overall difference between the prediction and measurement of skin temperature was calculated to be 0.98℃, slightly higher than 0.6℃ (Ehab and Kai, 2011). The difference between the two values was estimated to be attributable to the amount of time required for the stabilization of skin temperature.

COOLING EFFECT OF STANDING FAN

The values for the prediction and measurement of skin temperature differed. However, the values for h_c were correctly reflected in the prediction; thus, the cooling effects of the varied fan speed and the indoor temperature on each part of the human body were analyzed. The physical conditions of the subjects selected for the study were taken into account for the analysis of the cooling effect, and the final results of the analysis were presented through the mean values obtained from all three subjects. The equation presented by Yang et al. (2015) was used to process the experimental data collected to examine the cooling effect on skin temperature according to the changing level of indoor temperature and fan speed. The constant c1 represents the cooling effect at the target speed for the airflow generated by the standing fan.

$$|CE| = c_1 \cdot v \tag{3}$$

where, ∣CE∣ = absolute value of cooling effect (℃), c_1=constant (℃s/m), and v=target air speed by standing fan (m/s).

The larger values for c_1 presented in Table 5 indicate greater cooling effects. The cooling effects of the standing fan were derived from the predictions of skin temperature with varied levels of airflow from the fan based on the Pierce two-node model. The results showed an insignificant cooling effect on the clothed parts of the human body. In particular, the torso appeared to experience almost no cooling effect. The cooling effect on the head, forearm, and hands of the subjects can be summarized with the largest value of 3.23℃ on the left hand closest to the fan followed by 1.28℃ on the left forearm.

The height of 0.6m for the installed cooling fan was estimated to have a greater effect on the hands and forearms than on the heads of the subjects. In the study conducted by Stefano Schiavon and Arsen Kril or Melikov (2009), the height of the fan was set to 1.1m and the test showed the effects on the head that differed from those obtained in this study. The values of the constant tended to decrease along with an increase in the indoor temperature. This means that the higher indoor temperatures result in lower cooling effects on all parts of the human body.

Table 5. *Constants in cooling effect by indoor temperature for body parts*

i	c_1 (℃s/m)				
	22 (℃)	24 (℃)	26 (℃)	28 (℃)	30 (℃)
1	0.18	0.16	0.13	0.10	0.07
2	0.48	0.43	0.37	0.29	0.21
3	3.23	2.81	2.34	1.83	1.27
4	0.12	0.11	0.09	0.07	0.05
5	1.28	1.09	0.89	0.68	0.46
6	0.10	0.07	0.05	0.03	0.02
7	1.15	0.98	0.80	0.62	0.43
8	0.00	0.01	0.00	0.00	0.00
9	0.06	0.05	0.04	0.03	0.02
10	0.11	0.08	0.06	0.04	0.02
11	0.04	0.03	0.03	0.02	0.01
12	0.11	0.08	0.06	0.04	0.02
13	0.14	0.12	0.10	0.08	0.05
14	0.14	0.13	0.11	0.09	0.06

DISCUSSION

In this study, the cooling effect of a standing fan with varied fan speeds was examined. For the examination, the thermal manikin test was carried out along with a field test to verify the results obtained. The tests conducted showed some limitations.

Above all, the length of time required for the skin of the subjects to assimilate to the temperature of the test environment was not sufficient during the process of measuring skin temperature. Thus, specific areas on the bodies of the subjects were selected for measurement to reduce the time required for the stabilization of the skin. The stabilization of skin temperature for more than 1 hour is expected to reduce the difference between the prediction and measurement of skin temperature.

A limitation was also apparent in the derivation of the h_c from the manikin test. In this study, the cooling fan was placed on the left side, 1m from the manikin. According to previous studies, the orientation of the cooling fan was less influential on the cooling effect on the whole body. However, in this study, parts of the human body were individually examined and therefore, a difference in cooling effect resulted from the varied positions of the standing fan. In addition, the clothing of the manikin appeared to have almost completely blocked the cooling effect of the fan on the lower half of the manikin. The values of h_c derived by taking into account the distance and positional orientation of the cooling fan and therefore, the applicability to various parts of the human body, are thus expected to help with the derivation of more generalized results for the cooling effect of the fan.

CONCLUSION

The intention of this study was to evaluate the cooling effect of a standing fan on various parts of the human body through comparing actual measurements with predicted values. For this purpose, the thermal manikin test was carried out to derive the convective heat transfer coefficients for different parts of the human body depending on the fan speed, and the derived values were applied to the Pierce two-node model. By using the model, the skin temperatures at each part of the human body were predicted by varying the respective conditions of the indoor temperature (22℃~30℃) and the mode of operation for the standing fan (Off, Low, Medium, and High), and the predictions were compared with actual measurements. The cooling effects on parts of the human body, which varied according to the mode of operation of the standing fan, were then derived.

The overall results obtained from each case in the test conducted in this study revealed the most significant cooling effects on the left hand and left forearm of the upper half of the subjects' bodies situated closest to the fan and covered unclothed. In contrast, in the lower half of the body, and particularly for the torso, almost no cooling effect was observed.

A behavioral model for the operation of a cooling fan by occupants may be derived from the data for the cooling effects of a fan combined with the data collected through monitoring the operation of the cooling fan. The behavioral model can be exploited for an actual evaluation of the energy consumption used for the operation of cooling equipment.

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