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The Study of Thermal Environment during the Movement of Air-conditioned Train

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Abstract. During the movement of air-conditioned train, outdoor temperature is constantly changing with the shift of time and space, and the thermal environment of compartment is affected by periodic temperature variation. In this paper, we simulated outdoors thermal environment in the period of the movement of air-conditioned train, and obtained outdoor temperature wave, sol-air temperature waves and temperature waves of interior wall for all orientations of compartment. As the effect of periodic temperature variation, it leads to the variety of quantity of heat transmitted from enclosure to compartment. By calculated the attenuation and delay for temperature wave, the fluctuation of quantity of heat transmitted from enclosure is obtained. It will establish theoretical basis for the study of thermal comfort about compartment and real time regulation about air-conditioned unit.

1. Introduction

It is a hot topic about the study of thermal comfort in the field of air conditioning technique. 1980s, Fanger P O. et al studied the perception if draught in ventilated spaces [1,2], 1990s, there were many investigations about the influence that indoor temperature made on personal thermal comfort [3-6], and there were many scholars who had put forward some measures to improve indoor thermal environment [7,8]. However, up to now, there is little study about the influence that outdoors thermal environment makes on indoor thermal environment and comfort. Though in references [9], authors pointed out this question, but didn't do deep into it.

In China, air-conditioned train is the main means for passenger transport. The thermal environment of compartment has the direct influence to thermal comfort. Vast in territory, complicated climate and far travelling route for air-conditioned train, these all lead to outdoors environment parameters varying with time and space. The variety will affect on thermal environment and thermal comfort of compartment. In order to study the influence of outdoors thermal environment, above all, we should grasp the law of the variety of outdoors thermal environment during the movement of air-conditioner train. Only by grasping the law, can we obtain the quantity of heat transmitted from enclosure and take measures to improve the thermal comfort of compartment.

2. Imitation of Outdoor Air Temperature

During the movement of air-conditioned train, the variety of outdoor air temperature has a certain law. We take train T97 and T98 as the illustration to find the law. Table 1 and 2 show the main stations that these two trains pass, and figure 1 shows the specific position of these stations on map.

Table 1. Schedule for Train T97

Station	Beijing	Shi Jiazhuang	Zhengzhou	Wuchang	Changsha
Time	10.06	12.45	16.42	22.22	1.50
Station	Chenzhou	Shaoguan	Guangzhou	East of Guangzhou	Shenzhen
Time	5.20	7.01	9.15	9.31	13.10

Table 2. Schedule for Train T98

Station	Shenzhen	East of Guangzhou	Guangzhou	Shaoguan	Chenzhou
Time	15.00	17.47	18.49	21.02	22.41
Station	Changsha	Wuchang	Zhengzhou	Shi Jiazhuang	Beijing
Time	2.10	5.41	11.23	15.21	18.05

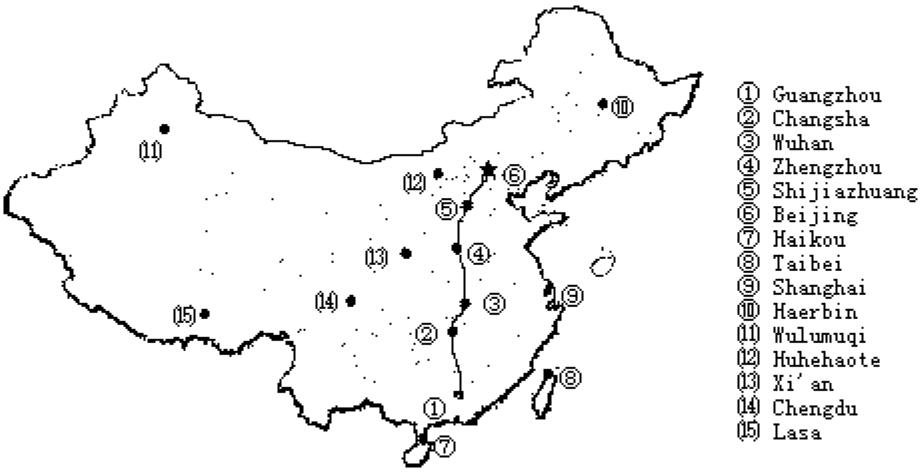

Figure 1. The Main Stations for Train T97 and T98

In order to grasp the law of periodic temperature variation, above all, we should know the average temperature and the instantaneous temperature during a running period of train (out and home once from jumping-off point to terminus as a period, to train T97 and T98, a period is 72 hours). We can obtain instantaneous temperature by formula (1) (during calculation, referenced design conditions come from design standards manual) [10].

$$t_{w,\tau} = t_{w,\max} - \alpha_\tau \Delta t_w \tag{1}$$

In this formula: $t_{w,\tau}$ —— outdoor temperature at τ hour, °C; $t_{w,\max}$ —— highest outdoor temperature, °C; α_τ —— modulus ratio; Δt_w —— difference in temperature between highest temperature and lowest one, °C.

Outdoor temperature has the characteristic of periodic variation. Its fluctuation can be expressed by harmonic wave. We use cosine function to express harmonic wave, formula (2) shows it [11].

$$t(\tau) = H\cos(\frac{360\tau}{Z} + \varphi) \tag{2}$$

In this formula: H —— Amplitude for harmonic wave, °C; τ —— starting time, hour; Z—— fluctuant periods, hour; φ —— original phase for harmonic wave, degree.

Actually, the variety of temperature involves disharmonic variables, and these variables also have their periodicity. We expand these varieties for Fourier progression, and use the sum of cosine functions to express it, and formula (3) shows it.

$$t(\tau) = H_0 + H_1 \cos(\frac{360\tau}{Z} - \varphi_1) + H_2 \cos(\frac{2\times 360\tau}{Z} - \varphi_2) + H_3 \cos(\frac{3\times 360\tau}{Z} - \varphi_3) + \cdots\cdots \quad (3)$$

In this formula: H_0 is the average value for temperature wave, and the second item of Fourier progression is the first step harmonic wave. Relative the first step, periods for all the other steps reduces 2, 3, 4…times.

Curve imitation is a method for data processing that uses a proper functional relation to express the inherent law of several discrete values. Fourier progression that is expressed by trigonometric function is an infinitude progression, and it is feasible to apply it to express seasonal function. In order to obtain the best outcome (simulative error smallest), we use 36 steps Fourier progression to simulate the fluctuation of temperature. Formula (4) is the mathematic model for curve imitation.

$$t = \frac{1}{72}\sum_{\tau=0}^{71} t_\tau + \sum_{n=1}^{N}\left\{\left[\frac{1}{36}\sum_{\tau=0}^{71} t_\tau \cos(5n\tau)\right]\cos(5n\tau) + \left[\frac{1}{36}\sum_{\tau=0}^{71} t_\tau \sin(5n\tau)\right]\sin(5n\tau)\right\} \quad (4)$$

We predigest formula (4) and obtain formula (5), it will benefit program [12].

$$t = \frac{1}{72}\sum_{\tau=0}^{71} t_\tau + \sum_{n=1}^{N}\left[\sqrt{M_n^2 + L_n^2} \cdot \cos\left(5n\tau - arctg\frac{L_n}{M_n}\right)\right] \quad (5)$$

In this formula: N —— the sum of steps for harmonic wave; n -- step; M_n —— amplitude of cosine wave, $M_n = \frac{1}{36}\sum_{\tau=0}^{71} t_\tau \cos(5n\tau)$; L_n —— samplitude of sine wave, $L_n = \frac{1}{36}\sum_{\tau=0}^{71} t_\tau \sin(5n\tau)$.

Instantaneous temperature can be obtained by formula (1), and use formula (5) for curve imitation. We obtained outdoor temperature wave for train T97and T98. Fig 2 and 3 show the results.

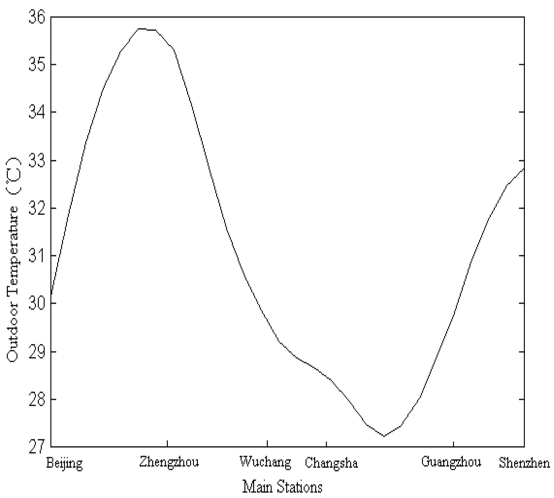

Figure 2. Outdoor Temperature Wave for Train T97

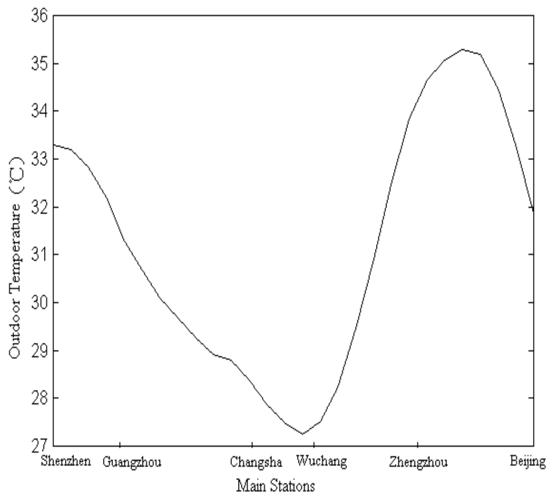

Figure 3. Outdoor Temperature Wave for Train T98

Fig 2 and Fig 3 show: to train T97 and T98, when they enter Zhengzhou, their outdoor temperature reach the maximum, and when they enter Changsha, outdoor temperature reach the minimum, the fluctuation of temperature is over 3 degrees.

3. Imitation of Sol-air Temperature

Sol-air temperature is a weather parameter that is synthesized by air temperature and solar radiation, and it can be obtained by formula (6) [10].

$$T_{zh,\ \tau} = T_{w,\ \tau} + \rho J(t) / a_w \tag{6}$$

In this formula: $T_{zh,\tau}$ — outdoor sol-air temperature in summer, °C; $T_{w,\tau}$ — outdoor instantaneous air temperature in summer, °C; ρ -- absorption coefficient of compartment for solar radiation; J(t) — solar radiation intensity, W/(m^2·°C); α_w — surface heat transfer coefficient for compartment, W/(m^2·°C), αw=9+3.5V0.66 [13], V is train velocity, km/h.

Sol-air temperature function can be expressed by formula (7).

$$T_{zh,\tau} = A_0 + \sum_{n=1}^{m} A_n \cos(\omega_n \tau - \varphi_n) \tag{7}$$

In this formula: A0 is the average value for sol-air temperature, the second item is the fluctuant value for instantaneous sol-air temperature.

Sol-air temperature is varies with different orientation and absorption coefficient for solar radiation. Solar radiation values that we used for calculation are each station's solar radiation value in design day [14]. Absorption coefficient of compartment is 0.7 (assume exterior is deep paint surface) [13]. Train velocity is 120km/h. After calculation, use formula (5) for curve imitation. We obtained outdoor sol-air temperature wave for train T97 and T98 when their movement. Fig 4 and 5 show the results.

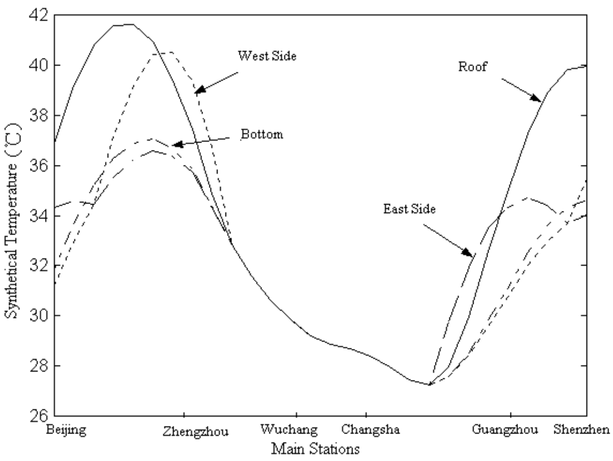

Figure 4. Sol-air Temperature Wave for Train T97

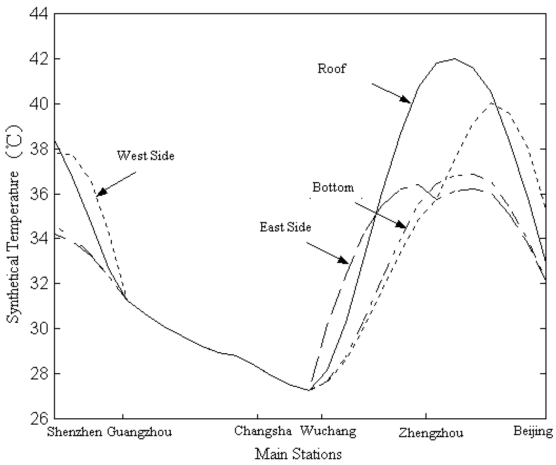

Figure 5. Sol-air Temperature Wave for Train T98

4. Imitation Temperature Wave for Compartment Surface

As compartment's wall has thermal stability, when outdoor sol-air temperature wave passing through wall to the inside surface, the wave will be delayed and attenuated. When temperature wave passing through a certain material, every step of Fourier progression will be attenuated and delayed, it is showed by formula (8), Fig 6 is temperature variation figure by unsteady heat conduction.

$$t(\tau)=t_{av}+\frac{H_1}{v_1}\cos(\frac{360\tau}{Z}-\varphi_1-\varepsilon_1)+\frac{H_2}{v_2}\cos(\frac{2\times 360\tau}{Z}-\varphi_2-\varepsilon_2)+\frac{H_3}{v_3}\cos(\frac{3\times 360\tau}{Z}-\varphi_3-\varepsilon_3)+\cdots\cdots \quad (8)$$

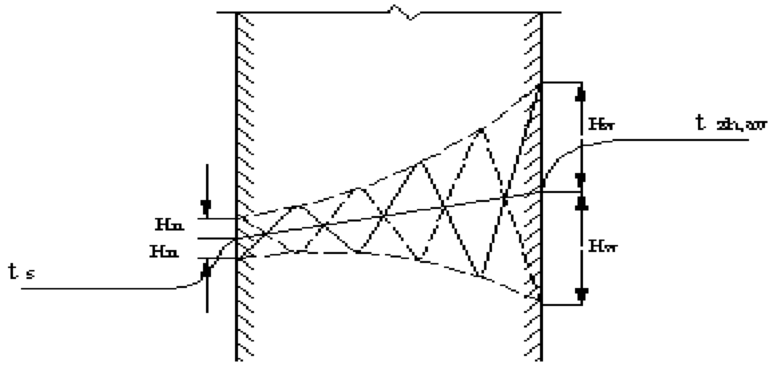

Figure 6. Temperature Variation at the Condition of Unsteady Heat Conduction

In this figure: $t_{zh,av}$ —— the average value for outdoor sol-air temperature; A_w — amplitude of temperature wave for exterior surface; A_n — amplitude of temperature wave for interior surface; t_s — average temperature for indoor air.

From reference [13] we know the whole constitution of wall for compartment. The main constitution of a compartment is following: roof is composed of 2mm steel plate, 70mm thermal insulation material and 5mm plywood; east and west of compartment are composed of 3mm steel plate, 65mm thermal insulation material and 10mm plywood; bottom is composed of 2mm steel plate, 85mm thermal insulation material and 20mm board. The main material for thermal insulation material is polystyrene. Table 3 shows the properties for all these materials.

Table 3. Properties for Materials

Material	Density (kg/m^3)	Specific Heat (kJ / kg.K)	Thermal Conductivity [W / (m·K)]
Plywood	600	2.513	0.151
Board	500	2.51	0.14
Polystyrene	25	0.837	0.035
Steel plate	7850	0.481	50

We should calculate delay and attenuation firstly so that we can obtain temperature wave for compartment surface. If periodic temperature variation influences on one side of a material, its surface temperature wave will has the same period. Storage heat coefficient of a material is the ratio of amplitude of rate of heat flow passing through surface to the amplitude of temperature wave for its surface, and formula (9) is the formula. Storage heat coefficient can show sensitive degree of a material to the fluctuation of heat flow. Material with big Storage heat coefficient has better thermal stability than that with small storage heat coefficient.

$$S=\sqrt{\frac{2\pi}{Z}\lambda C\rho} \quad (9)$$

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In this formula: S — exterior storage heat coefficient of material, W / (m^2 · K); Z — the fluctuant periods of rate of heat flow, hour; λ, C, ρ — thermal conductivity of material [W / (m · K)], specific heat [(W · h) / (kg · K)], density (kg/m^3).

Interior storage heat coefficient is an index that can show surface's sensitivity to the fluctuation of heat flow. At the same condition, temperature of a material is more stable if its storage heat coefficient bigger. If inner material layer doesn't thick, the amplitude of inner surface temperature wave is not only affected by its physical property, but also affected by that of the following material. Formula (10) is the formula for the interior storage heat coefficient.

$$Y_n = \frac{R_n S_n^2 + Y_{n-1}}{1 + R_n Y_{n-1}} \tag{10}$$

In this formula: Y_n — interior storage heat coefficient for n layer material; R_n — thermal resistance for n layer material, m^2 · K/W; S_n — exterior storage heat coefficient for n layer materials.

$$\nu = 0.9e^{\frac{\sum D}{\sqrt{2}}} \cdot \frac{S_1 + \alpha_i}{S_1 + Y_1} \cdot \frac{S_2 + Y_1}{S_2 + Y_2} \cdot \frac{S_3 + Y_2}{S_3 + Y_3} \cdot \frac{Y_3 + \alpha_w}{\alpha_w} \tag{11}$$

In this formula: V — thermal amplitude decrement for wall; ∑ D — thermal inertia index, ∑ D = R1S1+R2S2+…+ RnSn.

In formula (11), the last multiplier $\frac{Y_3 + \alpha_w}{\alpha_w}$ is the attenuation for temperature wave from outdoor to exterior surface of wall.

$$\varepsilon = 40.5\sum D - arctg\frac{\alpha_i}{\alpha_i + Y_i\sqrt{2}} + arctg\frac{Y_e}{Y_e + \alpha_w\sqrt{2}} \tag{12}$$

In this formula: ε— delay for wall, degree; arctg -- inverse trigonometric function; Yi — interior storage heat coefficient for wall; Ye -- exterior storage heat coefficient for wall; α_i—coefficient of convective heat transfer for interior surface of wall, in this paper, it equals to 8W/ m^2 · K [13].

In formula (12), the last item is the delay of temperature wave for exterior wall to outdoor sol-air temperature wave. The following process can calculate exterior storage heat coefficient for each layer.

Exterior storage heat coefficient for the first layer:

(1) If D_1>=1 then $Y_1 = S_1$; if D_1< 1 then $Y_1 = \frac{R_1 S_1^2 + \alpha_{in}}{1 + R_1 \alpha_{in}}$;

(2) To the following layers (m>1):

If D_m>=1 then $Y_m = S_m$, if D_m<1 then $Y_m = \frac{R_m S_m^2 + Y_{m-1}}{1 + R_m Y_{m-1}}$.

The delay and attenuation for each step harmonic wave of each orientation can be obtained by formula (9), (10), (11) and (12).

The average temperature of exterior wall and interior wall can be obtained according to the process of steady heat conduction.

$$\begin{cases} (t_{zh,av} - t_{w,av}) \times \alpha_w = (t_{w,av} - t_{n,av}) \times \dfrac{1}{\sum R} \\ (t_{zh,av} - t_{w,av}) \times \alpha_w = (t_{n,av} - t_s) \times \alpha_i \end{cases} \tag{13}$$

In this formula: $t_{zh,av}$ — average of outdoor sol-air temperature, ℃; $t_{w,av}$ — average temperature for exterior wall, ℃; $t_{n,av}$ — average temperature for interior wall, ℃; t_s — indoor temperature, ℃, in this paper, it equals to 26 ℃; $\sum R$ — the sum of thermal resistance for materials (m^2 · K)/W.

Table 4. The Temperature and Thermal Resistance

Orientation	average of outdoor sol-air temperature(℃)	the sum of thermal resistance for materials from each layer (m^2·K)/W	average temperature of exterior wall(℃)	average temperature of interior wall(℃)
Roof	33.9275	2.0344	33.8877	26.4568
East side	32.6591	1.9234	32.6237	26.4042
West side	31.7929	1.9234	31.7617	26.3516
Bottom	31.1462	2.5715	31.1255	26.2376

By calculation, we obtained temperature wave of interior wall for train T97 and T98 during their movement. Fig 7and figs 8 show the results.

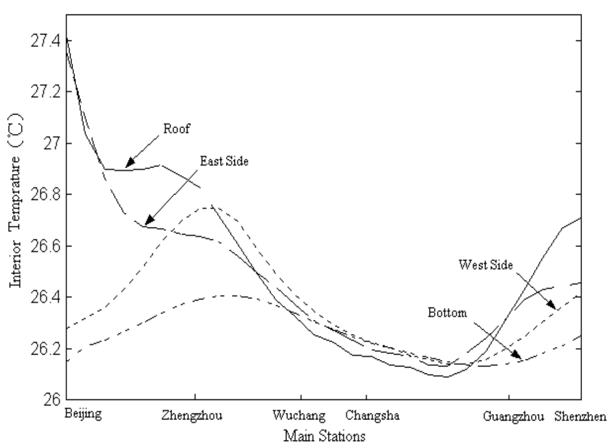

Figure 7. Temperature Wave of Interior Wall for T97

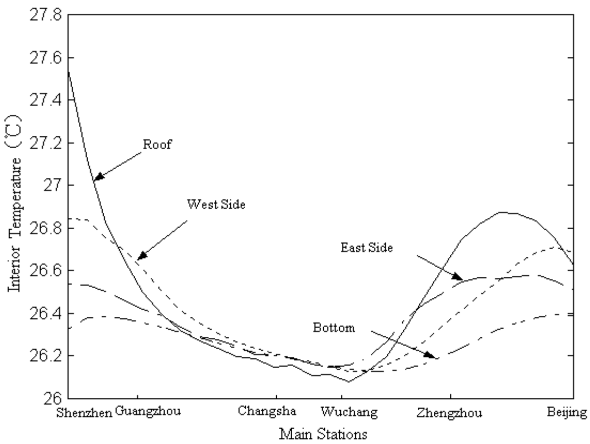

Figure 8. Temperature Wave for Train T98

Temperature wave of exterior wall can be obtained by calculated the delay and attenuation. Fig 9 and Fig 10 show the results.

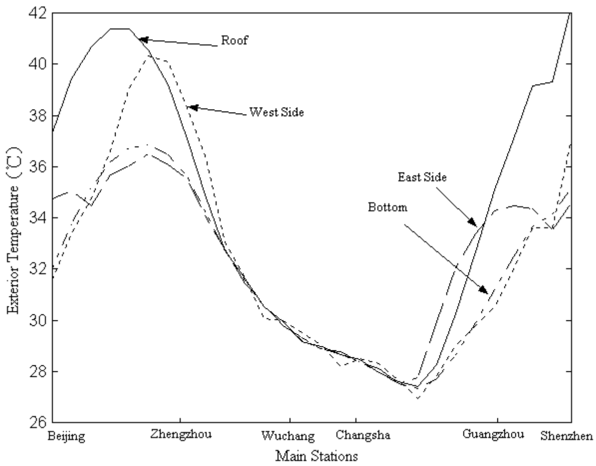

Figure 9. Exterior Temperature for Train T97

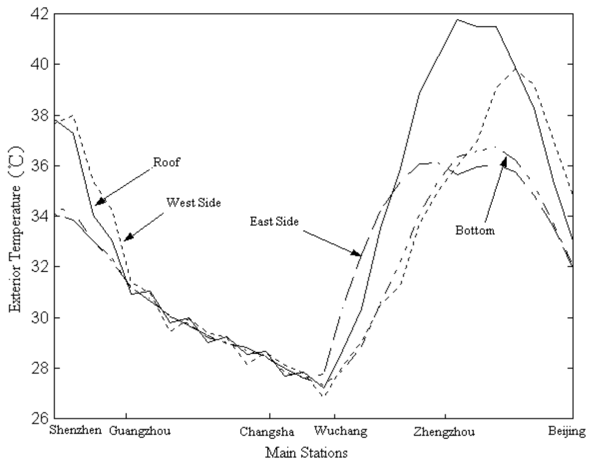

Figure 10. Exterior Temperature for Train T98

5. Quantity of Heat Transmitted from Enclosure

Quantity of heat transmitted from enclosure includes two parts, one is the quantity of heat transmitted from wall, and the other is from windows. Quantity of heat transmitted from wall can be obtained by formula (14).

$$Q = K(t_{zh,av} - t_s) + \alpha_{in}\frac{H_1}{v_1}\cos(\frac{360\tau}{Z} - \varphi_1 - \varepsilon_1) + \alpha_{in}\frac{H_2}{v_2}\cos(\frac{2\times 360\tau}{Z} - \varphi_2 - \varepsilon_2) + \cdots\cdots \quad (14)$$

In this formula: K -- overall coefficient of heat transfer for wall, W/ (m^2· K).

According to the delay and attenuation for each step harmonic wave and the formula for sol-air temperature, quantity of heat transmitted from wall to compartment can be obtained. Fig11 and 12 show the results.

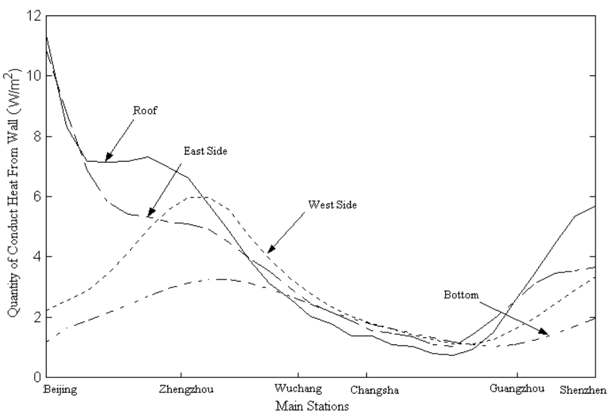

Figure 11. Quantity of Conduct Heat for T97

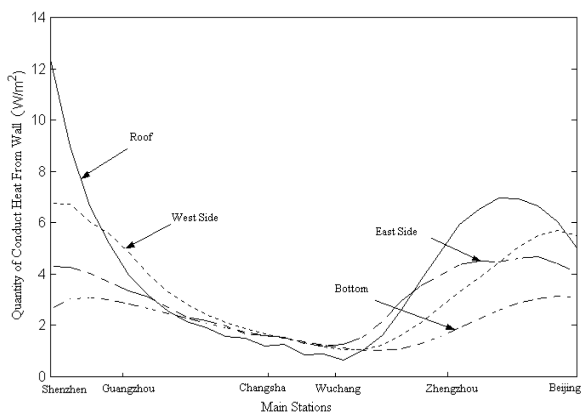

Figure 12. Quantity of Conduct Heat for T98

Quantity of heat transmitted from window is affected by solar radiation and the fluctuation of temperature. Solar radiation entering into compartment has two parts: one is that a portion of solar radiation gets straight into compartment with the form of short-wave radiation; the other is that windows improve temperature for itself by absorbed additional solar radiation, and then release the quantity of heat with the form of convection and long wave radiation. Quantity of heat transmitted from windows can be calculated by formula (15). Fig13 and 14 show the results.

$$Q = C_g C_n D_s + K_c (t_{zh} - t_s) \quad (15)$$

In this formula: Cg — shading coefficient for windows; Cn — shading coefficient for curtain; Ds — daily obtained heat factor.

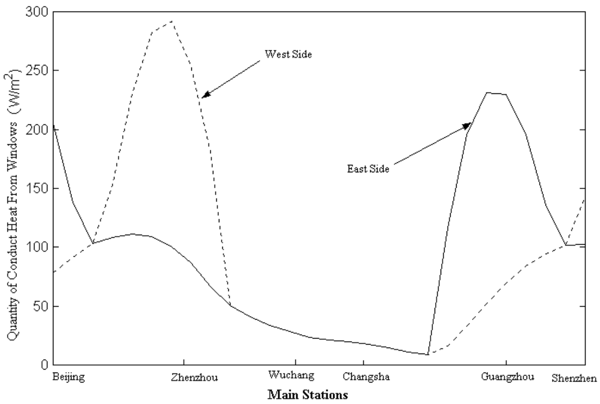

Figure 13. Quantity of Heat from Windows for T97

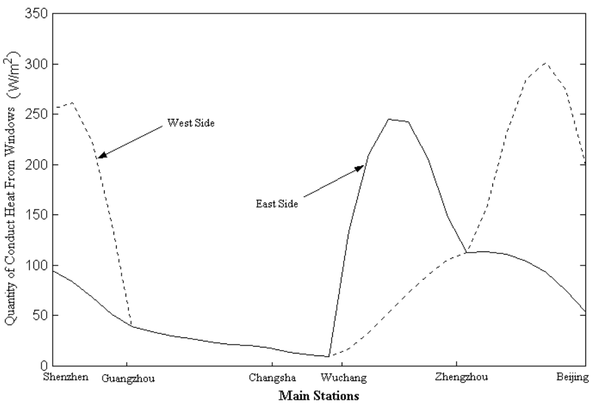

Figure 14. Quantity of Heat from Windows for T98

Fig (11), (12), (13), (14) show: at the same condition, quantity of heat transmitted from windows is bigger than that from wall, so different positions in compartment obtain different quantity of heat. It will lead to a condition that quantity of heat is not evenly distributing in compartment, and it would form superheat region (near window) and super-cooling region (apart from windows).

As the fluctuation of quantity of heat transmitted from window is big, even at the same region, the gained quantity of heat varies with time and space. In order to understand the influence that outdoors thermal environment make on the whole thermal load of compartment, the following task is obtaining the quantity of heat transmitted from the whole enclosure. To a certain compartment, it is 25.5meters length, 3.1 meters width, 2.42 meters height; the area of windows is 14m2 or so. On the basis of these conditions, we obtained the instantaneous quantity of heat transmitted from enclosure. Fig 17 and 18 show the results.

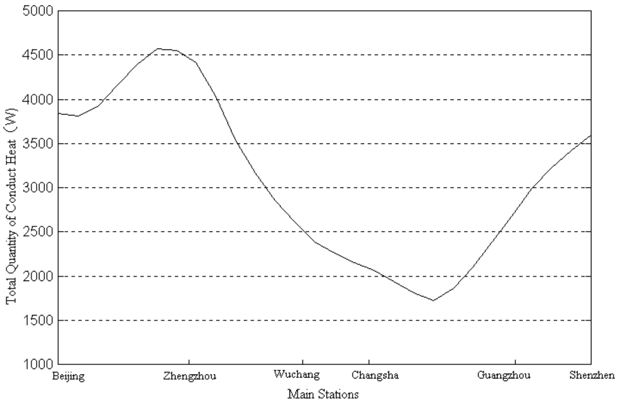

Figure 15. Quantity of Heat from Enclosure for T97

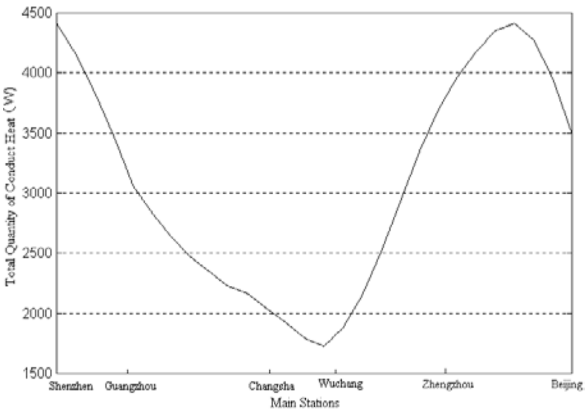

Figure 16. Quantity of Heat from Enclosure for T98

Figure (15) and (16) show: as solar radiation varying with time and orientation, and the fluctuation of outdoor temperature wave, these all lead to the quantity of heat transmitted from enclosure varied with time. To train T97, when it enter Zhengzhou, the quantity of heat reach the climax, at that time, we should supply much more quantity of cooling to restrain the increase of thermal load in compartment, when train enter Changsha, the quantity of heat decreased, this time, we should increase the quantity of cooling. To train 98, when it runs between Shenzhen and Wuchang, the quantity of heat gradually descend, at that time, we should relevant drop quantity of cooling, when train enter Wuchang, the quantity of heat increasing, this time, we should increase the quantity of cooling.

6. Conclusion

This paper simulated outdoors thermal environment of train, and obtained outdoor temperature wave, outdoor sol-air temperature wave for all orientations, temperature wave of exterior surface and interior surface, then at last, grasp the law of variation of quantity of heat transmitted from enclosure. According to the above study, we come to the following conclusion:

(1)Air-conditioned train is a movable building in a periods, it will pass through many different climatological districts, we shouldn't only consider a certain district when determining outdoor parameters, on the contrary, we should consider these climatological parameters synthetically, and make them corresponding to reality.

(2)The calculation shows: different train has different outdoors thermal environment, and the influence on indoor thermal environment also different, so it is different for the regulative scheme of refrigerating capacity.

(3)This paper offered a way to simulated the fluctuation of temperature and quantity of heat, by this way, we can grip the law for the change of air conditioning system load, and it also established theoretical basis for the study of thermal comfort for compartment and air conditioning system real time control.

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