Studying Influence of Preheating Conditions on Design Parameters of Continuous Paint Cure Ovens

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Abstract

This paper concentrates on a new procedure which experimentally recognises gears and bearings faults of a typical gearbox system using a least square support vector machine (LSSVM). Two wavelet selection criteria Maximum Energy to Shannon Entropy ratio and Maximum Relative Wavelet Energy are used and compared to select an appropriate wavelet for feature extraction. The fault diagnosis method consists of three steps, firstly the six different base wavelets are considered. Out of these six wavelets, the base wavelet is selected based on wavelet selection criterion to extract statistical features from wavelet coefficients of raw vibration signals. Based on wavelet selection criterion, Daubechies wavelet and Meyer are selected as the best base wavelet among the other wavelets considered from the Maximum Relative Energy and Maximum Energy to Shannon Entropy criteria respectively. Finally, the gearbox faults are classified using these statistical features as input to LSSVM technique. The optimal decomposition level of wavelet is selected based on the Maximum Energy to Shannon Entropy ratio criteria. In addition to this, Energy and Shannon Entropy of the wavelet coefficients are used as two new features along with other statistical parameters as input of the classifier. Some kernel functions and multi kernel function as a new method are used with three strategies for multi classification of gearboxes. The results of fault classification demonstrate that the LSSVM identified the fault categories of gearbox more accurately with multi kernel and OAOT strategy.

***Keywords**: radiation oven, dynamic optimization, radiation heat transfer, paint cure window.*

1. Introduction

Curing ovens from the view-points of curing rate and amounts of energy consumption has been of great attentions in most industries; in this regard further consideration is given to radiation cure ovens because of providing suitable curing conditions as well as consuming less amount of energy compared to other types of ovens. Designing this type of ovens for curing paint on complicated geometries or thermally-sensitive materials is often a great deal. Complications in design are usually due to providing circumstances for the curing body to experience uniform cure all over its geometry without any zone of over-cured or pre-cured. Among radiation paint cure ovens, the continuous type is more significant from standpoints of both energy and curing rate.

Widely used paint on automobile bodies consists of 5 layers:1. Phosphate layer 2. Electro deposition layer 3. Base coat layer 4. Top coat layer 5. Clear coat layer.

Any step of paint coating on the automobile body is preceded by curing in the continuous radiation oven to solidify paint particles and make the layer ready to embrace next layer [1]. Continuous oven is often in form of a long tunnel of rectangular section with a rail within; to transfer the curing body along the oven for experiencing thermal process predefined and be completely cured. Works of [2] and [3] can be pointed out in field of 3-dimensional simulation of ovens of this kind.

The most challenging problem in designing ovens of this kind is the method for arranging the thermal sources in a way that desired curing conditions all over the curing body be achieved.

Designing procedures are usually accompanied by considerable numerical costs these costs beside the computation costs due to heat transfer simulations deteriorate the conditions for design problems. Therefore proposing a fast precise approach for designing ovens is of great importance and as a result has been considered among many researchers from different points of view.

Numerical simulation of the radiation heat transfer in ovens with stationary loads has been discussed by many researchers. The zonal method (Lou and Huang, 2000)[4], the network model (Zueco, 2006)[5] and the finite element method (Daun et al., 2003, 2002 and 2006) [6-9] are commonly used numerical methods which provide a discrete algebraic model for the problem. Simulation of the heat exchanged between the radiation panels and a moving circular cylinder in a two-dimensional oven using the finite element method has been discussed by Mehdipour et al.[10].

The radiation exchange in enclosures is a classical topic discussed in many references [e.g. 11]. Computational methods applicable in the analysis of transient radiation enclosures are discussed in [12]. In most of the radiation oven applications, the assumptions of diffuse gray surfaces and non-participating medium are employed to simplify the problem.

Inverse method has been widely employed in conduction heat transfer problems. Complication of heat equations in conduction heat transfer problems usually accompanied by ill-posed solution matrices. Inverse methods are efficient in such cases from which researches [13-15] can be noted.

Three principle sections can be defined for the optimization loop: determination of the state or field variables, evaluation of the convergence and modification of the design parameter. The latter is known as the optimizer. For the optimization stage, there are basically two classes of methods available. In a group of approaches, evolutionary methods are employed to use the objective function evaluations to update the design parameter [16,17]. The other group commonly applies the classical gradient-based optimization technique [7].

Daun et al. [7, 8, 13] compare the relative merits of linear inverse and nonlinear programming methods to determine heater settings that result in prescribed conditions over a spatially fixed product surface.

Optimum thermal design of radiation ovens with moving loads, as a sub-class of dynamic optimization problems, is in general computationally demanding. Federov et al. [18] provide a design example in which the radiation panels are thermally designed to provide a target temperature history curve on a moving flat plate. In this reference, many aspects of dynamic thermal optimization of radiation ovens are discussed in the context of a material processing example.

Dynamic optimization of paint cure problems can scarcely be found in the literature. Xiao et al. report the application of an embedded ant colony system-based optimization method to deal with this problem [16].

Inverse methods in radiation problems have been also applied in medical treatments like radiation therapy or in tumor diagnosing [19,20].

In this study a new approach for designing continuous paint cure ovens is proposed. In this method heaters are set and arranged in a way that a proper cure is achieved all over the curing body. Decreasing design stages have been one of the most objectives of the authors in most of their researches [10,21-23]as well as the present research. In Ref.[10] a design approach based on employing cure window criterion is described and the method of defining the objective function in design procedure is comprehensively discussed. In this study influences of objective function on convergence of the solution and also on solution procedure are investigated. Before in Ref. [21] it had been demonstrated that proper definition of objective function decreases the solution steps while increases probability of achieving the solution. In that work a criterion named "equivalent isothermal Temperature " is introduced to be able to decrease numbers of optimization steps. Decrement in numerical costs employing the equivalent isothermal time criterion is studied in Ref. [22]. In that reference combination of neural network and finite element method made the approach such adequate that it can be applied for different geometries with high rates. In this study according to applying hybrid optimization method as well as some simplifications of the principle model, simulation rate and therefore designing rate is increased. This design method is claimed to be applicable for all geometries of any complication (this issue is investigated in Ref. [23] for a 2-dimensional geometry).

In order to solve the problem numerically it is necessary to employ some regularization method. Importance and effects of regularization in inverse problems have been comprehensively discussed in [24]. Significance and influences of step size in optimization problems have been studied in [25].

. Most similar researches are devoted to finding proper solution methods to obtain heaters characteristics. In the present study a method is applied for designing such ovens considering preheating conditions for the oven. It is proved that defining preheating conditions is of similar importance to heater characteristics and highly influences curing conditions. Different preheating conditions are considered in this study and for a 2D oven and the corresponding heaters characteristics are defined for each case to achieve a proper cure.

2. Procedure The design problem

A two-dimensional section of a curing oven along with a moving painted hollow cylindrical object is shown in Figure 2. The outer diameter of the cylinder is $0.6\ m$ and the inner diameter is $0.58\ m$. The oven is modeled as an enclosure, $L=20\ m$ and $b=2.97\ m$, with diffuse-grey walls filled with a transparent stagnant gas. Compass notation is employed to address boundaries of the solution domain as shown in Figure 1.

The outer surface of the moving body (B) is also assumed to be diffuse and grey. Heat exchange at the inner surface of the hollow cylinder is negligible. The body moves along the oven at a constant speed equal to 0.25 m/min. The boundaries of the computational domain are discretised with finite elements and the curing time (t_c) is also discretised using n_t equal intervals. All transient dependent variables are approximated as piecewise constant functions in the discrete model of the continuous dynamic process. Radiation shape factors and temperature history curves at arbitrary points on the body are examples of functions which are approximated by piecewise constant functions.

The finite elements around the cylinder are also shown in Figure 1. Note that while the elements such as e_1 and e_4 receive the thermal radiation directly from the heaters, elements such as e_2 and e_3 mostly receive thermal waves re-radiated from refractory elements. This discrepancy between the elements around the body makes it difficult to achieve a really uniform curing scenario. Therefore, severely restrictive objective functions may result in a design problem which does not have any solution as discussed before. Inlet and outlet sections of the oven are assumed to be at the constant atmospheric temperature. The objective of this dynamic thermal optimization problem is to determine the temperatures of the heaters (the design vector) such that the transient temperatures of all elements around the moving load comply with the pre-specified cure window and the NCP.

3. Modeling-Heat transfer analysis in the oven

Energy balance for each gray-diffuse element is written as:

$$C_i \frac{dT_i(t)}{dt} = Q_{i,g} - Q_{i,rad} \tag{1}$$

Where C_i is the total heat capacity of element i, $T_i(t)$ is the temperature of element i, $Q_{i,rad}$ denotes radiation heat transfer leaving the body and results in temperature reduction. $Q_{i,g}$ in the above correlation accounts for generated energy in the element which is zero except for elements of heaters. Heat balance for each elements in the oven is written as:

$$Q_{i,rad} = \sum_{j=1}^{N}[E_{b,i}A_i - Q_{i,rad}\frac{1-\varepsilon_i}{\varepsilon_i} - E_{b,j}A_i + Q_{j,rad}\frac{(1-\varepsilon_j)A_i}{\varepsilon_j A_j}]F_{ij} \tag{2}$$

Shape factor is calculated employing the correlation of finite elements [9]. Simulation of curing body motion has specific effect on calculation of heat transfer. Curing body motion is descritized to specified intervals at each of which heat transfer conditions assumed in quasi-equilibrium condition. For instance at kth interval, energy balance for an element after linearization is of following form:

$$Q^k_{i,rad} - \sum_{j=1}^{N}[\sigma(T_i^{k,old})^3 T_i^k A_i^k - \sigma(T_j^{k,old})^3 T_j^k A_i^k - (Q^k_{i,rad}\frac{1-\varepsilon_i}{\varepsilon_i} - Q^k_{j,rad}\frac{(1-\varepsilon_j)A_i^k}{\varepsilon_j A_j^k})]F^k_{ij} = 0 \tag{3}$$

Old index in the above equation, represents matrix solution at the iteration before linearization. Two variants considered for each node as unknown, are element temperature and absorbed radiation heat. Writing the above equation for each node results in N equations. In order to be able to solve the equation system N other equations are needed that are generated applying known boundary conditions or equation (1). This method is comprehensively described in [10].

4. Preheating the oven

Preheating the oven strongly influences the temperature distribution on the curing body. High temperature difference between the oven wall and the curing body results in non-uniform temperature differences on the curing body. For instance temperature difference for the elements adjacent to the oven floor becomes lower in comparison with the elements opposite the heaters. Designing the oven is more complicated in such a condition. Three different preheating conditions are considered for modeling the oven in this study:

Before entrance of the curing body to the oven, complete preheating is accomplished. In this case the oven is running some time before the body entrance and reaches to a uniform preheating condition. In this case depending on heaters temperature, a temperature distribution is formed on the oven walls.

The oven is preheated for a limited time as complete heating the oven walls may not be economic. Therefore temperature distribution on the oven's walls depends on the preheating period as well as heaters temperature.

In this case the oven's walls are prepared in constant temperature conditions.

It is assumed in all the above cases that the curing body motion has negligible effects on the oven conditions.

For the second case, after each iteration of optimization, when the new conditions for the oven are obtained, the steady state energy solution is accomplished and the temperature distribution on the oven's wall is obtained (Fig. 2). This stage consumes a little cpu time comparing to the prior stages.

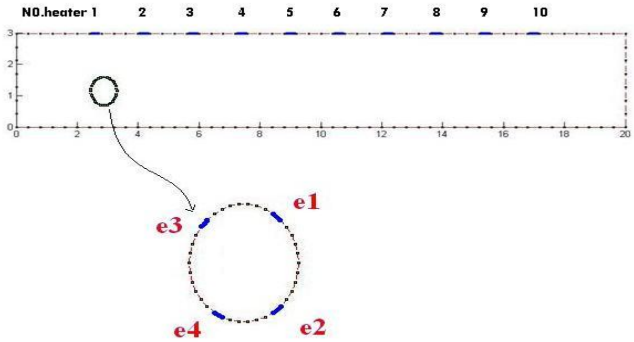


Fig1.. A two dimensional radiation oven.

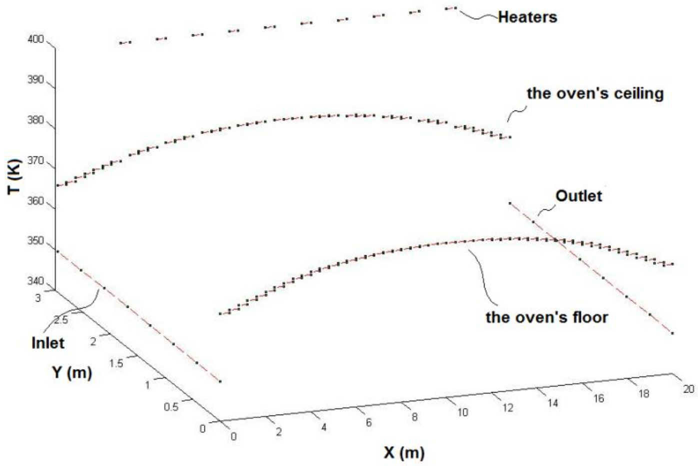


Fig2. Temperature distribution on the oven's wall for the first case of preheating

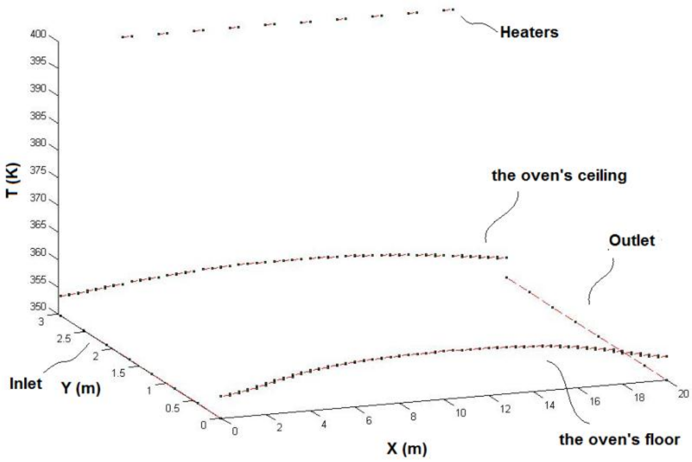


Fig3. Temperature distribution on the oven's wall for the second case of preheating

A different approach is employed for computing the gradient terms in the first case. This approach is applied for computation of $\frac{\partial E_{b,j}}{\partial(\theta_1)}$, $\frac{\partial Q_{j,rad}}{\partial(\theta_1)}$; as the heater temperature variation results in change in the oven's wall temperature and applying temperature constant condition for gradient terms, as was assumed before, may not be proper. To complete system of equations, the temperature variation of the oven's wall is used for the vacant oven as follows:

$$\frac{\partial Q_{i,rad}}{\partial(\theta_1)} = \int_{\Gamma_2} \left(\frac{\partial E_{b,i}}{\partial(\theta_1)} A_i - \frac{\partial Q_{i,rad}}{\partial(\theta_1)} \frac{1-\varepsilon}{\varepsilon} - \frac{\partial E_{b,j}}{\partial(\theta_1)} A_j + \frac{\partial Q_{j,rad}}{\partial(\theta_1)} \frac{(1-\varepsilon)A_i}{\varepsilon A_j} \right) dF_{i-dA} \tag{4}$$

where Γ_2, accounts for the area of oven's wall without heaters.

For the second case the preheating time is defined by the designer. The transient solution at the onset of each optimization iteration should be done. The solution in this stage is of same order of the solution of the oven containing the curing body. In other words computation time for the second case is about two times. Characteristics of preheating conditions considered in this study are listed in Table (1).

The solution procedure is comprehensively mentioned in [10].

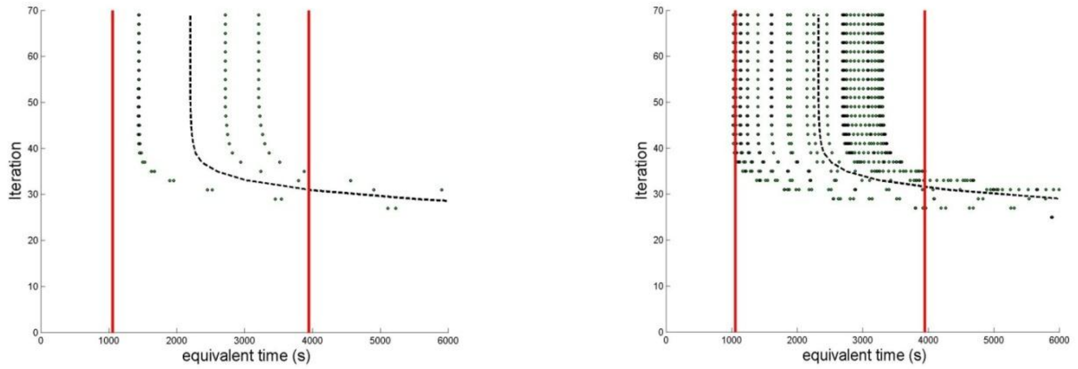
5. Results and Discussion

Optimization results for the first to third cases are demonstrated in Figs.4 to 6.the initial guess is assumed 900 K. in these figures the optimization problem is solved for the two cases: 1. the criterion function is based on 4 elements and 2. The criterion function is based on the entire elements.

As can be found from the figures, the optimization procedure is completely done for the first case of preheating and the problem constraints are satisfied. For the second and third cases of preheating the oven design has not be obtained in a way to have the optimum curing for the whole elements although the method has obtained the best condition for paint curing. This issue reveals the importance of preheating conditions. In other words it can be declared that the preheating conditions should be defined and considered as a design parameter.

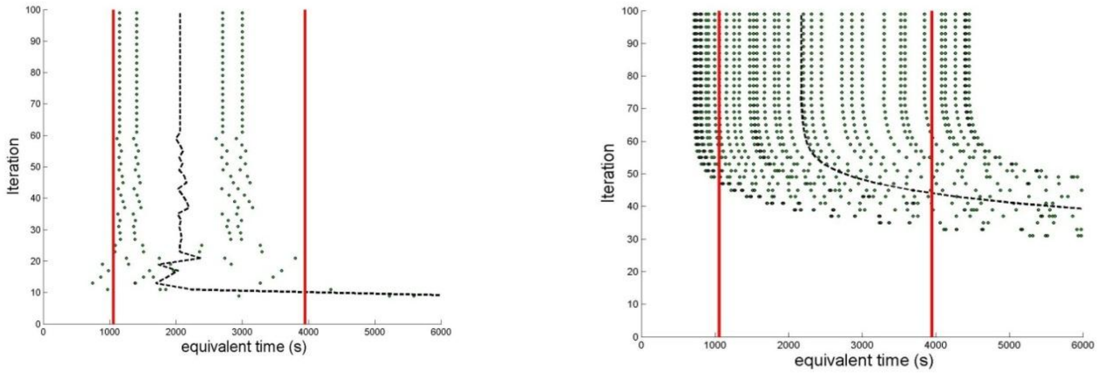
Table 1. Characteristics of different preheating conditions considered in this study

Absorption coefficient of the oven's wall	0.5	The oven length (m)	20
Density of the oven's wall (kg/m^3)	2640	The oven height (m)	2.97
oven's wall thickness (mm)	400	Inlet boundary temperature (K)	350
Heat capacity of the oven's wall (J/kg.K)	960	Outlet boundary temperature (K)	350
Preheating time(s)	30000		
Material used for the oven's wall	Refractory brick		



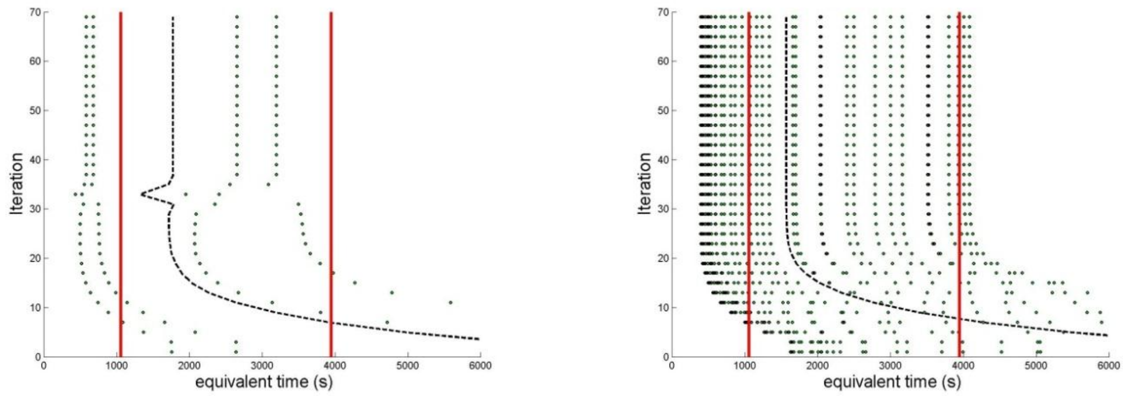
a) criterion function based on four element b) criterion function based on the entire elements

Fig4.. Optimization results for the first case of preheating



a) criterion function based on four elements b) criterion function based on the entire elements

Fig5.. Optimization results for the second case of preheating



a) criterion function based on four elements b) criterion function based on the entire elements

Fig6. Optimization results for the third case of preheating

6. Conclusion

In the present study applying continuous radiation ovens is recommended through emphasizing their advantages. Designing of this type of ovens has become a challenge for many years due to their concerning complexities. A design algorithm is proposed in this article and improved by applying the technique introduced by Mehdipour et al. [10]. Defining preheating condition and considering it as a design parameter is shown to be very important to achieve optimum paint cure.

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