numerical simulation are compared under steady-state conditions. The surrounding temperatures keep at 23 ℃, and the water temperature in the pipe is 16 ℃ for cooling. Heat transfer coefficients (HTCs) with a range of 4-20 W/(m^2 K) are evaluated.

Table 1 shows the average heat flow and average surface temperature for the studied slab using the simplified method and CFD simulation. The lower surface temperatures of the slab are very close using both methods, whereas the upper surface temperature by simplified method is a little bit lower than that from CFD simulation. Additionally, the differences of heat flow from both surfaces are within 5%.

Table 1. *Comparison of heat transfer using different methods*

	Simplified method				CFD simulation			
HTCs (W/(m^2 K))	q_1 (W/m^2)	q_2 (W/m^2)	Ts_1 (℃)	Ts_2 (℃)	q_1 (W/m^2)	q_2 (W/m^2)	Ts_1 (℃)	Ts_2 (℃)
4	13.4	24.6	19.7	16.9	12.9	24.7	19.8	16.8
8	17.1	44.7	20.9	17.4	16.3	44.9	21.0	17.4
12	18.5	62.0	21.5	17.8	17.7	62.0	21.5	17.8
16	19.1	77.2	21.8	18.2	18.4	77.0	21.9	18.2
20	19.3	90.7	22.0	18.5	18.7	90.2	22.1	18.5

Table 2 shows the maximum and minimum surface temperatures of the slab. It can be seen that the temperatures from both methods have a very small deviation. The simplified method has the uniform temperature for the upper surface, while the CFD simulation shows a temperature difference of 0.2 ℃ between the maximum and minimum temperatures on the upper surface.

Table 2. *Maximum and minimum surface temperatures for slab without insulation*

	Tmax/ Tmin (℃)					
	Simplified method		CFD simulation		Difference	
HTCs (W/(m^2 K))	Ts1	Ts2	Ts1	Ts2	Ts1	Ts2
4	19.6/19.6	17.3/16.0	19.9/19.7	17.2/16.1	0.3/0.1	0.1/0.1
8	20.9/20.9	18.1/16.1	21.1/20.9	18.1/16.2	0.2/0	0/0.1
12	21.5/21.5	18.7/16.2	21.6/21.4	18.7/16.2	0.1/0.1	0/0
16	21.8/21.8	19.1/16.3	21.9/21.8	19.2/16.3	0.1/0	0.1/0
20	22.0/22.0	19.5/16.3	22.2/22.0	19.6/16.4	0.2/0	0.1/0.1

Figure 5 shows the surface temperature distributions along the pipe distance. Both methods give the nearly same distribution for the lower surface temperature, and the only difference is the upper surface temperature. The reason for this deviation is that the simplified method transforms all different layers into one homogenous layer, but the hollow core actually exists and influences the uneven heat transfer in the upper part of the slab. Due to the pipes are closer to the lower surface, the pipes have small impacts on the heat transfer at the upper surface. If other layers like the insulation are considered, this impact would be neglected since the heat flow from the upper surface will be extremely low.

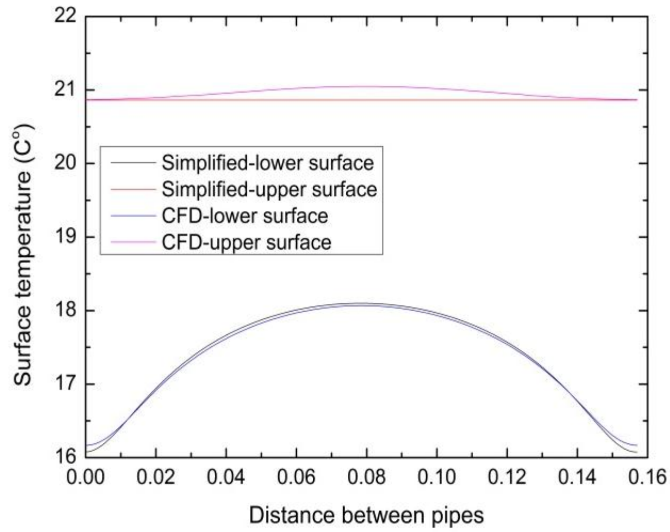

Figure 5. *Comparison of surface temperatures (h=8 W/(m^2 K))*

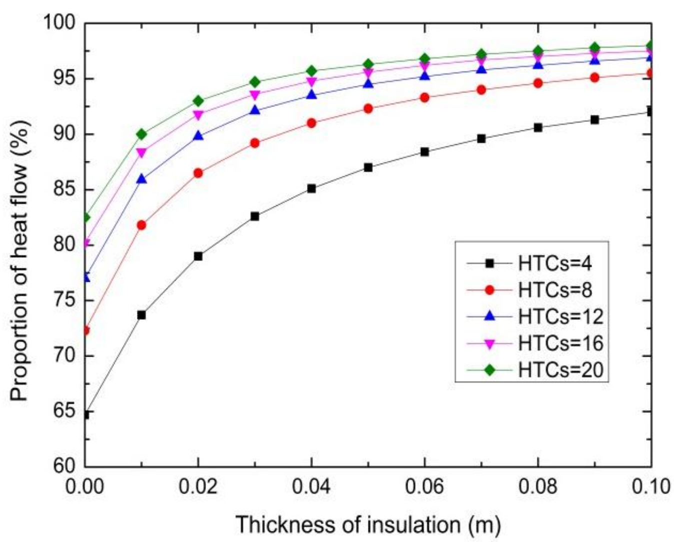

Figure 6. *Proportion of heat flow from the lower surface*

Influence of the thickness of insulation

In the practical application of radiant ceiling cooling, the upper side of the slab structure probably involves the insulation layer to reduce the heat flow from the water pipes to the upper zone. Based on the simplified method, the insulation layer can also be transformed into the homogenous slab structure. Thermal properties of the insulation used in this study are listed as follows: λ=0.04 W/(m K), ρ=400 kg/m^3, Cp=400 J/(kg K).

In this section, the thickness of the insulation varies from 0 to 0.1 m, and the proportion of heat flow from the lower surface of slab is recorded. When the insulation layer is considered, equivalent calculation is carried out as given in Table 3.

Table 3. *Equivalent calculation considering the insulation layer*

Thickness of insulation (m)	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Equivalent d1 (m)	0.4	0.85	1.30	1.75	2.20	2.65	3.10	3.55	4.00	4.45	4.9

Figure 6 depicts the proportion of heat flow from the lower surface of the slab under different HTCs. It can be seen that for the cooling ceiling with a heat transfer coefficient of 11.0 W/(m^2 K), if the proportion of heat flow from the lower surface needs to be kept above 95%, the insulation with a thickness higher than 0.06 m is indispensable.

Influence of the pipe

To consider the effect of pipe, this simplified method is further investigated and compared to CFD simulations. Table 4 shows the results from both methods considering the effect of pipe. Comparing results in Table 4 with that in Table 1, the pipe has a certain effect on the total heat transfer of this kind of element. In Table 4 a deviation of the heat flow from the upper surface exists but the difference of heat flow from the lower surface is very small with an error lower than 5% for low HTCs. The surface temperature has an error of 0.2 ℃ on the upper surface and an error of 0.1-0.2 ℃ on the lower surface. Generally, the simplified method is capable of sufficiently predicting the influence of pipe.

Table 4. *Heat transfer considering the influence of pipe*

	Simplified method				CFD simulation			
HTCs (W/(m^2 K))	q_1 (W/m^2)	q_2 (W/m^2)	Ts_1 (°C)	Ts_2 (°C)	q_1 (W/m^2)	q_2 (W/m^2)	Ts_1 (°C)	Ts_2 (°C)
4	13.0	23.1	19.7	17.2	12.1	23.3	20.0	17.2
8	16.6	39.9	20.9	18.0	14.8	40.9	21.2	17.9
12	18.0	52.8	21.5	18.6	15.7	55.0	21.7	18.4
16	18.7	63.1	21.8	19.1	16.0	66.8	22.0	18.8
20	19.0	71.4	22.0	19.4	16.0	76.8	22.2	19.2

CONCLUSIONS

In this paper, a simplified method using the equivalent thermal resistance is proposed for the heat transfer predictions of the hollow core concrete slab with TABS. This method is capable of transforming layers with different thermal parameters into one homogeneous layer as well as involving the influence of pipe on the heat transfer of this kind of system. The method has the same accuracy as the CFD simulation under steady-state conditions. Due to the characteristics of accurate and fast, this method would be beneficial to the heat transfer evaluation of this kind of TABS.

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