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Research of uniformity evaluation model based on entropy clustering in the microwave heating processes

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ABSTRACT

This paper proposes a uniformity evaluation method based on Spectral Clustering and Maximum Information Entropy (ECUEM) for clustering the simulation results in the microwave heating system. The proposed method can effectively evaluate the dataset of the electric field *E*, the magnetic field *H*, the temperature field *T*, and analyze the non-uniformity phenomenon in the microwave heating processes. Compared with other clustering algorithms, the ECUEM can get better clustering results for the dataset in simulation of microwave heating. In particular, in the resonant cavity, the experimental results show that the minimum the evaluation results, the better the materials heating uniformity. In addition, when the ECUEM method is used to analyze the experiment of waveguide moving, the best position (0, 11/20*do, 3/14*ho) of waveguide can be obtained; at the same time, the uniformity or efficiency of materials microwave heating is the best. Moreover, other rules have been obtained in the microwave heating processes. Thus, the proposed method would provide a new method to guide the researchers who are working in the area of dataset clustering in the microwave heating.

1. Introduction

Nowadays, the microwave heating (MH) has been popularly used in the food processing, petrochemicals, pharmaceutical, organic synthesis and other industrial fields [1]. Although the MH can potentially replace conventional heat processes widely used in the industrial applications, some problems still inherent in the MH technology, such as non-uniform temperature distribution in the materials heating. However, the MH leads to non-uniform temperatures distribution inside the materials due to different factors depending on microwave waveguide location, geometry and placement of materials inside the resonator, or other factors [2]. This feature is not accepted for industrial material processing owing to the lack of evaluation or controllability in the MH because MH is a nonlinear, multi-variable, time-varying and strong coupling complex process. Hence, the evaluation or controllability in the MH is the premise condition of improving the non-uniform temperatures distribution inside the materials. An algorithm based on cluster and entropy has been proposed, which is evaluated by the uniformity of temperatures distribution inside the materials [3].

Neurocomputing is a kind of computing that uses the models which simulate the nerve system, such as machine learning systems and artificial neural networks. Common clustering algorithms in machine learning systems include K-means, Spectral clustering, etc. The purpose of the clustering method is to group a set of data into some classes, where different classes have maximum dis-similarity than those in the same class [4]. In simulation of the MH, the complex and strong coupling between multi-dimensional data exists. Thus, the cluster analysis could be used to classify the non-uniform temperatures distribution inside the MH process. The most well-known traditional clustering algorithms include: K-means, EM, fuzzy C-Means (FCM) and so on [5]. The traditional clustering algorithms are non-supervised learning algorithms, because they cannot consider the prior knowledge or assumptions. The algorithm may obtain good results on the convex structure sample space, but is easy to fall into local optima when the sample space is non-convex [6,7]. So, some improved clustering algorithms based on k-means and FCM are presented, for example: Hierarchical clustering and Spectral clustering. In the real-world dataset, some attributes of data could be regarded as an independent parameter of the dataset. In the MH process, the attributes of simulation data (where the temperature field *T*, the electric field *E*, the magnetic field *H* and other multi-physics have a strong coupling relationship for each other in the microwave resonator) can be regarded as multi-dimensional datasets. To these datasets, the clustering results may be suboptimal based

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on the k-means or FCM which start with an initial estimation of the cluster center [8]. In addition, the Hierarchical clustering can get good cluster results by grouping the objects into a tree of clusters. But, the Hierarchical clustering approach decides which clusters should be merged at each step, namely, decision of merging two clusters cannot be undone later, and that may not be viewed as globally optimizing method [9].

However, the cluster analysis can be regarded as an NP-hard grouping problem, where the space complexity and the time complexity may hamper its application. Spectral clustering algorithm (SCA) is a method for high-performance computing widespread attention in recent years [10]. The SCA can get a global optimal solution when used on the sample space of arbitrary shape clustering [11]. The SCA may be effectively used in the clustering multi-dimensional datasets. The SCA is evolved by the spectral graph model, where the problem of graph min-cut based on the graph structure is produced by the object space [12]. Compared with the traditional clustering algorithms, the SCA is stable and powerful for clustering data due to its polynomial-time and deterministic scheduling features [13]. However, the shortcoming of SCA is the input weights of the data in each pair of objects, which needs to construct a matrix to reflect the similarity information among each pair of objects [14]. At the same time, the Gaussian function (as shown in formula (17)) has been widely and effectively used to construct an affinity matrix for the SCA. But the scale of the parameter σ needs to be manually adjusted by users, by which it controls the affinity between two data points. That means the spectral clustering results will be greatly affected by the selection of the scale parameter σ, which are in the clustering multi-dimensional data. The Maximum Entropy has been introduced in the SAC, which considers the selection of the scale parameter σ [15,16].

In this paper, a method of the Entropy Clustering Uniformity Evaluation Model (ECUEM) based on the maximum entropy and spectral clustering has been proposed, which is used in analyzing the distribution characteristics of non-uniform MH in the rectangular cavity. The result of material MH in the rectangular resonant cavity is the multi-dimensional data. The values of temperature field (the electric field or magnetic field) are regarded as the input of clustering X by dealing with the information entropy. The ECUEM aims to divide the multi-dimensional data$X=\{x_1,x_2,\cdots,x_n\}$ into K disjointed subsets $x_1,x_2,\cdots,x_K$, so that points in the same subset share common properties while points which belong to different subsets do not share these properties. Firstly, the dataset X is converted into a vector of sparse coefficients, according to sparse representation theories. Then proximity of any two data objects is assessed according to the similarity between their sparse representation vectors [17]. Next, the scale of the parameter σ is modified by

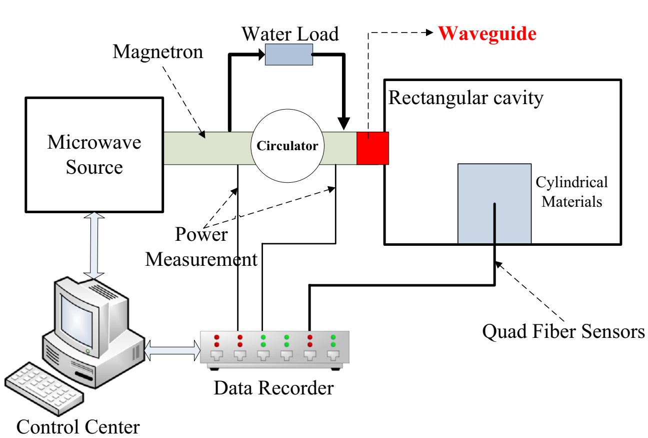

Fig. 1. The MH system.

the Maximum maxH in the formula (16). Finally, the evaluation results can be obtained by using the information entropy.

In addition, some rules or improvement measures for microwave non-uniform heating will be obtained by the ECUEM. Then, the proposed model demonstrated that it is able to improve the uniformity in the materials heating. Moreover, the optimal position of waveguide-port has been achieved by analyzing the results of ECUEM, where the uniformity and efficiency of materials heating have been improved. Thus, the dataset in the MH can be effectively processed or clustered by the ECUEM.

2. Preliminaries and problem statement

In the MH process, the microwave energy is supplied by an electromagnetic field throughout the bulk of the material [2]. However the non-uniform temperatures phenomenon has been found frequently in the material heating process, when changing the factors (e.g. the position of waveguide port, dielectric properties, etc.). The safety and reliability of microwave energy are severely restricted in industrial applications.

The MH system is shown in Fig. 1. The MH system includes the microwave source, the magnetron, the waveguide, the water load, the rectangular cavity, the control center, the data recorder, the cylindrical materials and others. The datasets can be obtained by the data recorder using the quad fiber sensors and the power measurement. In the MH system, the position of waveguide is fixed and cannot be moved. Thus, the simulation of the MH system and change in the position of waveguide is needed to analyze the electromagnetic field, the temperature field and so on.

2.1. Microwave heating mechanism

The MH is caused by the ability of the material to absorb microwave energy and convert it to heat. In the process of material heating, the MH mainly occurs due to the dipolar and ionic mechanisms. The presence of moisture or water in the material causes dielectric heating due to the dipolar nature of water. The permanently polarized dipolar molecules try to realign in the direction of the electric field, when the oscillating electric field is incident on the water molecules. When the material is put into a high frequency electromagnetic wave, the realignment occurs at a million times per second and causes internal friction of molecules resulting in the volumetric heating of the material.

The electromagnetic field distribution inside the microwave cavity is governed by Maxwell's equations. The Maxwell's equations for constant permittivity and permeability and with no sources can be written as

$$\begin{cases} \nabla\times E=-j\omega\mu H \\ \nabla\times H=j\omega\varepsilon\varepsilon_0 E \\ \nabla\cdot E=0 \\ \nabla\cdot H=0 \end{cases} \tag{1}$$

where, μ is the permeability, H is the magnetic field intensity and E is the electric field intensity, both defined as time harmonics. The ability of a material to convert microwave energy into heat can be understood by knowing its dielectric properties. The complex relative permittivity, ε, is defined as $\varepsilon=\varepsilon'+j\varepsilon''$, where, ε' is the dielectric constant and ε'' is the dielectric loss factor andε_0 $\left(\varepsilon_0=8.854\times10^{-12}F/\mathrm{m}\right)$ is the permittivity of free space. The real part of dielectric property ε', termed as dielectric constant, signifies the ability to store electric energy and the imaginary part of dielectric property ε'', termed as dielectric loss, signifies the ability to convert electric energy into heat.