Comparative study on heat transfer performance between three main types capillary ceiling radiant cooling panel

Yuchen Xiao[1], Linghong Xu[1, 2], Peng Ni[1] and Pingfang Hu[1]

[1] Department of Building Environment and Energy Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

[2] Corresponding author: lh.xu@hust.edu.cn

Abstract. This paper develop simulation models to analyses the effect of water supply parameters and structural parameters on radiant surface average temperature, radiant surface temperature range and temperature loss of three types capillary ceiling radiant cooling panel (CCRCP). In order to improve cooling capability of CCRCP, a lower water supply temperature should be applied. The best water supply velocity is around 0.11m/s. The suitable panel thermal conductivity is around 1 W/(m•K). Radiant surface should have higher emissivity. The G-type CCRCP have the best temperature uniformity, and the uniformity decreases in the order of G-type, U-type, S-type. Water supply temperature of U-type CCRCP can be lower when water supply velocity is slow, and water supply temperature of G-type CCRCP and S-type CCRCP can be lower when panel thermal conductivity is low.

1. Introduction

With the severe energy situation and economic development, people's requirements for office and living environment have been continuously improved, capillary ceiling radiant air conditioning system have been used more widely. In practical applications, the dew will gather on the surface of the capillary ceiling radiant cooling panel (CCRCP) in summer, which limits the cooling capacity of the air conditioning system. In order to understand how the dew gathering on CCRCP, the research on the heat transfer process of CCRCP has increased gradually.

Y Xai and SA Mumma fabricated of the heat transfer equations for a ceiling radiant cooling panel with conducting plates as the heat transfer medium, and investigated the effects of various geometries, materials of construction, fluid inlet temperatures and flow rates, room environments on heat transfer.[1]

Melanie Fauchoux and Mohit Bansal develop a new radiant panel that can transfer heat and moisture. And they used Fluent to construct a computational fluid dynamics model of the panel. The results show a 5% to 10% increase in the performance of the radiator radiant panel.[2]

F Causone and SP Corgnati evaluate the heat transfer coefficients between radiant ceiling and room in typical conditions of occupancy of an office or residential building. The results show that using the proper reference temperature selection is extremely important.[3]

Refet Karadag studied the relationship between convective heat transfer coefficient and radiation heat transfer coefficient of radiation ceiling, and find new correlations for convective and radiative heat transfer coefficients at the ceiling. [4]

This paper introduces the working principle of G, S and U-type CCRCP. In order to study the heat transfer of CCRCP, this paper use Fluent to develop simulation model of three types CCRCP. Then

the effect of water supply parameters and structural parameters on radiant surface average temperature, radiant surface temperature range and temperature loss were analysed.

2. Mathematical description of heat transfer in CCRCP

Heat transfer between CCRCP and indoor environment is complex. It can be divided into 3 processes: heat transfer between capillary fluid and capillary wall, heat transfer between capillary wall and plaster mortar panel, heat transfer between plaster mortar panel and indoor environment. The velocity of fluid in the capillary is generally between 0.05~0.2m/s. The diameter of capillary is generally 4.3mm and the supply water temperature will not exceed 20°C. According to the Reynolds equation:

$$R_e = \frac{\rho v d}{\mu} \tag{1}$$

It can be concluded that Re<2200 and fluid in the capillary is laminar flow.

The average temperature of indoor uncooled surface can be represented by average uncooled surface temperature (AUST). AUST can be calculated by the following formula [5]:

$$AUST \approx T_{out} - az \tag{2}$$

When the outdoor temperature is 26°C to 36°C, AUST changes from 26°C to 28°C according to the different envelope structure. AUST in this paper is 27°C.

Heat transfer between capillary fluid and capillary wall:

$$-\lambda \frac{\partial T}{\partial x} = h_w \left(T_w - T_{pipe} \right) \tag{3}$$

$$h_w = 1.86 \left(\text{Re} \Pr \frac{d}{l} \right)^{\frac{1}{3}} \frac{\lambda_w}{d} \left(\text{Re} < 2200 \right) \tag{4}$$

Heat transfer between capillary wall and plaster mortar panel:

The top of CCRCP is thermal insulation. Heat transfer of sidewall is neglected. The temperature at where plaster mortar panel and capillary wall are in contact is the same as capillary wall.

Heat transfer between plaster mortar panel and indoor environment can be divided into convective and radiative heat transfer.

$$-\lambda \frac{\partial T}{\partial x} = q_c + q_r \tag{5}$$

The heat flux of convective heat transfer between plaster mortar panel and indoor environment can be calculated by the following formula:

$$q_c = h_c \left(T_s - T_{air} \right) \tag{6}$$

The heat flux of radiative heat transfer between plaster mortar panel and indoor environment can be calculated by the following formula:

$$q_r = \varepsilon \sigma \left(T_s^4 - AUST^4 \right) \tag{7}$$

The physical meaning of each symbol in equations (1) to (7) is as follows:

Re——Reynolds number; ρ——density, kg/m^3; v——velocity, m/s; μ——viscosity coefficient, Pa•s; d——characteristic length; $AUST$——average uncooled surface temperature, K; a——room condition correction factor; z——outdoor temperature correction factor; h_w——the convective heat transfer coefficient between capillary fluid and capillary wall, W/(m^2•K); h_c——the convective heat transfer coefficient between plaster mortar panel and indoor environment, W/(m^2•K); λ_w——thermal conductivity of water, W/(m•K); q_c, q_r——density of heat flow rate of convective and radiative heat transfer, W/m^2; ε——radiant surface emissivity; σ——Stefan-Boltzmann constant, 5.67×10^{-8}W/(m^2•K); T_{out}, T_w, T_{pipe}, T_s, T_{air}——the outdoor temperature, water temperature, tube wall temperature, radiant surface temperature and indoor air temperature, K.

Equations (1) to (7) are mathematical descriptions of heat transfer of CCRCP.

3. CCRCP heat transfer model

The research object of this paper is CCRCP which made of capillary mats and plaster mortar panel. The structure of capillary mats is shown in Figure 1.There are 3 main types: S, G and U. Capillary mats is fixed on ceiling. Then 10~20mm plaster mortar panel is paint on ceiling to cover capillary mats. This paper develops models of S, G and U type CCRCP. Each model contains 6 capillaries and plaster mortar panel.
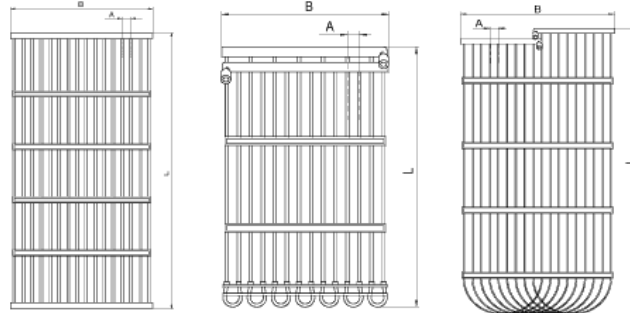

Figure 1. G-type, S-type and U-type CCRCP.

Figures 2 show the models constructed in this paper. To exclude interference factors and highlight the main factors, this paper makes following assumptions: the physical parameters of capillary fluid, capillary wall and plaster mortar panel are constant; heat transfer of sidewall and top of CCRCP is neglected; heat transfer of water supply pipe and return pipe is neglected; the bend of S and U type capillary mats is considered semicircle.
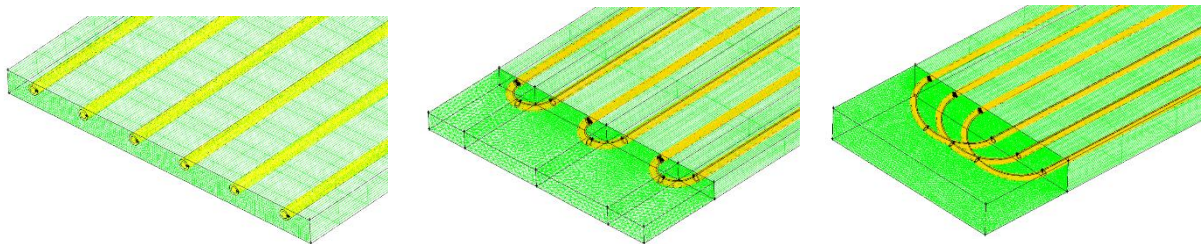

Figure 2. Models of G-type, S-type and U-type CCRCP.

4. Simulation results

Flow velocities in capillary is same as flow velocities in human capillary and is 0.05 to 0.2 m/s. Indoor design temperature is 26°C. Dew temperature is 14.8°C (26°C, relative humidity50%), so water supply temperature is generally not less than 16°C. In this paper, water supply temperature is 16~20°C, thermal conductivity of plaster mortar panel is 0~1W/ (m•K), radiant surface emissivity is 0 ~1. Table 1 shows the calculation results. The temperature range of radiant surface is the difference between the minimum and maximum temperature of radiant surface. Temperature loss is the difference between the water supply temperature and minimum temperature of radiant surface.

Table 1. Calculation results.

Num-ber	Water supply velocity (m/s)	Water supply tempera-ture (°C)	Panel thermal conductivity (W/(m•K))	Radiant surface emissi-vity	Radiant surface average temperature (°C)			Radiant surface temperature range (°C)			Temperature loss (°C)		
					G	S	U	G	S	U	G	S	U
1	0.05	16	0.81	1	19.68	22.07	21.30	3.26	6.26	4.50	1.88	2.44	3.22
2	0.08	16	0.81	1	19.15	20.35	20.72	2.34	5.78	3.98	1.86	2.30	3.16
3	0.11	16	0.81	1	18.88	19.78	19.89	1.87	5.55	3.97	1.85	2.22	2.89
4	0.14	16	0.81	1	18.72	19.44	19.60	1.59	5.43	4.13	1.84	2.16	2.57
5	0.17	16	0.81	1	18.62	19.21	19.41	1.41	5.36	4.24	1.83	2.12	2.36
6	0.20	16	0.81	1	18.54	19.05	19.27	1.27	5.21	4.32	1.83	2.19	2.21

7	0.11	17	0.81	1	19.61	20.41	20.53	1.70	5.03	3.6	1.68	2.01	2.62
8	0.11	18	0.81	1	20.34	21.07	21.16	1.52	4.50	3.23	1.51	1.81	2.35
9	0.11	19	0.81	1	21.08	21.72	21.80	1.35	3.98	2.85	1.33	1.60	2.08
10	0.11	20	0.81	1	21.81	22.37	22.43	1.17	3.46	2.47	1.16	1.39	1.81
11	0.11	16	0.2	1	20.56	21.04	21.45	1.85	6.15	6.33	3.52	3.68	3.01
12	0.11	16	0.4	1	19.55	20.24	20.52	1.86	6.17	5.37	2.51	2.77	2.85
13	0.11	16	0.6	1	19.12	19.94	20.12	1.87	5.87	4.58	2.09	2.41	2.86
14	0.11	16	1	1	18.74	19.70	19.76	1.88	5.30	3.64	1.71	2.12	2.83
15	0.11	16	0.81	0.2	17.67	18.30	18.37	1.14	4.29	2.93	1.06	1.28	1.74
16	0.11	16	0.81	0.4	17.98	18.72	18.81	1.35	4.76	3.3	1.28	1.53	2.06
17	0.11	16	0.81	0.6	18.32	19.11	19.20	1.53	5.10	3.58	1.50	1.78	2.36
18	0.11	16	0.81	0.8	18.61	19.46	19.56	1.68	5.37	3.79	1.70	2.00	2.64

4.1. Average temperature of radiant surface
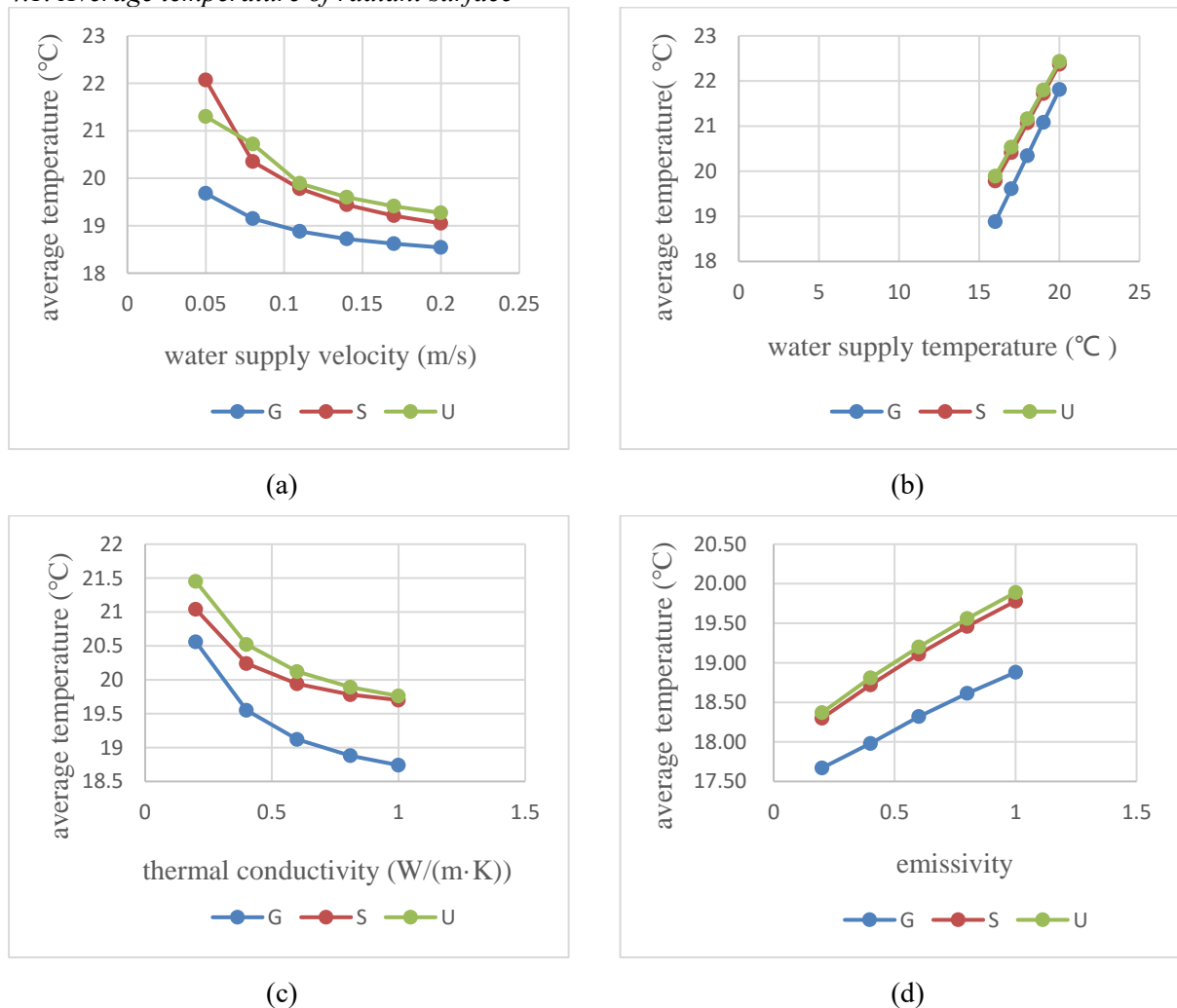

(a)

(b)

(c)

(d)

Figure 3. The changing curve of radiant surface average temperature with different variables.

Average temperature of radiant surface reflects the cooling capacity of CCRCP. Figure 3 shows that the radiant surface average temperature of 3 types CCRCP are all increase with water supply temperature and radiant surface emissivity increasing and are decrease with water supply velocity and panel thermal conductivity increasing. Water supply temperature makes biggest influence. The change

rate of radiant surface average temperature decrease obviously when water supply velocity is more than 0.11m/s. Surface average temperature of U-type CCRCP and U-type CCRCP tend to be same when panel thermal conductivity is more than 1 W/(m•K). In order to improve cooling capability of CCRCP, water supply temperature should be lower. The best water supply velocity is around 0.11m/s. The best panel thermal conductivity is around 1 W/ (m•K). Since CCRCP eliminates the heat load by radiative heat transfer, radiant surface emissivity should be higher.

4.2. Temperature range of radiant surface
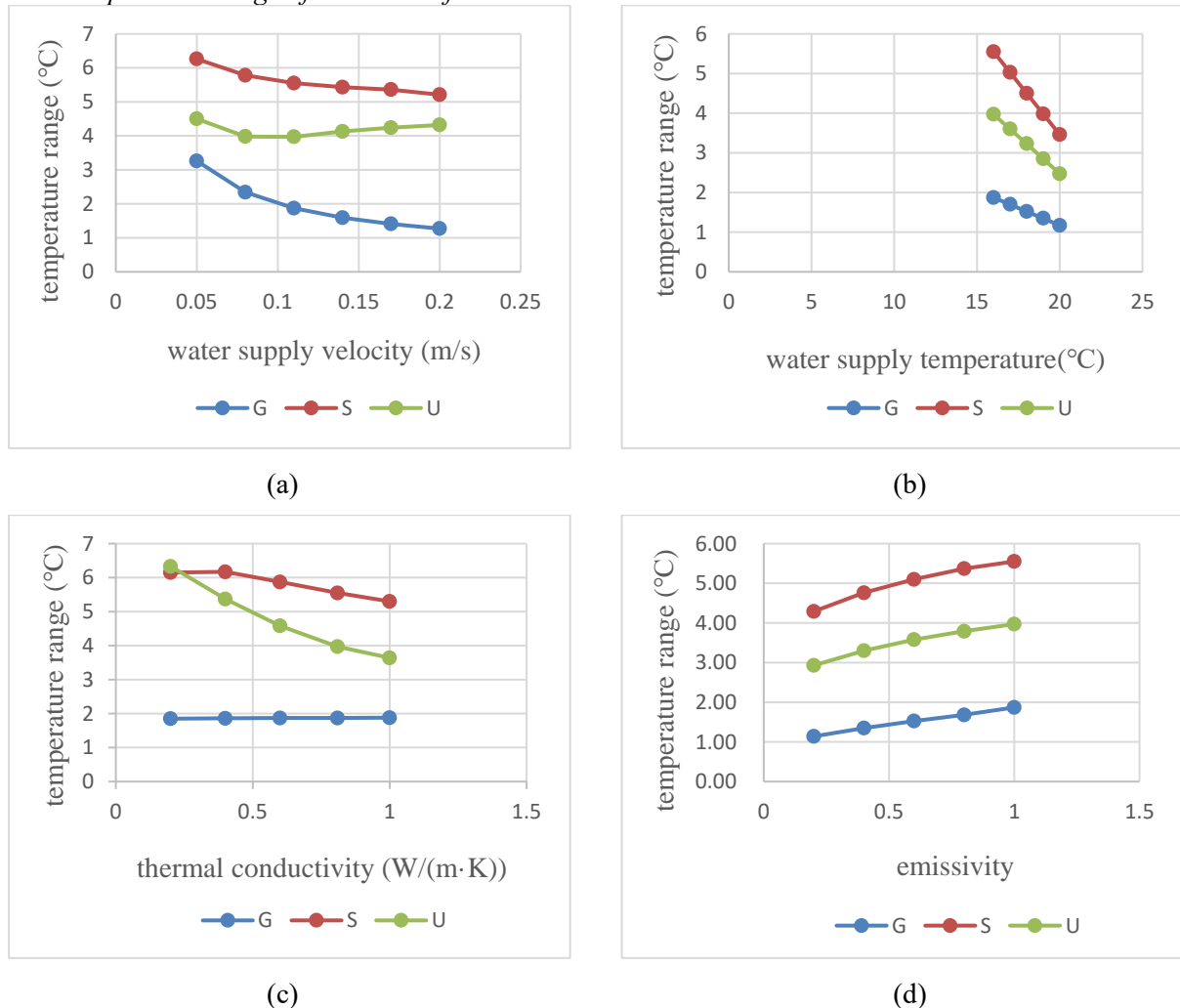

(a)

(b)

(c)

(d)

Figure 4. The changing curve of radiant surface temperature range with different variables.

Temperature range of radiant surface reflects the temperature uniformity of radiant surface. Figure 4 shows that radiant surface temperature ranger of G-type and S-type CCRCP decrease with water supply velocity increasing. Radiant surface temperature range of G-type CCRCP decrease on the first then increase when water supply velocity increasing. Radiant surface temperature range of S-type and U-type CCRCP increase with panel thermal conductivity increasing, and radiant surface temperature range of G-type CCPC changes slightly. Radiant surface temperature range of 3 types CCRCP are all increase with radiant surface emissivity increasing and are decrease with water supply temperature increasing. When water supply temperature is constant, the possibility of dew gathering on radiant surface is smaller if temperature is more uniformity. It can be seen that G-type CCRCP have biggest temperature uniformity, and S-type CCRCP have least.

4.3. Temperature loss of CCRCP

In order to prevent radiant surface from gathering dew, water supply temperature is generally about 1°C lower than indoor dew temperature. However in real condition, heat will lost when transfer in CCRCP, and radiant surface temperature will higher than water supply temperature. In order to improve cooling capacity, water supply temperature can be lower. Temperature loss reflects cooling potential of CCRCP. Figure 5 shows that temperature loss of S-type and U-type CCRCP decrease with water supply velocity increasing, and temperature loss of G-type CCRCP changes slightly. Temperature loss of 3 types of CCRCP are all increase with radiant surface emissivity increasing and are decrease with water supply temperature increasing. Temperature loss of G-type and S-type CCRCP decrease with panel thermal conductivity increasing, and temperature loss of U-type CCRCP changes slightly. It can be seen that water supply temperature of U-type CCRCP can be lower when water supply velocity is slow. Water supply temperature of G-type and S-type CCRCP can be lower when panel thermal conductivity is low.
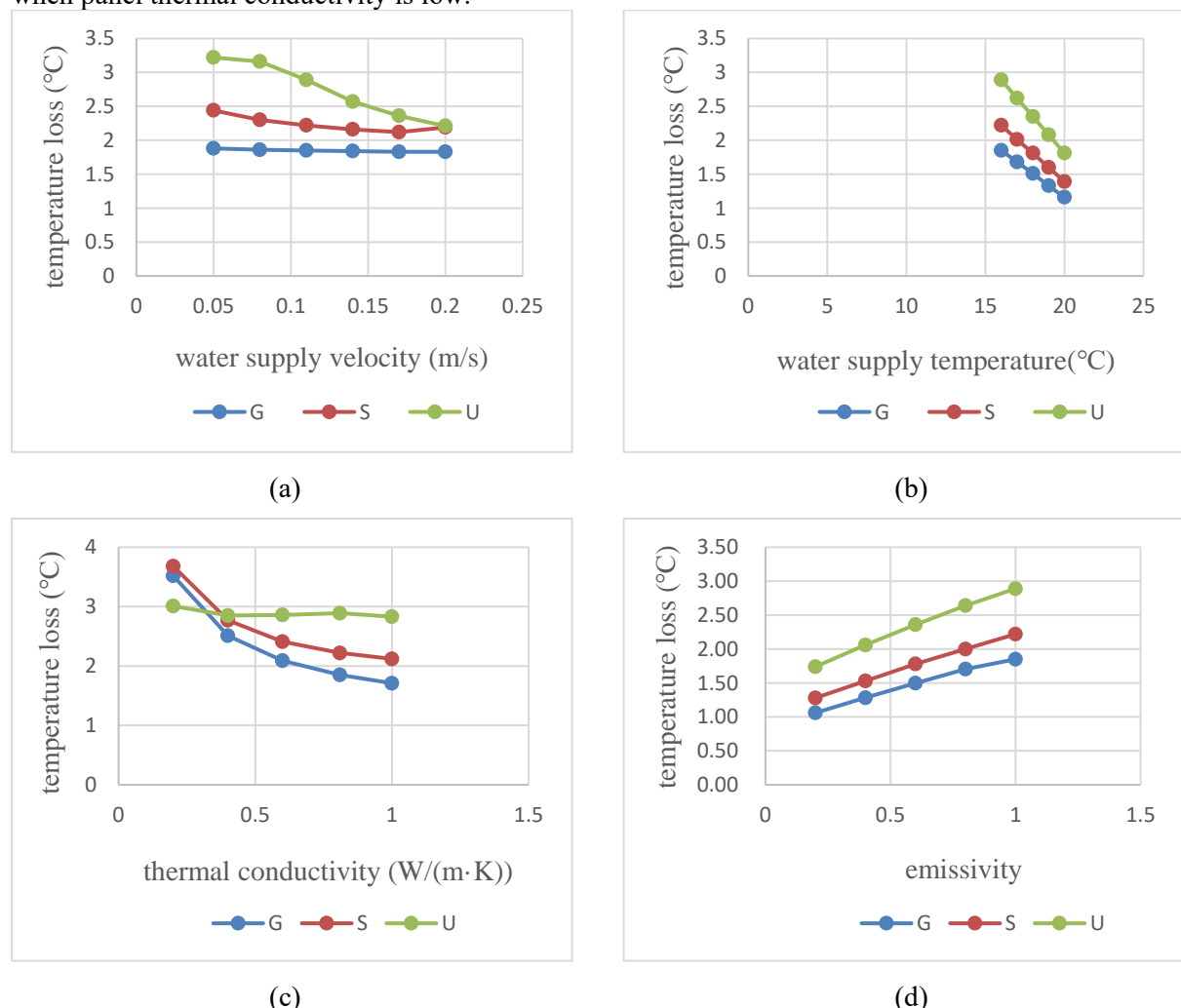

(a)	(b)

(c)	(d)

Figure 5. The changing curve of temperature loss with different variables.

5. Conclusions

In order to improve cooling capacity of CCRCP, a lower water supply temperature should be applied. The best water supply velocity is around 0.11m/s and the best water supply velocity is around 0.11m/s. Since CCRCP eliminates the heat load by radiative heat transfer, the radiant surface should have a high emissivity. When water supply temperature is constant, the possibility of dew gathering on radiant surface is smaller if temperature is more uniformity. It can be seen that G-type CCRCP have

biggest temperature uniformity, and the uniformity decreases in the order of G-type, U-type, S-type. However, because the water supply and return ports are arranged on different sides of the CCRCP, the arrangement of the G-type is more complicated. A lower water supply temperature can be used for the CCRCP with a high degree of temperature loss. Water supply temperature of U-type CCRCP can be lower when water supply velocity is slow. Water supply temperature of G-type CCRCP and S-type CCRCP can be lower when panel thermal conductivity is low.

Acknowledgments

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