International Journal of u- and e- Service, Science and Technology
Vol.9, No. 1 (2016), pp.243-252
http://dx.doi.org/10.14257/ijunesst.2016.9.1.26

Research on the Working-wavelength Selection Method of the MSP Non-source Temperature Calibration Method Based on Cuvre Similarity Principle

Sun Kun*, Yu Jia, Sun Hui and Li Wei

The Higher Educational Key Laboratory for Measuring & Control Technology and Instrumentations of Heilongjiang Province, Harbin University of Science and Technology, Harbin, China
**Corresponding author: sunkun1982@126.com*

Abstract

In the field of multi-spectral temperature measurement, the high-temperature blackbody furnace is applied to calibrate the multi-spectral pyrometer (MSP). The material of the blackbody furnace is graphite and its melting point is 3000 ℃. As a result, the MSP is not able to be calibrated above 3000 ℃ (non-source temperature) and the measurement range of MSP is limited to lower than 3000 ℃. Currently, the needs of the temperature measurement above 3000 ℃ are gradually increasing. To solve the problem above, the non-source temperature calibration method based on curve similarity principle (NCCSP) is proposed. The core idea of the NCCSP is that the mathematical model is formed based on curve similarity of the MSP output and the power function and then the derivative fitting which can control the curve trend well is applied to obtain model parameters to achieve the purpose that apply the calibration data below 3000 ℃ to predict the calibration data above 3000 ℃. The NCCSP is significance to expand multi-spectral pyrometer measurement range and supplement multispectral temperature measurement theory. The working-wavelength number of MSP is from a few to hundreds, under which the NCCSP is more accurate needs to be further researched. Therefore, in this paper, the impacts on the NCCSP accuracy of the working-wavelength selection are researched. Combine with Planck's law by theoretical simulation method to get the working-wavelength selection basis.

Keywords*: Non-source temperature calibration； Curve similarity principle； Working-wavelength； Extrapolation Accuracy*

1. Introduction

Calibration technique is a key technology in the field of multi-spectral temperature measurement, in a sense, to study it even more important than the study of MSP instrument itself [1-3]. At present, the MSP used in high-temperature measurement has already had high resolution and high signal to noise ratio. However, the non-source temperature calibration falls far behind the development of the MSP and the existing methods which are the one-point calibration method and the warming filter calibration method have already seriously hindered the precision and application range of the pyrometer [4,5]. In order to break through the limitation of calibration of non-source temperature, the calibration method based on curve similarity principle has been put forward in previous paper [6]. Due to the number of the MSP work-wavelength ranging from a few to a few hundred, the work-wavelength under which the application of the NCCSP has higher accuracy needs to be researched. In this artcle, the impacts on the

ISSN: 2005-4246 IJUNESST

NCCSP accuracy of the wavelength are researched to get the work-wavelength selection regular.

2. Principle of the NCCSP

The NCCSP is that the temperature-voltage (T-U) model is formed based on curve similarity principle where output voltage U of the MSP is derived from its corresponding known temperature point. Based on the model, the Derivative least square method (MDLS) is used to obtain the parameters of the model to realize the non-source temperature calibration.

2.1 The Principle of Derivative Least Squares Method

The derivative directly controls the curve trend and the derivative is applied legitimately in the process of the curve extrapolation prediction can make the extrapolating results more accurate and persuasive. On the basis above, the MDLS is proposed. Compared to the traditional least squares method, the MDLS combines the curve fitting with the all derivatives fitting of each point reasonably to predict curve trend accurately[7][8].

Assume x and $t=(t_1,t_2,\cdots,t_s)^T$ have the following relationship:

$$x = f(t,\theta_0,\theta_1,\cdots,\theta_q)+\varepsilon \tag{1}$$

In function (1), θ_j are the unknown value, $\theta_j=(\theta_{j1},\theta_{j2},\cdots,\theta_{jr_j})^T$, $j=0,1,\cdots,q$; ε is the error.

Assume j-th order derivative of x is $x^{(j)}$, and a set of observations is $\left(t_{ji},x_i^{(j)}\right)$, $i=0,1,\cdots,n_j$. Assume j-th order derivative of $f(t,\theta_0,\theta_1,\cdots,\theta_q)$ is $f^{(j)}(t,\theta_0,\theta_1,\cdots,\theta_q)$, let

$$Q_j = u_j^T V_k^{-1} u_j,\quad j=0,1,\cdots,q \tag{2}$$

In function (2), u_j —— $u_j=(u_{j1},u_{j2},\cdots,u_{jn_i})^T$, u_{ji} —— $u_{ji}=x_i^{(j)}-f^{(j)}(t_{ji},\theta_0,\theta_1,\cdots,\theta_q)$, V_j —— $Cov(X_j,X_j)=\sigma_j^2V_j=\sigma_j^2(v_{jk})_{n_j\times n_j}$, X_j —— $X_j=(x_1^{(j)},x_2^{(j)},\cdots,x_{n_j}^{(j)})^T$.

The derivative least squares estimated value of $\theta_j=(\theta_{j1},\theta_{j2},\cdots,\theta_{jr_j})^T$ is obtained by equation (3).

$$\frac{\partial Q_j}{\partial\theta_j}=2\frac{\partial u_j^T}{\partial\theta_j}V_j^{-1}u_j=O_{r_j\times1},\quad j=0,1,\cdots,q \tag{3}$$

In function (3), $O_{r_j\times1}$ is zero vector.

When V_j is the unit matrix, the equation (3) can be reduced to the following equation:

$$\begin{aligned}\frac{\partial Q_j}{\partial\theta_j}&=-2\sum_{i=1}^{n_j}[x_i^{(j)}-f^{(j)}(t_{ji},\theta_0,\theta_1,\cdots\theta_q)]\times\frac{\partial f^{(j)}(t_{ji},\theta_0,\theta_1,\cdots,\theta_q)}{\partial\theta_j}\\&=O_{r_j\times1},\quad j=0,1,\cdots,q\end{aligned} \tag{4}$$

The parameters of θ_j can be obtained by equations (3) or (4). The above method is the derivative least squares method.

2.2 The NCCSP Principle

Fig.1 shows two-channel brightness temperature calibration curves in source temperaure of the MSP for solid rocket motor plume temperature measurement developed by HIT, which the working-wavelengths are 0.554μm and 0.594μm. Fig.2 shows commonly used functions. As can be seen from the Fig1 and Fig2, the output curve of the MSP has a high similarity with power function when the power is less than 1, so it can be assumed that multispectral pyrometer output function is a power function or a power function-based complex function.

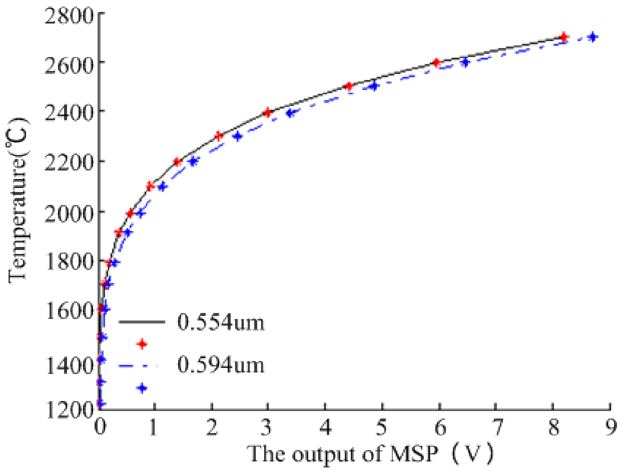

Figure 1. The Brightness Temperature Calibration Curves of Multi-spectral Pyrometer

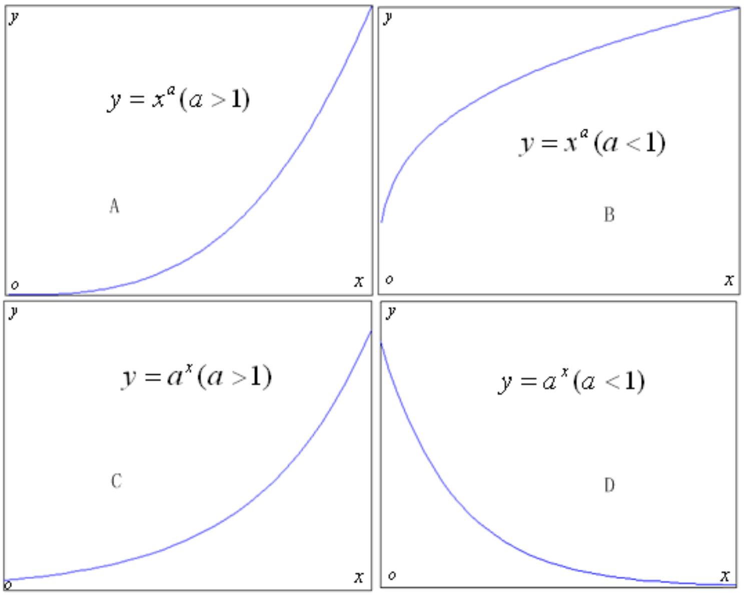

Figure 2. The Curves of Commonly used Functions

The actual temperature T of blackbody furnace has the following relationship with output voltage U when the working wavelength is λ:

$$T = a + bU^c \tag{5}$$

In function (5), a, b and c are the unknown value, use the the derivative least squares method, let

$$Q_0 = \sum_{i=1}^{n} w_i \left[(T_i - a - bU_i^{\,c}) \right]^2 \tag{6}$$

$$Q_1 = \sum_{i=1}^{n-1} w_i^{'} \left[(T_i^{'} - c\frac{\bar{T}_i}{\bar{U}_i} + ca\frac{1}{\bar{U}_i}) \right]^2 \tag{7}$$

Then, the model parameters a, b and c can be obtained from the following functions.

$$\frac{\partial Q_0}{\partial b} = -2\sum_{i=1}^{n} w_i \left[(T_i - a - bU_i^{\,c}) \right] \times U_i^{\,c} = 0 \tag{8}$$

$$\frac{\partial Q_1}{\partial a} = -2\,c\sum_{i=1}^{n-1} w_i^{'} \left[(T_i^{'} - c\frac{\bar{T}_i}{\bar{U}_i} + ca\frac{1}{\bar{U}_i}) \right] \times \frac{1}{\bar{U}_i} = 0 \tag{9}$$

$$\frac{\partial Q_1}{\partial c} = -\,2\sum_{i=1}^{n-1} w_i^{'} \left[(T_i^{'} - c\frac{\bar{T}_i}{\bar{U}_i} + ca\frac{1}{\bar{U}_i}) \right] \times \left(\frac{\bar{T}_i}{\bar{U}_i} - a\frac{1}{\bar{U}_i} \right) = 0 \tag{10}$$

$$c = \frac{S_{tt}S_{xx^{'}} - S_{tx}S_{tx^{'}}}{S_{tt}S_{xx} - S_{tx}^{2}} \tag{11}$$

$$a = \frac{S_{tx}S_{xx^{'}} - S_{xx}S_{tx^{'}}}{S_{tt}S_{xx^{'}} - S_{tx}S_{tx^{'}}} \tag{12}$$

$$b = \frac{S_{xm} - aS_{1m}}{S_{2m}} \tag{13}$$

$$S_{tt} = \frac{1}{n-1}\sum_{i=1}^{n-1} \frac{w_i^{'}}{\bar{T}_i^{2}} \tag{14}$$

$$S_{xx} = \frac{1}{n-1}\sum_{i=1}^{n-1} \frac{w_i^{'}\bar{U}_i^{\,2}}{\bar{T}_i^{2}} \tag{15}$$

$$S_{tx} = \frac{1}{n-1}\sum_{i=1}^{n-1} \frac{w_i^{'}\bar{U}_i}{\bar{T}_i^{2}} \tag{16}$$

$$S_{tx^{'}} = \frac{1}{n-1}\sum_{i=1}^{n-1} \frac{w_i^{'}U_i^{'}}{\bar{T}_i} \tag{17}$$

$$S_{xx^{'}} = \frac{1}{n-1}\sum_{i=1}^{n-1} \frac{w_i^{'}\bar{U}_i U_i^{'}}{\bar{T}_i} \tag{18}$$

$$S_{xc} = \frac{1}{n}\sum_{i=1}^{n} w_i \bar{U}_i T_i^{c} \tag{19}$$

$$S_{1c} = \frac{1}{n}\sum_{i=1}^{n} w_i T_i^{c} \tag{20}$$

$$S_{2c} = \frac{1}{n}\sum_{i=1}^{n} w_i T_i^{2c} \tag{21}$$

$$S_{xc-1} = \frac{1}{n}\sum_{i=1}^{n} w_i \bar{U}_i T^{c-1} \tag{22}$$

$$S_{1c-1} = \frac{1}{n}\sum_{i=1}^{n} w_i T_i^{c-1} \tag{23}$$

$$S_{2c-1} = \frac{1}{n}\sum_{i=1}^{n} w_i T_i^{2c-1} \tag{24}$$

$$U_i^{'} = \frac{U_{i+1} - U_i}{T_{i+1} - T_i}, \qquad i = 1, 2, \cdots, n-1 \tag{25}$$

$$\bar{T}_i = \eta T_{i+1} + (1-\eta) T_i, \qquad i = 1, 2, \cdots, n-1 \tag{26}$$

$$\bar{U}_i = \eta U_{i+1} + (1-\eta) U_i, \qquad i = 1, 2, \cdots, n-1 \tag{27}$$

Where w_i and $w_i^{'}$ are the corresponding weight of known temperature T_i. The rules of value-taking are 1) the weight value near extrapolation range is large; 2) the weight value of actual measurement is large. However, in the process of 100℃-interval calibration of known temperature range, every calibration point is subjected to random and systemic errors, and the relationship of which is hard to predict. Therefore, in order to reduce the interference of the error of one point to the whole curve, let $w_i = w_i^{'}$, and use the known temperature point near the extrapolation range. In function (26) and (27), parameter ε is set as 1/2 in actual practice.

3. The Impacts on the NCCSP Accuracy of the Work-wavelength Selection

Theoretically, in high temperature measurement, the commonly used spectral range of MSP is from 0.4μm to 1.1μm in which blackbody temperature-radiation curves under different work-wavelengths is used to verify the method. The specific method is as follows: the Planck function calculation values of five 100℃-interval points from 2600℃ to 3000℃ are taken as calibration value of source temperature range. The Planck calculation value at temperature point over 3000℃ is taken as the output of MSP. Then, through NCCSP, the corresponding temperature value is obtained. Table 1 to table 8 shows the results when λ is equal 0.4μm, 0.5μm, 0.6μm, 0.7μm, 0.8μm, 0.9μm, 1.0μm and 1.1μm.

Table 1. The Results and Errors of Theoretical Extrapolation when λ is 0.4 μm

ER(℃)	TV(℃)	EV(℃)	E(%)	ER (℃)	TV(℃)	EV(℃)	E(%)
100	3100	3102.363	0.0762	1000	4000	3964.947	-0.8763
200	3200	3202.065	0.0645	1100	4100	4055.068	-1.0959
300	3300	3300.097	0.0302	1200	4200	4139.157	-1.3353
400	3400	3399.056	-0.0278	1300	4300	4231.475	-1.5936
500	3500	3496.182	-0.1099	1400	4400	4317.739	-1.8696
600	3600	3592.206	-0.2164	1500	4500	4402.703	-2.1621
700	3700	3687.163	-0.3469	1600	4600	4486.368	-2.4702
800	3800	3780.965	-0.5009	1700	4700	4568.736	-2.7928
900	3900	3873.570	-0.6777	1800	4800	4649.814	-3.1289

Extrapolation range – ER; Theoretical value – TV; Extrapolation value – EV; Error – E

Table 2. The Results and Errors of Theoretical Extrapolation when λ is 0.5 μm

ER(℃)	TV(℃)	EV(℃)	E(%)	ER (℃)	TV(℃)	EV(℃)	E(%)
100	3100	3101.288	0.0415	1000	4000	3962.657	-0.9336
200	3200	3200.707	0.0221	1100	4100	4052.819	-1.1508
300	3300	3299.396	-0.0183	1200	4200	4141.741	-1.3871
400	3400	3397.250	-0.0809	1300	4300	4229.409	-1.6417
500	3500	3494.176	-0.1664	1400	4400	4315.814	-1.9133
600	3600	3590.100	-0.2750	1500	4500	4400.953	-2.2010

700	3700	3684.957	-0.4066	1600	4600	4484.827	-2.5038
800	3800	3778.697	-0.5606	1700	4700	4567.437	-2.8204
900	3900	3871.274	-0.7366	1800	4800	4648.791	-3.3150

Extrapolation range – ER; Theoretical value – TV; Extrapolation value – EV; Error – E

Table 3. The Results and Errors of Theoretical Extrapolation when λ is 0.6 μm

ER(℃)	TV(℃)	EV(℃)	E(%)	ER (℃)	TV(℃)	EV(℃)	E(%)
100	3100	3100.714	0.0230	1000	4000	3962.028	-0.9494
200	3200	3199.996	-0.0001	1100	4100	4052.362	-1.1619
300	3300	3298.578	-0.0431	1200	4200	4141.498	-1.3929
400	3400	3396.355	-0.1072	1300	4300	4229.421	-1.6413
500	3500	3493.238	-0.1932	1400	4400	4316.123	-1.9063
600	3600	3589.151	-0.3013	1500	4500	4401.601	-2.1866
700	3700	3684.033	-0.4315	1600	4600	4485.856	-2.4814
800	3800	3777.832	-0.5834	1700	4700	4568.891	-2.7896
900	3900	3870.507	-0.7562	1800	4800	4650.712	-3.1102

Extrapolation range – ER; Theoretical value – TV; Extrapolation value – EV; Error – E

Table 4. The Results and Errors of Theoretical Extrapolation when λ is 0.7 μm

ER(℃)	TV(℃)	EV(℃)	E(%)	ER (℃)	TV(℃)	EV(℃)	E(%)
100	3100	3100.380	0.0122	1000	4000	3962.416	-0.9396
200	3200	3199.599	-0.0125	1100	4100	4053.048	-1.1145
300	3300	3298.147	-0.0561	1200	4200	4142.526	-1.3684
400	3400	3395.923	-0.1199	1300	4300	4230.843	-1.6083
500	3500	3492.841	-0.2046	1400	4400	4317.989	-1.8639
600	3600	3588.827	-0.3104	1500	4500	4403.963	-2.1342
700	3700	3683.822	-0.4373	1600	4600	4488.766	-2.4181
800	3800	3777.777	-0.5848	1700	4700	4572.400	-2.7149
900	3900	3870.652	-0.7525	1800	4800	4654.875	-3.0234

Extrapolation range – ER; Theoretical value – TV; Extrapolation value – EV; Error – E

Table 5. The Results and Errors of Theoretical Extrapolation when λ is 0.8 μm

ER(℃)	TV(℃)	EV(℃)	E(%)	ER (℃)	TV(℃)	EV(℃)	E(%)
100	3100	3100.176	0.0005	1000	4000	3963.484	-0.9129
200	3200	3199.374	-0.0196	1100	4100	4054.010	-1.1097
300	3300	3297.934	-0.0626	1200	4200	4144.423	-1.3233
400	3400	3395.758	-0.1248	1300	4300	4233.238	-1.5526
500	3500	3492.762	-0.2068	1400	4400	4320.942	-1.7968
600	3600	3588.880	-0.3089	1500	4500	4407.531	-2.0549
700	3700	3684.053	-0.4310	1600	4600	4493.008	-2.3259
800	3800	3778.234	-0.5728	1700	4700	4577.376	-2.6090
900	3900	3871.388	-0.7336	1800	4800	4660.642	-2.9033

Extrapolation range – ER; Theoretical value – TV; Extrapolation value – EV; Error – E

Table 6. The Results and Errors of Theoretical Extrapolation when λ is 0.9 μm

ER(℃)	TV(℃)	EV(℃)	E(%)	ER (℃)	TV(℃)	EV(℃)	E(%)
100	3100	3100.048	0.0015	1000	4000	3964.979	-0.8755
200	3200	3199.252	-0.0234	1100	4100	4056.442	-1.0624
300	3300	3297.851	-0.0651	1200	4200	4146.868	-1.2650
400	3400	3395.754	-0.1249	1300	4300	4236.251	-1.4825
500	3500	3492.880	-0.2034	1400	4400	4324.583	-1.7140
600	3600	3589.167	-0.3009	1500	4500	4411.862	-1.9586
700	3700	3684.560	-0.4173	1600	4600	4498.091	-2.2154
800	3800	3779.015	-0.5522	1700	4700	4583.273	-2.4836
900	3900	3872.497	-0.7052	1800	4800	4667.414	-2.7622

Extrapolation range – ER; Theoretical value – TV; Extrapolation value – EV; Error – E

Table 7. The Results and Errors of Theoretical Extrapolation when λ is 1.0 μm

ER(℃)	TV(℃)	EV(℃)	E(%)	ER (℃)	TV(℃)	EV(℃)	E(%)
100	3100	3099.966	-0.0011	1000	4000	3966.718	-0.8320
200	3200	3199.191	-0.0252	1100	4100	4058.656	-1.0084
300	3300	3297.847	-0.0652	1200	4200	4149.620	-1.1995
400	3400	3395.847	-0.1221	1300	4300	4239.601	-1.4046
500	3500	3493.117	-0.1967	1400	4400	4328.594	-1.6228
600	3600	3589.594	-0.2891	1500	4500	4416.598	-1.8533
700	3700	3685.229	-0.3992	1600	4600	4503.613	-2.0954
800	3800	3779.982	-0.5267	1700	4700	4589.643	-2.3480
900	3900	3873.820	-0.6712	1800	4800	4674.695	-2.6105

Extrapolation range – ER; Theoretical value – TV; Extrapolation value – EV; Error – E

Table 8. The Results and Errors of Theoretical Extrapolation when λ is 1.1 μm

ER(℃)	TV(℃)	EV(℃)	E(%)	ER (℃)	TV(℃)	EV(℃)	E(%)
100	3100	3099.914	-0.0028	1000	4000	3968.567	-0.7858
200	3200	3199.172	-0.0259	1100	4100	4060.987	-0.9515
300	3300	3297.893	-0.0639	1200	4200	4152.494	-1.1311
400	3400	3395.998	-0.1177	1300	4300	4243.081	-1.3237
500	3500	3493.419	-0.1880	1400	4400	4332.740	-1.5286
600	3600	3590.097	-0.2751	1500	4500	4421.471	-1.7451
700	3700	3685.985	-0.3788	1600	4600	4509.275	-1.9722
800	3800	3781.045	-0.4988	1700	4700	4596.155	-2.2095
900	3900	3875.247	-0.6347	1800	4800	4682.116	-2.4559

Extrapolation range – ER; Theoretical value – TV; Extrapolation value – EV; Error – E

The model parameters a, b, and c under working-wavelengths of 0.4μm, 0.5μm, 0.6μm, 0.7μm, 0.8μm, 0.9μm, 1.0μm and 1.1μm and the non-source temperature extrapolation ranges when the calibration precisions are greater than 3‰, 1% and 3% are shown in table 9.

Table 9. The Theoretical Extrapolation Ranges and Model Parameters

WW (μm)	MP a	MP b	MP c	ERPGT 3‰(℃)	ERPGT 1% (℃)	ERPGT 3% (℃)
0.4	1481.856	193.121	0.167	600	1000	1700
0.5	1498.333	85.796	0.210	600	1000	1700
0.6	1506.057	40.163	0.252	600	1000	1700
0.7	1508.064	19.757	0.294	500	1000	1700
0.8	1505.480	10.222	0.335	600	1000	1800
0.9	1498.992	5.571	0.374	600	1100	1900
1.0	1489.220	3.200	0.411	600	1100	1900
1.1	1476.759	1.935	0.446	600	1100	2000

Working-wavelength – WW; Model parameters– MP; Extrapolation range when precisions are greater than 3%– ERPGT 3%; Extrapolation range when precisions are greater than 1%– ERPGT 1%; Extrapolation range when precisions are greater than 3‰– ERPGT 3‰

As can be seen from the table 1 to table 9 above, when the calibration precisions are greater than 3%, the minimum extrapolation range is 1700℃. Take 17 100- interval temperature points from 3100℃ to 4700℃ to calculate the variances and means of the errors under different working-wavelengths. The results are shown in table 10.

Table 10. The Means and Variances of Theoretical Extrapolation Errors

WW(μm)	M	V	WW(μm)	M	V
0.4	-0.00936	0.00318	0.8	-0.00949	0.00306
0.5	-0.00984	0.00326	0.9	-0.00909	0.00292
0.6	-0.00994	0.00324	1.0	-0.00862	0.00276
0.7	-0.00980	0.00318	1.1	-0.00814	0.00261

Working-wavelength – WW; Means– M; Varinances– V

From the simulation results of the work-wavelength selection effects on the NCCSP accuracy, it can be known that:

When the working-wavelength range is between 0.4μm and 0.6μm, the working-wavelength has almost no effects on the precision of the NCCSP. When the working-wavelength range is between 0.6μm and 1.1μm, the precision of the NCCSP will increase when the working-wavelength increases. When the working-wavelength is equal to 1.1μm, the precision is the highest.

In the no-source temperature range, the NCCSP can extrapolate 500℃ when the precision is greater than 3‰, extrapolate 1000℃ when the precision is greater than 1%, and extrapolate 1700℃ when the precision is greater than 3%.

4. Conclusion

The non-source temperature calibration method based on curve similarity principle has been put forward in previous paper. In this paper, the NCCSP is further researched. The working-wavelength selection effects on the NCCSP precision is researched when the wavelength range is 0.4μm to 1.1μm and then get the working-wavelength selection method. That is when the working-wavelength is from 0.4μm to 0.6μm, the wavelengths selection is arbitrary. When working-wavelength is from 0.6μm to 1.1μm, the wavelengths selection is to select large wavelengths as possible. The regular above provides a theoretical basis for working-wavelength selection of the NCCSP.

Acknowledgements

This research is supported by Technology Research Project of Heilongjiang Province Education Department (12541104). The constructive comments from the reviewers are of this paper gratefully acknowledged which have helped the author to improve the paper.

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