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Research Paper

Three-dimensional temperature uniformity assessment based on gray level co-occurrence matrix

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HIGHLIGHTS

- Existing uniformity indices take no account of the temperature distribution location.
- Temperature gradients were measured by the element-value distributions of GLCM.
- The proposed index could be used as the goal of engineering design and optimization.

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ABSTRACT

Temperature uniformity dominates the performance of various industrial systems. However, its improvement has been limited by the lack of accurate assessment of the uniformity. Focus on addressing this issue, this paper, based on the fact that image gray-level distribution characteristics could be described by its textural features, proposed a systematic and quantitative methodology for evaluating the temperature distribution uniformity within a three-dimensional object, through referencing the texture analysis method, i.e. the gray level co-occurrence matrix (GLCM). Firstly, temperature gradients of the three-dimensional temperature distribution were found to be directly related to the element-value distributions of the corresponding GLCM: the smaller the temperature gradients, the more clustered the element values around its main diagonal, and the larger the temperature gradients, the more scattered the element values. Then five textural statistics, which measure the element-value distributions of the GLCM from different angles, were adopted to reflect the temperature uniformity. Finally, their linear weighted sum was advocated to obtain a comprehensive assessment of the uniformity. Additionally, the applications of this method were also illustrated with a flat-plate example, where the derived uniformity evaluation results were validated by the relevant thermal stresses.

1. Introduction

In engineering applications, temperature uniformity within a three-dimensional object often dominates the performance of many systems. For example, temperature uniformity within the laminar viscous pipe flow affects the equality of heat treatment for pharmaceutical formulations, polymer melts, and food products in industry [1], while temperature non-uniformity within the crystal rod would seriously restrict the output characteristics of diode-pumped solid-state laser (DPSSL) [2]. On the other hand, temperature uniformity within the reactor affects the polymerase chain reaction (PCR) in genetic engineering [3], the preferential oxidation (PROX) for CO removal of hydrogen-rich reformates in hydrogen storage and transport [4], as well as the processing and recycling of energy-intensive materials in solar furnaces heated by concentrated solar power (CSP) [5]. Additionally, temperature uniformity within the test chamber in the combined environmental testing decides the improvement in reliability of the spacecraft on the ground [6]. In particular, non-uniform temperature distribution across a structure would induce thermal stresses, which govern the wafer failure of semiconductors during rapid thermal processing (RTP) [7], and sharply shorten the strength and life of turbine vane and rotor blade [8].

As a result, numerous studies have been conducted to improve the temperature uniformities among these systems. However, they are all limited by the lack of proper measures of temperature uniformity. To promote the temperature uniformity in viscous pipe flow, Tian and Barigou [1] reported an enhanced vibration technique and assessed its performance with CFD (Computational Fluid

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Dynamics) simulations, where the ratio of temperature standard deviation to temperature mean was taken as the temperature uniformity measure. Meanwhile, the temperature profile or temperature distribution was also used to compare the temperature uniformity. Moreover, Chen et al. [2] put forward the temperature standard deviation to determine the temperature distribution uniformity in laser working medium, and analyzed its influencing factors with ANSYS finite-element simulations. Additionally, the maximum temperature difference was also frequently employed to reflect temperature uniformity [3,6], with which Li et al. [5] optimized the design of a new type test setup to improve the temperature homogeneity condition in the reaction chamber of the solar furnace with ABAQUS. So far, these four are the only ways available to describe temperature uniformity [4,7,9–13]. Nevertheless, all these indices essentially failed to represent the temperature gradient except simply characterizing some aspects of the uniformity.

In conclusion, the uniformity of temperature distribution has not yet been comprehensively quantified. Furthermore, as far as the authors know, there is no quantitative and systematic method for assessing the temperature distribution uniformity within a three-dimensional object in open literature. The objective of this article is to present such an approach based on the gray level co-occurrence matrix in image texture analysis, which could then be applied in the performance evaluation and quantificational design of the aforementioned systems, as well as the performance optimization of them. As an application example of this method, temperature uniformities within a flat-plate under five different cases were evaluated and compared. Meanwhile, the assessment results were verified by the corresponding thermal stress calculations. Finally, the engineering applications of the proposed method were also briefly discussed.

2. Methodology

In a grayscale image, the spatial variations of pixel gray levels are characterized as its textural features [14–16]. For regions where the gray levels of neighboring pixels are in close proximity, the texture would be coarse. Otherwise, if the gray levels are quite different, the texture would be fine [17]. Moreover, texture direction indicates the orientation where the gray levels change the least frequently [14]. Obviously, textural features actually describe the gray-level distribution uniformity [14,16]. Similarly, after establishing the one-to-one correspondence between temperature and gray level, textural feature analysis of the temperature field would also reveal the temperature distribution uniformity.

2.1. Temperature graying

Before assessing temperature uniformity with the texture analysis methods, temperature data have to be converted into gray values. These values are proportionally transformed from the relevant temperatures with the following formula [18,19]:

$$g = round\left[\frac{T - T_{\min}}{T_{\max} - T_{\min}} \times (G - 1)\right] + 1 \tag{1}$$

where T is the temperature value while g is the corresponding gray level. *round* is the operator that rounds the computed value to the nearest integer, and G is the quantized levels of grayscale and $T_{\min}$ and $T_{\max}$ are respectively the minimum and maximum temperature values within the three-dimensional temperature field. Evidently, G affects the quantized coarseness or fineness of temperature data and decides the amount of textural information contained in the temperature field [19,20]. Therefore, a higher quantization level is preferred for a narrow temperature distribution. In practical applications, G is commonly chosen as 256 [21,22].

2.2. 3D gray level co-occurrence matrix

The gray level co-occurrence matrix (GLCM) has been theoretically proved to be a promising approach to analyzing textural features of image and many practical applications have also identified this [23–27]. The GLCM, which is established on the second-order joint conditional probabilities of gray levels of pixel pairs [28,29], describes textural features with the spatial relationships among the gray levels through examining all pixels within the image space and counting the gray-level dependencies between two pixels separated by a certain interval distance along a particular direction [30]. The derived results directly reflect the spatial arrangements of pixel gray levels as well as their distribution uniformity [16,31]. However, the conventional GLCM method originally proposed by Haralick et al. [14,17] principally measures the planar gray-level distribution within a two-dimensional dataset, and it couldn't fully characterize the spatial gray-level distribution among the three-dimensional space [32,33]. Therefore, the 3D GLCM method is needed to comprehensively investigate the temperature distribution uniformity within a three-dimensional object.

The 3D GLCM method is basically equivalent to the conventional GLCM, only except that it counts the spatial gray-level correlations between two points among the entire three-dimensional space rather than those merely within a single two-dimensional plane [34–36]. To be specific, the element P_{ij} in the 3D GLCM **P** is defined as the co-occurring frequencies of i and j, which are the gray levels of two respective points (i.e. the reference point and its neighboring point) separated by a certain adjacent distance d in a given direction among the three-dimensional space [14], and the expression of GLCM **P** under the three-dimensional Cartesian coordinates is presented as follows.

$$\begin{aligned} P_{ij} = \#\{&((x, y, z), (x + dx, y + dy, z + dz)) \\ &\times |g(x, y, z) = i, g(x + dx, y + dy, z + dz) = j\} \end{aligned} \tag{2}$$

in which # denotes the number of point pairs in the set. (x, y, z) is the coordinate of the reference point with gray level $i = g(x, y, z)$, while (x + dx, y + dy, z + dz) is that of the neighboring point with gray level $j = g(x + dx, y + dy, z + dz)$. Moreover, $1 \leqslant i, j \leqslant G$ (number of the grayscale quantization levels). As illustrated in Fig. 1, the neighboring points could be situated in 13 directions relative to the reference point [36], whose positive sides are respectively depicted by the arrows, while the corresponding relationship between the displacement vector (dx, dy, dz) and a given direction

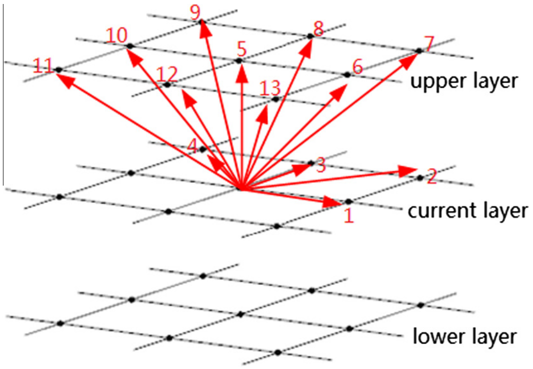

Fig. 1. The possible directions for a reference point among the three-dimensional space when defining the 3D GLCM **P**.