Study on a transient optical fiber high temperature measurement system

Cai Lulu, Liu Yusha, Wang Yutian
Hebei Key Laboratory of Measurement Technology and Instrument,
Yanshan University, Qinhuangdao, 066004, China

ABSTRACT

High temperature is one of the most important parameters in the fields of scientific research and industrial production. At present, thermocouple, thermo resistive and radiance thermometer are already technologically mature which can be adopted to measure the general temperature, but when it comes to the transient high temperature that changes pretty quickly in wretched conditions, those traditional pyrometers can not meet the requirements any more. In this paper, we designed a transient optical high temperature measurement system. First, design of the temperature measurement probe. The system took blackbody cavity sensor together with optical fiber to receive the measured signal, here, the integrated emissivity model of the blackbody cavity was established and the optimum structure parameters were confirmed. Secondly, design of the entire temperature measurement system. A contact-noncontact measurement method was applied, which is to make the blackbody cavity and the measured high-temperature source contact, the fiber probe and the blackbody cavity noncontact, as a result, the error caused by contact measurement is overcame and the precision is guaranteed at the same time. In addition, a fiber grating was introduced as the wavelength filter device which can realize the dynamic filter of narrow-band signals and reduce the impact of background light. Thirdly, signal processing. In this part, we applied labVIEW software and wavelet analysis method. All of the signal acquisition and processing were realized in the labVIEW environment. Through calling matlab in labVIEW, the signals from optical fiber detector were wavelet denoised and decomposed, thus the temperature information was extracted, and the temperature value was obtained. On basis of wavelet transformation, the paper adopted the 4dB wavelet with horizontal scale of 5 to realize the feature extraction and noise removal, parts of the signals before and after the wavelet noise removal were given and analyzed. Finally, the experimental result shows: the resolution is 1℃,the measurement range is 500~2000℃ and the dynamic response time is 5s.In view of possessing a high precision and resolution, resisting high temperature and corrosion, and being able to realize the continuous measurement of the dynamic temperature, this transient optical fiber high temperature measurement system can be applied widely in the continuous temperature measurement of molten steel and heating furnace kiln temperature measurement and so many other fields of engineering technology.

Keywords: blackbody cavity, contact-noncontact, fiber grating, labVIEW

1. INTRODUCTION

Temperature is one of the main parameters in the fields of industrial and agricultural production and scientific experiments which need constant measurement and control; it is also closely related to our daily life, so the measurement of temperature is vitally important. At present, primary tool for temperature measurements is the thermocouple, which is susceptibility to electro magnetic interference and has a short lifetime, moreover, it has a rather poor reliability in some special harsh environments (e.g. iron producing, glass reprocessing, heating furnace kiln) when the temperature is very high and changes pretty quickly, which is typical of many industrial environments. In 1980s, a new type of sapphire fiber optic temperature sensor was invented in America which belongs to a contact temperature measurement and possesses a high accuracy and resolution, wide range of measurement, fast response time and anti-jamming, etc.Sapphire fiber optic temperature sensor is a significant progress in temperature measurement, however, because of its' sky-high cost, high difficulty of production, it is not helpful to universal application. In this paper, we issued a compound (contact-noncontact) temperature measuring method based on the sapphire fiber optic temperature sensor. A blackbody cavity was chosen as the temperature-sensitive component which is contact with the measured temperature source, and the ordinary optical fiber receive the radiate signal from the cavity in a noncontact way through a confined space, then via narrow-band signals dynamic filter by fiber grating and conversion by photoelectric detector, an almost same effect

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was achieved compared to the sapphire optical fiber sensor with a quite low cost. In the part of dynamic measuring, the dynamic mathematical model of the sensor was established and the traceable dynamic calibration system was designed, so this system could realize the continuous and transient temperature measurement and obtained the precise value of temperature. This developed compound temperature sensor has a high accuracy and resolution, and its' dynamic response time is less than 5s.Successfully combining blackbody cavity and optical fiber temperature sensor into a single sensor system that possesses all the major advantages of both of them, it fulfilled the needs for real-time accurate monitoring of temperatures and could be used in numbers of industrial fields widely.

2. SYSTEM STRUCTURE AND PRINCIPLE

This compound optical fiber high-temperature measurement system uses a contact-noncontact measuring technology. The structure of the entire system is shown in Figure 1.It is composed of blackbody cavity probe (spherical-cylindrical), lens group, optical fiber collimator, transmission fiber, fiber circulator, fiber grating filter, photoelectric detector, signal amplification, data acquisition and the computer.

In practice, the blackbody cavity which can stand high temperature is made direct contact with the measured high temperature source; these two achieve thermal equilibrium through heat exchange. Blackbody radiation issued by the blackbody cavity is delivered to the optical fiber probe which is not direct contact to the high temperature source through a confined space. The fiber probe is composed of lens group and optical fiber collimator, which couples the blackbody radiation into the transmission fiber, as a result, the signal light was transmitted to port 1 of the fiber circulator from measurement site by way of the transmission fiber. Light out of port 2 arrived at the fiber grating filter then returned and is last output from port 3 of the fiber circulator. Photoelectric detector transforms the light signal to voltage, and then through signal amplification and data acquisition circuit, the signal is processed and displayed finally by the computer.

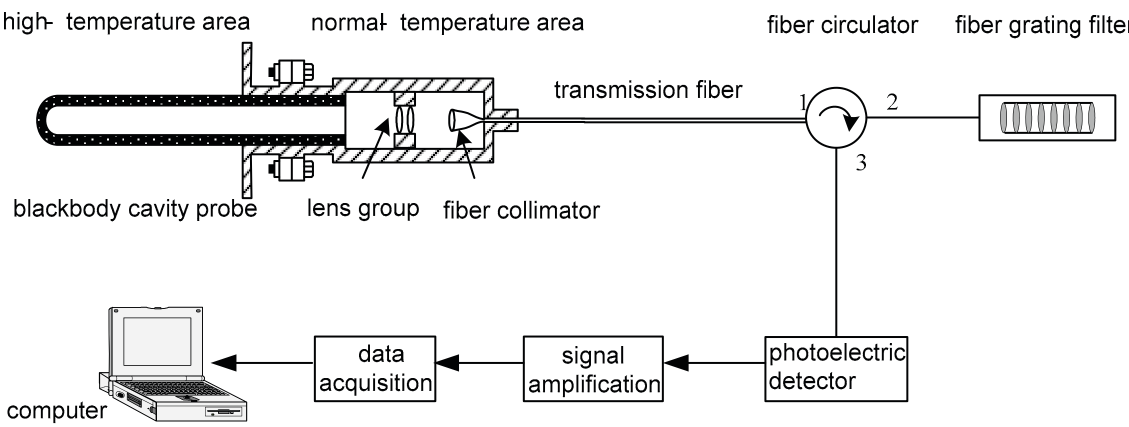


Fig. 1. System structure

2.1 Structure of the blackbody cavity

There are many structure styles for the blackbody cavity, such as cylindrical, conical-cylindrical and spherical-cylindrical. (See Fig 2) Take the cylindrical blackbody cavity as an example, the structure model of which is shown in figure 3. R and L are the radius and length of the cavity, R_0 is the aperture, R_D is the radius of the detector and H_0 is the distance between cavity and detector.

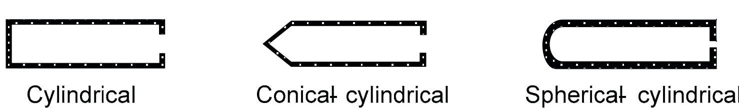


Fig.2. Styles of blackbody cavity

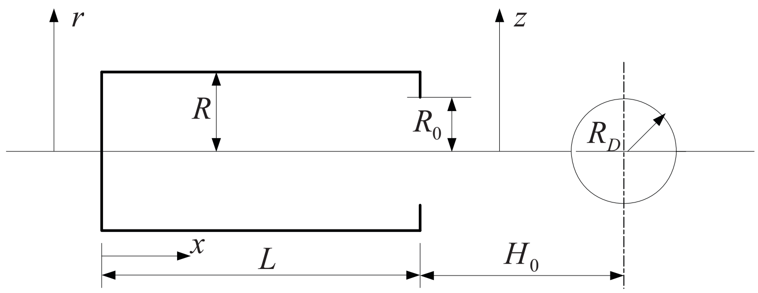


Figure.3. Structure of cylindrical blackbody cavity with a cover

The integrated emissivity of this cavity which is a crucial parameter expressing the radiation characteristic of the blackbody cavity can be expressed as

$$\varepsilon^c = \frac{\int_0^R \varepsilon_a(r)dF_{r,D}dA_r + \int_0^L \varepsilon_a(x)dF_{x,D}dA_x + \int_{R_0}^R \varepsilon_a(z)dF_{z,D}dA_z}{\int_0^R dF_{r,D}dA_r + \int_0^L dF_{x,D}dA_x + \int_{R_0}^R dF_{z,D}dA_z} \tag{1}$$

Where ε_a is the efficiency emissivity of every point in the cavity, dA_r , dA_x and dA_z are the area of micro-ring in the coordinate of r, x and z, $dF_{r,D}$, $dF_{x,D}$ and $dF_{z,D}$ are the angel coefficients from micro-ring in cavity to the detector. Usually ε^c should be made as close as to the ideal value 1, so the radiation of blackbody cavity could be absorbed entirely by the detector.

To solve the integrated emissivity ε^c of the cavity, the efficiency emissivity of every point in the cavity (ε_a (x), ε_a (r) and ε_a (z)) must be solved beforehand, where a Buckley-Sparrow integral equation theory and trapezoidal area approximation proposed by Bedford and Ma were applied, with which the efficiency emissivity of every point in the axis of x is expressed as

$$\varepsilon_a(x_m) = \varepsilon + (1-\varepsilon)\left\{\sum_{i=1}^{N1}\frac{1}{2}\left[\varepsilon_a(x_{i+1}) + \varepsilon_a(x_i)\right]\left|dF_{xm,xi+1} - dF_{xm,xi}\right| + \sum_{j=1}^{N2}\frac{1}{2}\left[\varepsilon_a(r_{j+1}) + \varepsilon_a(r_j)\right](dF_{xm,rj+1} - dF_{xm,rj}) + \sum_{k=1}^{N3}\frac{1}{2}\left[\varepsilon_a(z_{k+1}) + \varepsilon_a(z_k)\right](dF_{xm,zk+1} - dF_{xm,zk})\right\}$$

$$m = 1, 2, \ldots, N_1 + 1 \tag{2}$$

The ones in the axis of r and z can be obtained in the same theory. Through analysis, the optimal parameters are obtained, that is , suppose the radius of cylinder is unit length of 1,then the axis length had better be 10~20, the aperture 0.5, the radius of detector 0.3 and the distance between the aperture and the detector 4.

2.2 Radiation temperature measuring system

The blackbody cavity emits electromagnetic radiation corresponding to the measured temperature with the law of blackbody radiation, of which the spectral power density exit rate can be expressed as formula Plank

$$E(\lambda, T) = \varepsilon(\lambda, T)\frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]} \tag{3}$$

Where C_1, C_2 are the first and the second Plank radiant constants, λ is wavelength of the radiation light, T is temperature of the blackbody radiation and $\varepsilon(\lambda, T)$ is effective emissivity of the blackbody cavity, which is related to the material and geometrical dimension of the blackbody cavity.

Before photoelectric conversion, a fiber grating filter is introduced in order to realize the narrow-band filter of dynamic signals. We use two fiber grating filters here which form into a differential pattern aiming at realizing the temperature compensation. After the filter, two peak value wavelengths are present, λ_1= 1550.185nm and λ_2=950.161nm, which is shown in figure 4.

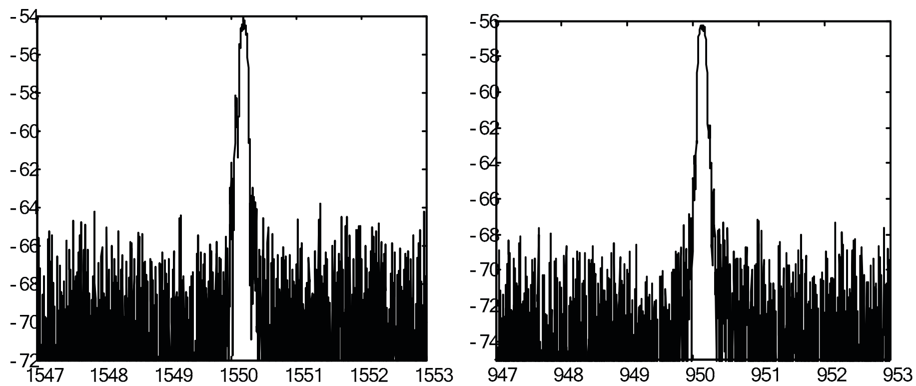


Fig.4. Signals after fiber grating filter

For the part of photoelectric, suppose couple efficiency of the optical fiber probe is $\eta(\lambda)$, spectral response function of the fiber grating narrow-band filter is $R(\lambda)$ while the one of the photoelectric detector (Si PIN tube) is $D(\lambda)$, center wavelength is λ_B ,bandwidth is $2\Delta\lambda$, then the output voltage transformed from the radiation light signal is

$$V(\lambda_B, T) = \int_{\lambda_B - \Delta\lambda}^{\lambda_B + \Delta\lambda} \eta(\lambda) \times R(\lambda) \times D(\lambda) \times E(\lambda, T) \cdot d\lambda \tag{4}$$

From formula (4), we can see, $\eta(\lambda)$, $R(\lambda)$ and $D(\lambda)$ are all related to the wavelength of the filter, not to the measured temperature T, so through design of the filter and calibration, $\eta(\lambda)$, $R(\lambda)$ and $D(\lambda)$ become constants .Like this, the output voltage can reflect the measured temperature directly.

Finally the voltage signal is sampled into the computer through applying a MSP430FE425, which is a low-power mixed signal microcontroller with 16-bit A/D conversion and embedded signal processor core, and then in labVIEW environment, signals are denoised and decomposed by calling matlab and applying wavelet analysis, afterwards, via the process of linearization, the ultimate results are displayed.

3. EXPERIMENT

3.1 Dynamic response

Due to blackbody cavity and measured temperature source being contact, the material, geometrical structure and exist of protect bushing of the blackbody cavity would make the sensor signal hysteresis,that is ,the temperature we measured always be hysteresis to the change of the actual temperature. For this problem, a traceable dynamic calibration system is developed, the principle of which is shown in figure 5.A high frequency laser is chosen as the transient heat source, which make the temperature of the sensor surface rise. The calibrated sensor and the radiation thermometer implement the temperature measurement at the same time then a voltage-time curve of them in a certain temperature is obtained respectively. Through the voltage-temperature curve and the voltage-time curve, we receive the corresponding temperature-time curve. Because of the frequency response characteristic of the radiation thermometer being much better than that of the calibrated sensor, the response signal of the thermometer could be regarded as the input signal of the calibrated sensor and the acquired response curve as the output signal, like this, the dynamic response characteristic of the latter is calibrated by the former, in other words, the temperature-time curve of the calibrated sensor is calibrated by the one of the radiation thermometer.

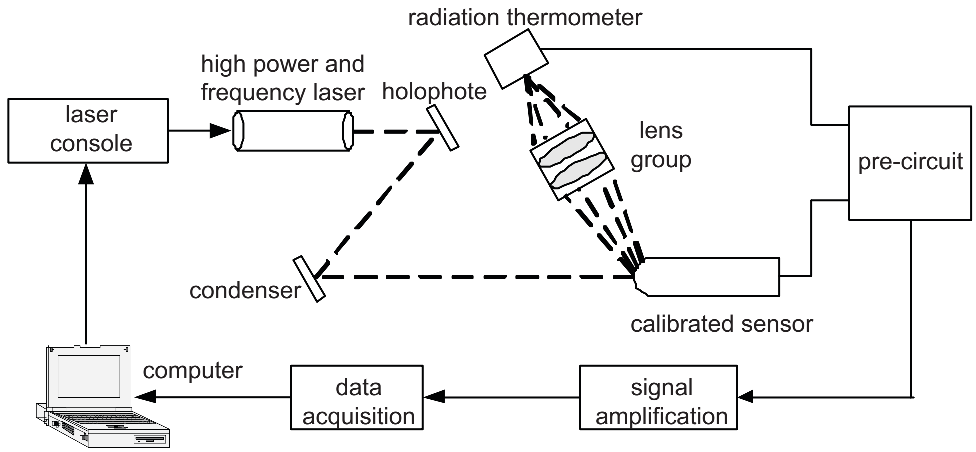


Fig.5. Traceable dynamic calibration system

The dynamic mathematics model of the sensor is also established, where the heat exchange model of blackbody cavity is applied combining the method of neural network identification. When it works, the signal of radiation thermometer is viewed as input $u(k)$, and that of the calibrated sensor as output $y(k)$.Supposed the dynamic characteristic of the temperature sensor is

$$y(k) = -\sum_{i=1}^{n} a_i y(k-i) + \sum_{i=1}^{n} b_i u(k-i) + \varsigma(k) \tag{5}$$

Where $\{u(k)\}$ and $\{y(k)\}$ are the sequence of input and output respectively, $\varsigma(k)$ is the noise interference.

The dynamic model of the calibrated sensor can be established with the application of 3-layer BP neural network structure and the training to network by choosing appropriate input node and sufficient study sample copy to make the weight and threshold value converge to stable. On the basis of dynamic model and voltage signal the sensor measured, the measuring of traceable replicable transient temperature is realized.

3.2 Signal Processing

The noise of the output of photoelectric detector and preamplifier that can't be ignored compared to detecting signal and locates in forward-level of signal processing plays an important role for improvement of the signal-to-noise ratio. So a wavelet analysis is used in the part of signal processing to remove the high frequency noise.

In this compound temperature measuring system the white noise is the primary component of the disturbance signals which obeys the Gaussian distribution being generalized random distribution and is singular everywhere, so the characteristic of wavelet transform of signal and noise under different scales differs extremely. The amplitude and density degree and square-error of corresponding signal wavelet transform are increased with the increasing of scale. But the amplitude and density degree and square-error of corresponding white noise wavelet transform are decreased with the increasing of scale. So after doing many times wavelet transform, the coefficient of corresponding white noise wavelet transform is very small and the residual coefficient is controlled primarily by signal. The signals with noise can be discomposed according to above principle.

The multiresolution analysis theorem of wavelet transform is stated as follows: Suppose $\{V_j\}_{j\in Z}$ is one multiresolution analysis (MRA) of $L^2(R)$and W_j is orthogonal auxiliary space of V_j in coordinate V_{j+1}, namely $W_j \oplus V_j = V_{j+1}$. Suppose $f(x)$ is the signal function whose approximate signal is $A_j^d f$ and detailed signal is $D_j f$ under the scale j.

The decomposing procedure of $f(x)$ is the decomposing procedure from scale j to scale j+1 step by step. Decompose $A_{j+1}^d f$ to approximate signal $A_j^d f$ and detailed signal, $D_j f$ namely

$$\begin{cases} A_j^d f = \sum_i h(k-2n) A_{j+1}^d f \\ D_j f = \sum_i g(k-2n) A_{j+1}^d f \end{cases} \tag{6}$$

Where h and g are shock response of corresponding filters respectively. Suppose f (x) $\in V_0$, namely f (x) = $A_0^d f$, decomposing f (x) as follows

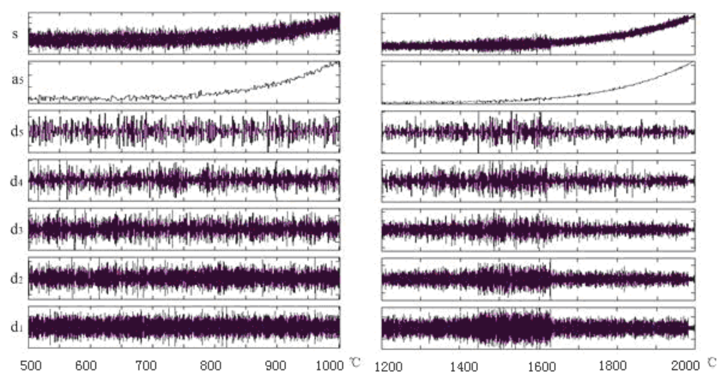
$$f(x) = A_0^d f = A_{-J}^d f + \sum_{j=-1}^{-J} D_j f \qquad j = 1,2,\cdots,J \tag{7}$$

Where J is optimal scale and decided by Shannon Entropy, namely

$$E(S) = \sum_i p(k) \times \log \frac{1}{p(k)} \tag{8}$$

Where $p(k) = \left| S(k)^2 \right| / \left\| S \right\|^2$ is the standardized energy of k-th element and when $p = 0$, $p \log(1/p) = 0$ which means solving Entropy for original signal $f(x)$ and the k level detailed coefficient. If the Entropy of detailed coefficient compared with original signal can be ignored, the acquired decomposing progression, which decomposes five to six scales, meets the demands.

When the signal-to-noise ratio is very small, the chosen wavelet function must be normal. In this part, a Haar wavelet is used which can separate low frequency and high frequency signal well. After above decomposition, original signal is decomposed into sub-signals of different frequency. The noise mainly centralizes in high frequency parts and signal mainly centralizes in low frequency parts in sensor signals, so let the coefficient of high frequency equal zero which can remove high frequency noise and then wavelet reconstruction is made.



(a) λ =1.55μm (b) λ =0.95μm

Fig.6. When λ =1.55μm and 0.95μm, the output of photoelectric detector and wavelet decomposition of five scales

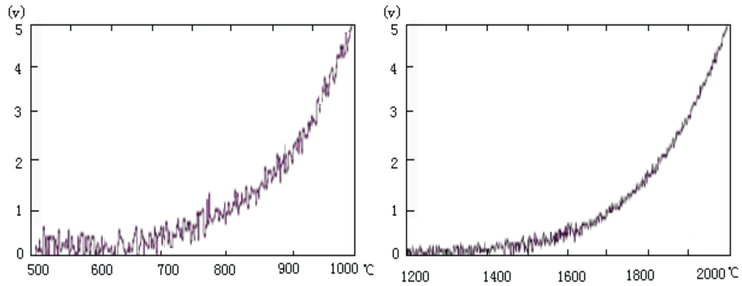


Fig.7. The reconstructive signals

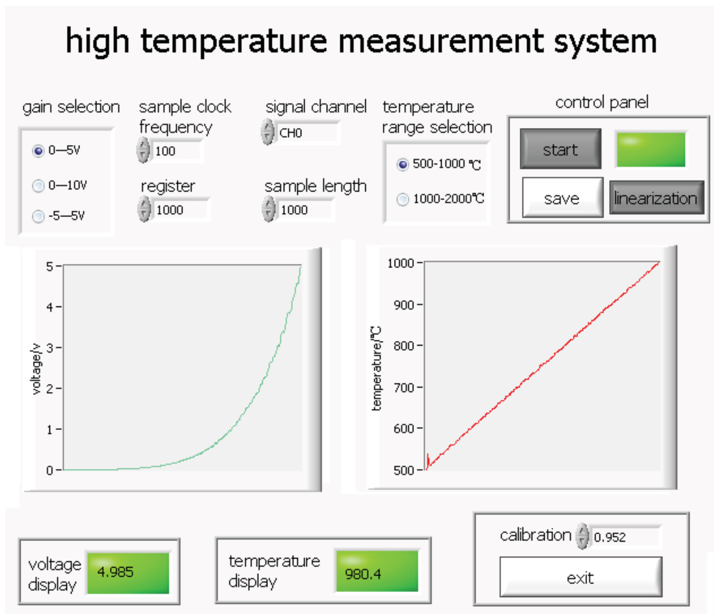


Fig.8.Test results of system from 500-1000℃

When λ =1.55μm and λ =0.95μm, the output of photoelectric detector and wavelet decomposition of five scales are described in figure 6. From the approximate signal a5, noise is almost removed. The reconstructive signals are described in figure 7.After linearization in labVIEW environment, the finally result is shown in figure 8.

4. CONCLUSION

This system adopts contact and noncontact temperature measuring method that combining the blackbody cavity and optical fiber sensor together. The optimal design of the blackbody and application of the fiber grating filter for the photoelectric detector could fulfill a best temperature-radiation energy-voltage conversion while the establishments of traceable dynamic calibration system and the dynamic mathematic model of the sensor resolved the problem of signal hysteresis and improved the dynamic response performance. In labVIEW environment through signal processing of applying wavelet technology and linearization, the accurate, rapid, compensable and real-time temperature measurement was realized .Experiment shows: the resolution is 1℃, the measurement range is 500~2000℃ and the dynamic response time is 5s.From analysis and experiment result, we can see, this compound temperature measuring system has some advantages over other pyrometers and can be used widely in future.

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