Designing Continuous Radiation Ovens Using Gradient Optimization Technique

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Abstract

Continuous radiation ovens are of widely used apparatuses in paint cure and coating industries. The most important issue that guarantee the quality of paint curing is suitable thermal condition. Designing of these ovens for curing paint on bodies of complex geometries has become a challenge for many years. In the present study a new designing approach is introduced and advised because of its acceptable capabilities as well as its high speed. This approach is based on cure window criterion and applies gradient optimization technique. The present work can be divided into two parts: first, geometric and thermal simulation of the curing body and second, preparing the design tool.Since a significant part of designing procedure usually devotes the iterations of optimization procedure, defining a proper objective function efficiently reduces the time consumed for designing procedure. Procedure of finding an appropriate objective function has been comprehensively discussed in the present article. In this regard a new approach, called Hybrid method, applying an objective function based on few number of elements on the curing body is introduced. That is more fast and capable relative to other methods addressed in this study. Capability of the proposed methods is then evaluated for a typical complicated geometry.

Keywords: *radiation oven; dynamic optimization; radiation heat transfer; paint cure window; objective function.*

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1. Introduction

Coating processes are usually suitable remedies for making surface resistant against corrosion and probable strikes and for improving surface physical properties and appearance. Paint is commonly used for the coating objectives. The painted body should be provided with specific thermal conditions in order to let chemical reactions take place between paint compositions and let the paint be cured. Unsuitable curing processes result in some defects in paint, like orange peels, craters, blisters, runs, sags, and fish eyes. Continuous ovens are the most popular curing devices in the industry. In continuous ovens, the products enter consequently from one side of the oven, experience specific thermal conditions and then exit from the other side.

Radiation ovens are of great consideration recently because of proper cure, low energy consumption and high internal environment safety, compared with other kinds of ovens. Radiation waves of special wavelengths are capable of penetrating through paint layers and result in advances in paint chemical reactions. Radiation ovens are more complicated to design compared with convective types. Heat transfer in radiation ovens is usually because of direct radiation from the thermal sources while in convective ovens heat transfers through the air around the body. Although for the geometrically complicated bodies, exerting uniform cure conditions on the curing body inside of convective ovens is simpler than that in radiation ovens, radiation ovens have been widely introduced to the industries due to their above-mentioned advantageous. To overcome the difficulties in designing this kind of ovens, a robust design method capable of predicting proper location and temperature of heaters is needed. This method is attempted to be developed in the present article.

Paint cure and the effective parameters on cure phenomenon are extensively studied in the literature [1-4]. Modelling procedures and the effective parameters on paint cure are studied in [5-7].

Heat transfer simulation is the first step for designing paint cure ovens. Ashrafizadeh et al. [8] simulated ED paint cure oven 3dimensionally by applying CFD and compared their achieved results with experimental ones. They also studied the effective parameters on the curing process. Lou et al. [9] simulated the base paint curing process, applying zone method for increasing computational rate. Network Model [10] along with CFD and zone methods is another simulating technique. Finite surface element methods [11-13] among other modelling methods are usually suggested because of simplicity and consistency.

The second step in designing paint cure ovens is to choose a paint cure criterion. Some designers [14,15] use the variation of temperature profile of proper paint cure versus time as the cure criterion. In such conditions design parameters are chosen in a way that the criterial temperature history is achieved in all points of the curing body. Applying such criterion usually causes the problem face with ill-conditioned matrix of solution. Paint cure window is an industrial criterion, to evaluate paint cure conditions. Paint manufacturers are responsible of determining this criterion for their production. This criterion demonstrates the proper range for the paint not to be over baked and not to remain crude. Xiao [16] investigated this criterion. Turi [17] has discussed and compared available and mostly used cure criteria and presented a full description of paint cure window criterion and its advantages.

Inverse design methods and optimization methods are usually applied in design problems [18,19]. Daun et al. [11-13] studied and evaluated different methods of inverse designing and optimization. Employing optimization methods with those of evolution, like ant colony, genetic algorithm and neural networking, can be observed in studies of Xiao [16] and Hugget [20]. Optimization of design parameters in dynamic conditions i.e. considering curing body motion while curing procedure is of significant point of Xiao 's study. Dynamic optimization and transient inverse is also found in works of Erturk [14] ,Daun [21], Ertürka[22], Mehraban[23] and Federov [15] as well as [24,25].

The basis of researches in references [26-28] is proposing an algorithm capable of prompt and efficient designing of cure ovens. Designing of paint cure ovens based on the cure window criterion is explained in Ref. [28]; in this reference ([28]) Methods of Defining the objective function has been comprehensively discussed Influences of the objective function form on the convergence procedure as well as solution steps have been investigated. In order to improve the design procedure a criterion called Equivalent Isothermal Time is introduced and is demonstrated in Ref. [26] that such criterion reduces numbers of optimization steps. Reducing numerical costs is assessed in Ref. [27] by applying neural network and finite element method simultaneously. The similar hybrid method (neural network along with finite element method) for optimization together with exerting some simplifying assumptions on the principal model have increased rate of designing in the mentioned work [27].

In the work of Mehdipour et al. [28] an algorithm is represented for using paint cure in ovens. In Ref. [26] it has been attempted to increase possibility of solution convergence by introducing "equivalent curing temperature". Although in all mentioned works appropriate form of objective function is the most effective issue in the solution procedure. In the present study two issues are considered simultaneously, first complications in the geometry and second the most suitable form for the objective function.

The present study is concerned with designing heaters of radiation ovens. A model is proposed for designing a two-dimensional oven for curing a painted middle cross section of passenger car as the curing body. Motion of the curing body is considered in the present model. Cure evaluation is accomplished applying paint cure window criterion. It will be demonstrated that applying this criterion, increases the probability of solution existence while decreasing stages for obtaining the solution and helps the objective function to be discharged of unnecessary constraints like having similar temperature history on the entire curing body.

Determination of a proper objective function, results in considerable decrease in number of iterations necessary to achieve design parameters. If the objective function is of convex form and especially of second order form, gradient optimization methods result in their best efficiencies.

In the present study, defining the most suitable objective function as well as the design procedure is discussed. It is concluded that if the objective function and design parameter were of same genus, design procedure may become more routine.

At the end of this paper a hybrid approach is introduced to decrease computation costs due to optimization. Combination of this method with themethod presented in Ref. [27] (for decreasing modelling calculation rate) may provide possibilities for employing this method on common computers for designing 3D ovens.

2. Description of the Problem

In cure industries heater’s temperature play an important role in the conclusive curing quality. Designing the oven is in turn, associated with finding the appropriate temperatures for the heaters which lead to the desired cure on entire points of the curing body.

The present work can be divided into two parts: first, geometric and thermal simulation of the curing body and second, preparing the design tool. This section is devoted to the design approach and although designing procedure is not restricted by the applied model as the curing body, a more clear and simplified model can better reveal the procedure probable weaknesses. The objective of this study is to Evaluate and increase capability of the proposed designing approach.

Regarding what mentioned above, the present geometry is considered 2D. To evaluate the model in analysis of complicated geometries with high curvatures, the central cross section of a real vehicle (used in Ref. [8]) is applied as the 2 dimensional geometry. By defining geometric characteristics as well as shape factor and some other parameters of elements for 3D geometry instead of 2D, the model can be then generalized for 3D analysis.

Some simplifying assumptions (listed in section 2.1) are exerted to the model to study influences of changes in effective parameters of optimization method on the design procedure. It should be noted that although the mentioned simplifying assumptions cause a deviation in the model with real physical condition, and therefore introduced precisions in Ref. [8] cannot be achieved, they don't restrict the designing approach. For instance in the employed method, type and form of the elements even selection of elements in form of 2D or 3D, insert no restriction in the design procedure and the model precision can be increased by considering wavelength-dependent conditions for emissivity and absorptivity.

Fig. 1 shows the cross-section of painted passenger vehicle moving along a radiation paint cure oven. The oven and the automobile as the curing body are assumed infinite in depth. The oven is modelled as an enclosure, 20 meters long and 2.97 meters wide, with diffuse-gray walls filled with a transparent stagnant gas. Compass notation is employed to address boundaries of the solution domain as shown in Fig. 1. The outer surface of the moving body (B) is also assumed diffuse and gray. Heat exchanges at the inner surface of the body are negligible. The body moves at a constant speed equal to 0.25 m/min. The curing time (t_c) is also discritized using n_t equal intervals. Time dependent functions relevant to the moving body are approximated as piecewise constant functions in the discrete model of the continuous dynamic process.

The underneath elements are considered reflective in this study. In some cases heaters are installed at the bottom of the oven but for the paint-cure ovens it is avoided as it increases the probability of paint plashing. It should be noted that oven designing, considering underneath elements reflective, is more complicated compared to the case that heaters are installed under the vehicle.

The surfaces that are either located opposite (e.g. e1, e4 in Fig.1)orposterior to the heaters (e.g. e2, e3 in Fig.1) complicate the heaters' design. Inlet and outlet sections of the oven because of being in touch with the atmosphere are assumed to have constant temperatures equal to that of the environment. The rest of elements are supposed refractory.

The curing body should be descritized to some elements. Characteristics of centre of these elements, called node, are applied in the calculations.

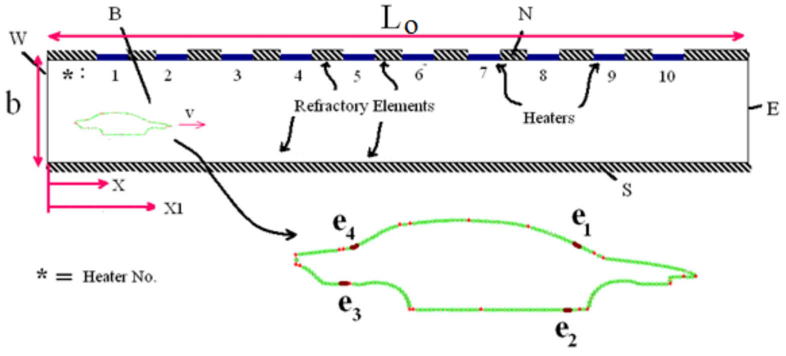


Fig1. The curing body in the two dimensional radiation oven

2.1 Governing Equations

For determination of temperature history curve on each node of the curing body, heat transfer between heaters, refractory walls and body (considering curing body motion in the oven) should be simulated. Some assumptions are considered during the present modelling process:

The environment is assumed non-participating. All walls of the oven are diffuse gray. Since the ratio of element thickness to its length is negligible, the lumped capacitance condition is applied. The paint film temperature is equal to the body temperature because the paint film is thin. Thermo-physical properties are constant. Conduction heat transfer on curing body is negligible. Quasi-equilibrium condition is applied at each time interval.

In fact the mentioned assumptions may deviate from the real curing condition in some cases but some simplifications are needed to decrease the time consumed for the modelling while this issue in turn helps in better evaluation of the performance of the presented design method.

The energy balance for each gray-diffused element on the body or the oven, is written as [29]:

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

In Eq. (1), C_i accounts for the total heat capacity (J/K) of the element i , $T_i(t)$ is the temperature of the element i at time t and $Q_{i,g}$ denotes the heater heat flux. It should be noted that for the heaters, the left hand side of the Eq. (1) is diminished therefore $Q_{i,g}$ will be equal to $Q_{i,rad}$. For the rest of elements we have $Q_{i,g} = 0$.

$Q_{i,rad}$ is the net radiation between element and the enclosure. Following equation can be written for each element:

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

Where, N is the total nodes on the oven wall and the curing body. The radiation shape factors for all elements around the body at each position are calculated using the integral formulas described in Ref. [30], applying assumed transient heater settings.Radiation shape factors, F_{ij} , are calculated using the integral formulas described by Daun [30].

In the present modelling procedure, all equations are discritized in time region. The body moves in axial direction slow enough to assume view factors constant at each time step.Variation of view factors against time is accountedversus the body location. As mentioned before, thermo-physical properties are assumed constant, in order to make equations linear. Considering this assumption, the correlation (1) and (2), can be written as:

$$C_i \frac{T_i^k - T_i^{k-1}}{\Delta t} - Q_{i,g}^k + Q_{i,rad}^k = 0 \tag{3}$$

$$Q_{i,rad}^k - \sum_{j=1}^{N} [E_{b,i}^k A_i^k - E_{b,j}^k A_i^k - (Q_{i,rad}^k \frac{1-\varepsilon_i}{\varepsilon_i} - Q_{j,rad}^k \frac{(1-\varepsilon_j) A_i^k}{\varepsilon_j A_j^k})] F_{ij}^k = 0 \tag{4}$$

Where superscript k denotes the k^{th} time interval. Eq. (4), which relates $Q_{i,rad}^k$ to the temperature of all elements in the enclosure, is linearized as:

$$Q_{i,rad}^k - \sum_{j=1}^{N} [\sigma (T_i^{k,old})^3 T_i^k A_i^k - \sigma (T_j^{k,old})^3 T_j^k A_i^k - (Q_{i,rad}^k \frac{1-\varepsilon_i}{\varepsilon_i} - Q_{j,rad}^k \frac{(1-\varepsilon_j) A_i^k}{\varepsilon_j A_j^k})] F_{ij}^k = 0 \tag{5}$$

Where superscript “old” refers to the most recent available data in the nonlinear iterations. There is a term of forth order of temperature inequation (5) which should be linearized to be solved simply. Thus, the third order of temperature in this equation is kept constant at each solving step, and its value approximated from the former iteration. Two unknown variables are considered for each node, its temperature and its absorbed heat. By calculating coefficients of the above relation, N correlations are obtained.

N new equations are created using Eq. (1) and the specified boundary conditions like known heat flux and temperature. It should be noted that Eq. (1) is associated with the elements which are receiving energy like curing body. If correlations are descritized in implicit form, 2N equations of following form will be obtained. The unknown variables are all obtained by solving the above equations [28].

In the thermal analysis of the oven, two situations should be considered separately; the warm up period of the empty oven and the curing of the moving body in the pre-heated oven.

The body enters through the oven with temperature equal to that of atmosphere ($T = T_{atm}$). During the first time interval, Δt_1, the temperature of the body is assumed to be equal to the initial atmospheric temperature, i.e. T_{atm}.

Finally the matrix of solution is obtained at each time step. Solving this matrix will lead to determination of temperature and heat flux in all elements at specific time. Generalized Minimum Residual Method (GMRES)is employed for solving the matrix.

Radiation shape factors and temperature history curves at arbitrary points on the body are examples of functions which are approximated by piecewise constant functions. This means that, for example, view factors corresponding to the body at position x_i are used for the calculation of radiation exchange in the time interval during which the cylinder moves from $(x_i - 0.5V\Delta t)$ to $(x_i + 0.5V\Delta t)$ .This procedure is repeated until the body reaches the end of the oven.

After obtaining time history at each element, the new time histories will be compared with those of previous solution step. If the differences are more than a pre-specified value, the linearization factors will be modified and the procedure will be repeated. After convergence takes place, The thermal analysis of the paint cure oven is finished and the temperature history curves for all elements on the body are available.

In optimization methods, sensitivity matrix should be known to obtain heaters temperature. Sensitivity matrix, in turn, is obtained by utilizing temperature history (which will be explained in section of “Optimization Algorithm”). After determining heaters temperature the above-mentioned procedure of temperature history will be repeated at each optimization step.

2.2 Paint Cure window

Taking a glance at the literature, it is revealed that most of previous studies of the same field, had tried to determine heaters condition in a way that all points of the body follow a specific thermal history. It has been proved by experience that this approach aggravates the ill-condition property of inverse solution and decreases the probability of solution existence. In the paint curing industry, a standard criterion, named paint cure window is introduced. Related diagrams of this standard criterion are obtained from experimental studies on different points of a curing body. A paint manufacturer should determine the cure window, for each of his product. These diagrams are simple to obtain. Painted pieces of standard dimensions, are placed in a constant temperature oven, then the times in which suitable curing is embarked, or the paint is burned, are measured to form a window as Fig.2.c.

In continuous ovens, variation of temperature of each point of curing body with time makes it difficult to apply cure window criterion. In the classical approach, evaluation of paint cure in the oven is performed connecting thermal sensors on specific parts of body to measure temperatures and time period of heating for each part. A typical diagram like what is shown in Fig.2.a is then obtained using the measured data. It should be investigated whether a Transformed temperature (TT) curve crosses a given paint cure window or not.

TT curve is obtained, putting some points together. The x-value of each point of TT curve is, the duration that a typical point on the curing body is kept between specific temperature and maximum temperature. While the y-value denotes the mentioned specific temperature. A typical transformed curve is demonstrated in Fig.2 a&b.

This diagram is then compared with the cure window introduced for the specific paint. The suitable curing is associated with the condition that all lines enter the cure window from the left side. If the data line of a specific point had no intersection with the cure window boundaries, it means that the paint on the mentioned point is not cured properly. In another condition, if a data line intercepts the cure window from the top it can be concluded that the paint of the mentioned point has been over-baked.

As it seems, the above mentioned criterion is not precise. Xiao [16] used Equivalent Isothermal Time (EIT) criterion for evaluating the paint cure. This criterion was proposed by Touri [17]. The EIT is calculated as below:

$$\Phi_i = EIT_i\big|_{Tr} = \int_0^{tc} \exp\left[C_0 \left(\frac{T_i(t) - T_r}{T_i(t) T_r} \right) \right] \Delta t \qquad (6)$$

Where, T_r is the nominal curing point temperature. The above mentioned time, demonstrates the concept of equivalent time of a steady state process which has a similar cure to the transient one at temperature T_r and then it can be evaluated with paint cure window.

In the present study, the cure window criterion is used to determine the objective function. The effect of some important parameters like film thickness, reaction and volatile substance fraction in the paint is considered in determination of paint cure window.

2.3 Objective Function

The classical objective function, used in designing paint cure ovens, is defined based on a Target Transient Temperature (TTT) curve. The TTT curve simply provides the desirable temperature variation of the paint layer so that the paint does not get over-baked or under-baked. Transient temperature curves at two arbitrary points of the body are shown in Fig. 2a. A TTT curve provides, in essence, the desirable level and duration of the heating process in the form of a function $T^*(t)$. The design objective is, therefore, to minimize the deviation of the transient temperature of all points at the painted surface from the TTT. In other words, the following objective function needs to be minimized:

$$OF_1 \equiv \sum_{i=1}^{n}\sum_{j=1}^{m}\left|(T_i^{*j} - T_i^{j})\right| \tag{7}$$

Subscript i refers to the element number and superscript j refers to the discrete time level. Use of such an objective function is discussed in [14]. In the mentioned definition for the objective function in some references like [14], the OF_1 is a rather restrictive objective function. In other words it might not be possible to force the temperature variation at all points on the body to get very close to the TTT. This issue can be accounted as a weak point for such definitions. Therefore, one should either accept to force the optimality constraint at only few points at the painted surface or to relax the definition of the objective function.Xiao et al. [16] proposed that instead of using the TTT curve as the design target, one may employ a paint cure window and try to confine the heat transfer process at every point of the painted body inside the cure window. To employ the cure window, the TTT curve needs to be converted to another curve in which the horizontal axis represents the curing time (CT in Fig. 2b) and each point along the vertical axis shows the minimum applied temperature corresponding to the relevant curing time. Further details can be found in [28].

To employ the concept of the cure window in a more efficient manner the objective function is defined as follows:

$$OF_2 \equiv \sum_{i=1}^{n}\left|(EIT_i - EIT^*\right| \tag{8}$$

EIT^* is also called the target nominal cure point (NCP). An alternative definition for the OF_2 has been defined and used in [28]:

$$F_{avg}(\theta) = \frac{1}{n_B}\sum_{i=1}^{n_B}(a_1\left[\Phi_i(\theta) - \Phi_{t\arg et}\right]^2 + P_i(\theta)) \tag{9a}$$

$$P_i(\theta) = a_2[\Phi_{\min} - \Phi_i(\theta)]^2 H[\Phi_{\min} - \Phi_i(\theta)] + a_3[\Phi_i(\theta) - \Phi_{\max}]^2 H[\Phi_i(\theta) - \Phi_{\max}] \tag{9b}$$

Minimum and maximum time durations $(\Phi_{\min}, \Phi_{\max})$ corresponding to the reference temperature (T_r) in Eq. (2) are shown in Fig. 2d as points 1 and 2. The NCP in Fig. 2d is simply a preferred, factory-recommended, curing point between points 1 and 2 along the T_r line.

Considering the fact that the OF_2, or its equivalent $F_{avg}(\theta)$, provides an adequate constraint as far as the paint quality is concerned, and it can also be more easily satisfied, it is now the industry standard criterion used by many manufacturers in body paint shops. Finding the objective function will be comprehensively discussed in further sections.

3. Optimization Algorithm

After achieving the temperature history and the objective function for each element, the heater's temperature should be changed to attain a better cure. It should be noted that the objective function at each element demonstrates the element deviation from the desired cure. To achieve the mentioned objective, the optimization method and specifically, the BFGS-Quasi-Newton method is applied. In the Quasi-Newton method, variables at each iteration are modified by the following relation:

$$\vec{\boldsymbol{\theta}}_{r+1} = \vec{\boldsymbol{\theta}}_r + \alpha_r \vec{\boldsymbol{p}}_r \tag{10}$$

Where, $\vec{\mathrm{p}}_r$ accounts for the direction of variations and α_r demonstrates variation step size. The parameter α_r is calculated at iteration r as follows:

$$\frac{\partial F(\vec{\theta}_r + \vec{\mathrm{p}}_r\alpha_r)}{\partial\alpha_r} = 0 \tag{11}$$

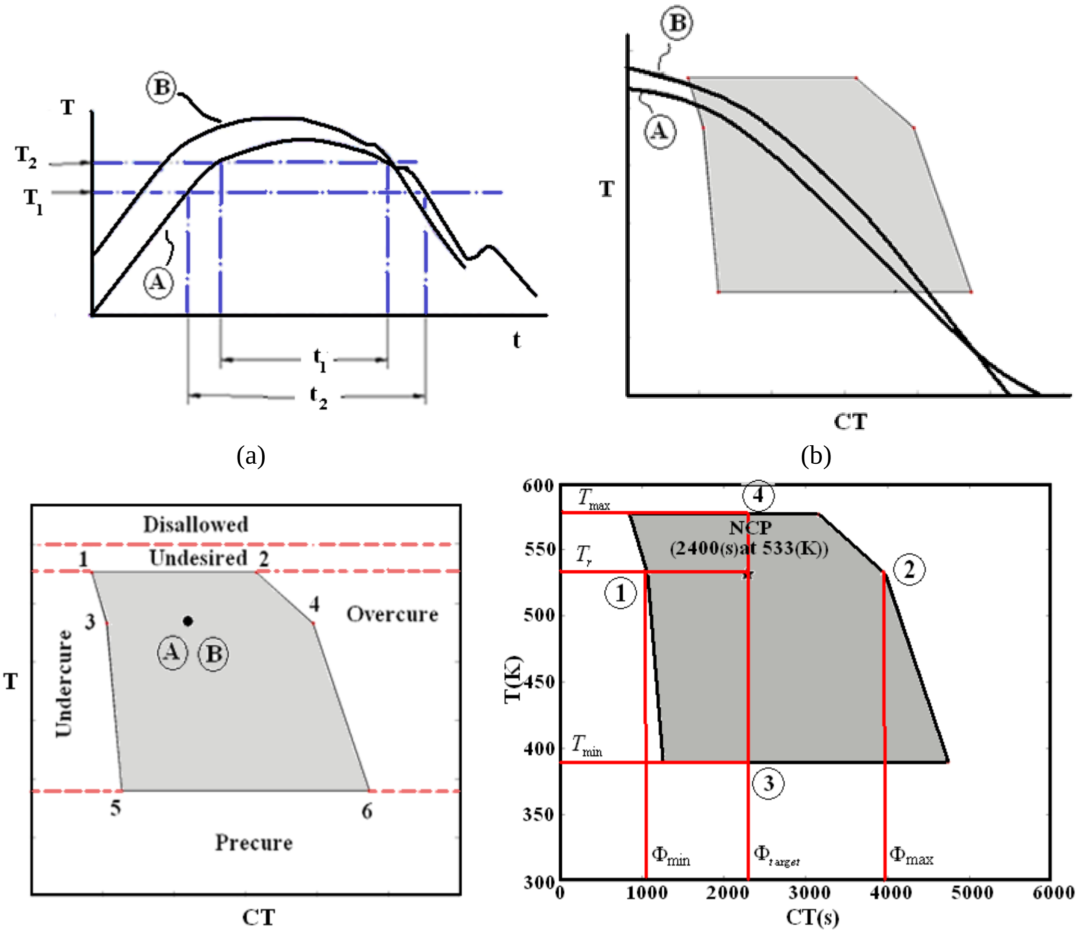
For instance, the BFGS-implementation of the quasi-Newton method [31] calculates the search direction according to

$$\vec{\mathrm{p}}_r = -\tilde{\mathbf{H}}_r^{-1}\vec{\mathrm{g}}_r \tag{12}$$

Where the Hessian is approximated by:

$$\begin{aligned}
&\tilde{\mathbf{H}}_{\boldsymbol{r}} = \tilde{\mathbf{H}}_{\boldsymbol{r-1}} + \tilde{\mathbf{M}}_{r-1} + \tilde{\mathbf{N}}_{r-1} \quad , \ r = 1,2,...\\
&\tilde{\mathbf{H}}_{\mathbf{0}} = \mathbf{I}\\
&\tilde{\mathbf{M}}_{r-1} = \left(\frac{1 + \boldsymbol{y}_{r-1}^T\tilde{\mathbf{H}}_{r-1}\boldsymbol{y}_{r-1}}{\boldsymbol{y}_{r-1}^T\boldsymbol{P}_{r-1}}\right)\frac{\vec{\boldsymbol{p}}_{r-1}\vec{\boldsymbol{p}}_{r-1}^T}{\vec{\boldsymbol{p}}_{r-1}^T\vec{\boldsymbol{y}}_{r-1}}\\
&\tilde{\mathbf{N}}_{r-1} = -\frac{\vec{\boldsymbol{p}}_{r-1}\vec{\boldsymbol{y}}_{r-1}^T\tilde{\mathbf{H}}_{r-1} + \tilde{\mathbf{H}}_{r-1}\vec{\boldsymbol{y}}_{r-1}\vec{\boldsymbol{p}}_{r-1}^T}{\vec{\boldsymbol{y}}_{r-1}^T\vec{\boldsymbol{p}}_{r-1}}\\
&\vec{\boldsymbol{y}}_{r-1} = \vec{\boldsymbol{g}}_r - \vec{\boldsymbol{g}}_{r-1}
\end{aligned} \tag{13}$$

The elements of the gradient vector correspond to the objective function sensitivities with respect to the design parameters (heater panel temperatures):



(a) (b)

(c) (d)

Fig2.. a) TH curves for arbitrary body points A and B, b) corresponding TT curves, c) corresponding EITs, d) A user-specified NCP in a factory-provided paint cure window.

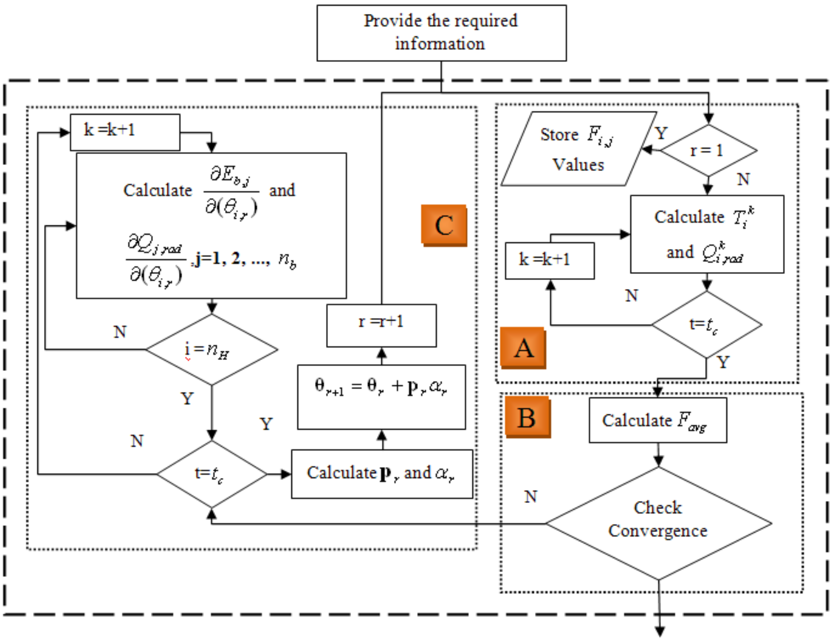


Fig3. The design algorithm.

$$\vec{g}_i(\vec{\theta}_r)=\left[\frac{\partial f_i(\vec{\theta}_r)}{\partial \theta_{1,r}} \quad \frac{\partial f_i(\vec{\theta}_r)}{\partial \theta_{2,r}} \quad \cdots \quad \frac{\partial f_i(\vec{\theta}_r)}{\partial \theta_{v,r}}\right]^T$$
$$=\left[g_{i1}(\vec{\theta}_r) \quad g_{i2}(\vec{\theta}_r) \quad \cdots \quad g_{iv}(\vec{\theta}_r)\right]^T \qquad (14)$$

In the process of obtaining the sensitivity vector, depending on the definition of the objective function, the magnitude of $\partial T_{i(t)} / \partial(\theta_{1,r})$ should be calculated. This magnitude can be obtained by differentiating equation (5) and imposing boundary conditions. Procedures of finding this value and in result obtaining the sensitivity vector are illustrated in the appendix. A ([28]).

After finding the sensitivity matrix, $g(\vec{\theta}_r)$, is obtained. The Hessian matrix, step size and vector of variations are calculated applying equations 13, 11, and 12 respectively. Then eq. 10 can be applied to compute the heaters temperature for achieving better curing. The optimization procedure will be continued until reaching a minimum value of the objective function which is equal to approaching in to the centre of cure window.

The design procedure based on optimization method, can be divided in to 3 major stages: First stage is basically a thermal analysis routine in which the field or state variables are updated. At the second stage, the objective function is simply evaluated and checked against a convergence criterion. Finally, at the third stage, the design variables are updated to ultimately nullify the objective function, up to a convergence criterion. Flowchart of the calculation is shown in Fig. 3.

3.1 Appropriate Definition for the Objective Function

In this part, we are to determine heaters power, such that a suitable cure condition is obtained on the body. The suggested method for the inverse solution is the gradient based optimization method and as mentioned before, the objective function is determined using the cure window criterion. As shown in Fig.2, two different thermal profiles in the cure window locate at a point (star point) and both have the same condition in the cure window. Although selecting a profile from infinite probable profiles simplifies the calculation process, it has no logical basis and all profiles can be appeared in experiment. Here in the present study, by using an objective function based on the cure window, it is tried to consider all permissible profiles.

Definition of the objective function, as mentioned before, is based upon the equivalent time. Since objective function (time) and the design parameter (heaters temperature) are not of same genus, the time-based objective function is not a good choice for obtaining the best and precise design.

The original idea for the definition of the new objective function is borrowed from the definition of the EIT. While the EIT employs a reference temperature (T_r in Eq. 2) to provide an equivalent curing time, the equivalent isothermal temperature ($EITe$) introduces a reference time (t_r in the following equation) to provide an equivalent curing temperature.

It can be proved that for the case of similar cure in two different conditions, the following relation is governed on the ratio of their individual cure time [16].

$$\frac{t_2}{t_1}=\exp(\frac{E}{R}(\frac{T_1-T_2}{T_1T_2}))=\exp(C_0\,\frac{T_1-T_2}{T_1T_2}) \qquad (15)$$

Equivalent isothermal temperature (EITe) can be achieved through applying EIT (eq. 6) and above equation:

$$TE_i\big|_{tr}=\frac{C_0}{\left[\ln(t_r)-\ln(X)\right]} \quad , \quad X=\int_0^{tc}\exp\left[-\frac{C_0}{T_i(t)}\right]\Delta t \qquad (16)$$

This temperature, demonstrates the concept of equivalent temperature of a steady state process which has a similar cure to the transient one in the period of t_r. The objective function can be written in terms of equivalent temperature:

$$F_{avg}(\theta)=\frac{1}{n_B}\sum_{i=1}^{n_B}[a_1(TE_i\big|_{tr}(\theta)-T_r)^2+F_i(\theta)]^{0.5} \qquad (17)$$

$$F_i(\theta)=a_2[T_{\min}-TE_i\big|_{tr}(\theta)]^2H[T_{\min}-$$
$$TE_i\big|_{tr}(\theta)]+a_3[TE_i\big|_{tr}(\theta)-T_{\max}]^2H[TE_i\big|_{tr}(\theta)-T_{\max}] \qquad (18)$$

Constant-time line crosses the cure window in two points of 3 and 4, shown in Fig. 2.d, which are associated with cure temperature of $T_{\min}$ and $T_{\max}$ respectively.

The objective function in the above-mentioned form has the benefit of depending on the first order of temperature difference and applying it for modification of heaters temperature, removes the deficiency due to the order discrepancy observed in the previous form. In other words, it can be shown that for the initial guess of far from the solution, the EIT method, because of applying EIT concept, correctly calculates direction but not the vector scale. This problem occurs as a result of different unit definition between objective function and design parameters and must be solved by applying intelligent steep sizes and putting some restrictions on direction scale. It is worth noting that the second method is rarely faced with the mentioned problem.

Both introduced design criteria (EIT and EITe) have been applied in this study. In the present problem to achieve the precision of $3*10^{-6}$ EIT-based design needs 54 optimization iterations while EITe-based design needs 23 optimization iterations. It deems that defining the objective function based on the Isothermal equivalent temperature has better performance in designing process. Now attempts are devoted to find the best form of objective function versus this temperature. To study different possible forms of the objective function, the following general equation is chosen:

$$F(\theta)=\frac{1}{n_B}\sum_{i=1}^{n_B}[a_1((TE_i|_{tr}(\theta)-T_r)^2)^{l_1}+a_2 f(T_{\min}-TE_i|_{tr}(\theta))((TE_i|_{tr}(\theta)-T_{\min})^2)^{l_2}$$
$$+a_3 f(TE_i|_{tr}(\theta)-T_{\max})((TE_i|_{tr}(\theta)-T_{\max})^2)^{l_3}]^{0.5} \quad (18)$$

f, in the above relation, is defined as below:

$$f(x)=\frac{1}{1+e^{-\beta x}} \quad (19)$$

In Fig. 4 behavior of the above function for different values of β is demonstrated. This function acts same as Heaviside function although there is no jump for the slope at x=0 and the function is continuous therefore.

When the f is defined as “Heaviside function”, fluctuations may occur in the solution trend and the calculated value for the step vector may be wrong, especially when the isothermal equivalent temperature of each node is around the boundary of the cure window. This issue can be due to discontinuity of the objective function at the boundaries of the cure window.

For the specific case of $l_1=l_2=l_3=1$ and $\beta>5$, relations (18) and (17) will be equal. As it deems in relation (18), a_1 ، a_2 ، a_3 و Φ_{target} are the parameters influence the objective function. Proper values of these parameters may lead to a good convergence and satisfaction of the cure criterion. For the cases when factors a_2 ، a_3 are greater than other factors in value, design parameters are achieved in a way that the cure criteria are satisfied for all the points but locate far from the centre of cure window, adjacent to its lateral boundary. Greater values of a_1 result in approaching the points in the cure window to T_r. For the case of same magnitude for all of the factors, an effect of the first term in the above relation is dominant. Therefore variations in magnitude of T_r will influence the locations of the points in the cure window. In other words the location of final solution can be changed by these parameters.

Convergence trends or in other words variation of the objective function via design iterations is studied and demonstrated in Fig.5 for different powers ($l_1=l_2=l_3=L$ and $\beta=0.25$) of equation (18).

It has been observed for the large values of L that the magnitude of $\vec{p}_r$ is not calculated correctly and obtaining the location of minimum point is accomplished through more iterations. Although for small values of Lsome fluctuations are observed at the terminal iterations of the solution trend. For L=0.3, the truncation error grows such that terminates the solution trend. The best performance has been observed for L=1.

It should be noted that this problem is optimization-type and according to what mentioned before, obtaining a solution for the objective function to become zero is almost impossible; from the other hand this problem may has multiple solutions. Some fluctuations are seen at the end of solution procedure that may correspond to movement of solution between minimums of the objective function. Existence of partial minimums and number of them directly depend on form of the function, f (eq.18).

Decrement in value of f (eq.18) is representative of better curing of entire points. In this problem due to the mentioned weight functions, if f becomes lower than 10^{-5}, mean curing of entire points are desirable but the final check should be accomplished for all points with the cure window. Only if all points are located in the cure window desirable cure is achieved. The more the objective function decreases, curing condition of points are more similar to the Centre of cure window conditions and the design is more satisfactory.

3.2 hybrid” method

The presented method based on EITe and the proposed objective function performs acceptable and is capable enough for designing this type of ovens. The defect is that existence of partial minimums in the objective function due to nature of problems of these kinds increases stages of design.

In this part a method capable of reducing number of optimization stages as well as computation costs is introduced. Effects of number of elements in defining the objective function are studied in this part. In the case that just an element is applied in defining the objective function, it is expected that the design procedure finds heaters temperatures to provide the best thermal conditions for the considered point. Results of temperature profile in different iterations and situations of the design point relative to the cure window, just for the considered element (e1 Fig.1) are demonstrated in Fig.6.At the end of the optimization procedure, the isothermal equivalent time of this element is located at the Centre of the cure window.

Results show that the proposed model has minimized the objective function for the considered element but it could not provide a proper cure for the underneath elements. In other words as the underneath elements have no role in definition of the objective function, obtained heaters arrangement may not lead to satisfactory cure of those elements.

Reducing number of employed elements for definition of the objective function obtains heaters arrangement in a way that some regions of the geometry does not experience appropriate cure.it seems that it is better to apply more elements in defining of the objective function; But when the number of applied elements in defining the objective function increases, the number of local minimums will increase and therefore the gradient-based methods may not work properly.

It is obvious that two typical adjacent elements are approximately in similar curing conditions therefore considering both elements, in definition of the objective function, may result in formation of two local minimums with small-amplitude fluctuations in the solution procedure.

It can be concluded from the above discussions that by decreasing number of elements involved in definition of the objective function, curing in some sides may be ignored because of lack of elements in there. In other hand increase in number of elements causes increment in computation costs as well as increment in partial minimums of the solution andthe latter may result in fluctuations in solution. For such a problem, definition of the objective function based on reduced/increased numbers of elements has become a dilemma. Based on what mentioned above a new approach called Hybrid method is introduced.

Based on the Hybrid method, at the onset of optimization procedure, the objective function is defined based on few number of elements.After that the problem is solved the optimization procedure will be repeated this time applying a pre-obtained heaters arrangement and a new objective function that is defined based on considering entire elements.

Applying few number of elements in defining of the objective function makes it straightforward to approach to the mean minimum point of the objective function. In this condition situation of the selected elements relative to heaters is of great importance. In other words elements should be selected in a way that include both the best-positioned elements and the worst-positioned ones from curing view point to assure that the final result is almost near to the case of considering all elements.

To have a good selection of elements in this approach, the geometry is categorized in to some zones of different thermal conditions. Then an element is picked out from each zone as a representative of the zone. Following zones can be classified for the considered geometry of the present study:

a) The forward zone opposite to the heater (in Fig.1 element e1 as representative)

b) The backward zone opposite to the heater (in Fig.1 element e4 as representative)

c) The forward zone underneath the geometry (in Fig.1 element e2 as representative)

d) The forward zone underneath the geometry (in Fig.1 elemente3 as representative)

In this algorithm the four demonstrated elements in Fig.1 are applied. It should be noted that these elements as representatives, are different for each geometry. Element categorization for each geometry concerns to the geometry shape; by the proper categorization and selecting a suitable representative element, solution iterations can be decreases significantly.

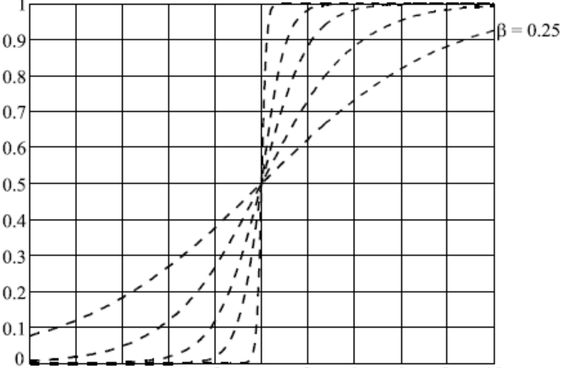


Fig4. Variations of eq. (19) against β

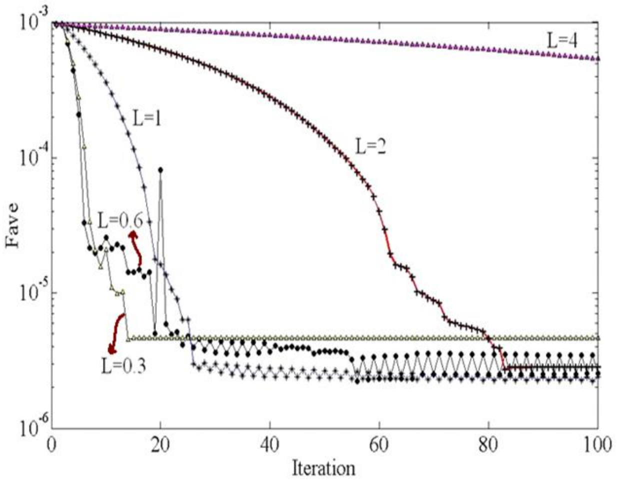


Fig5. Variations of design performance versus power of the objective function(L).

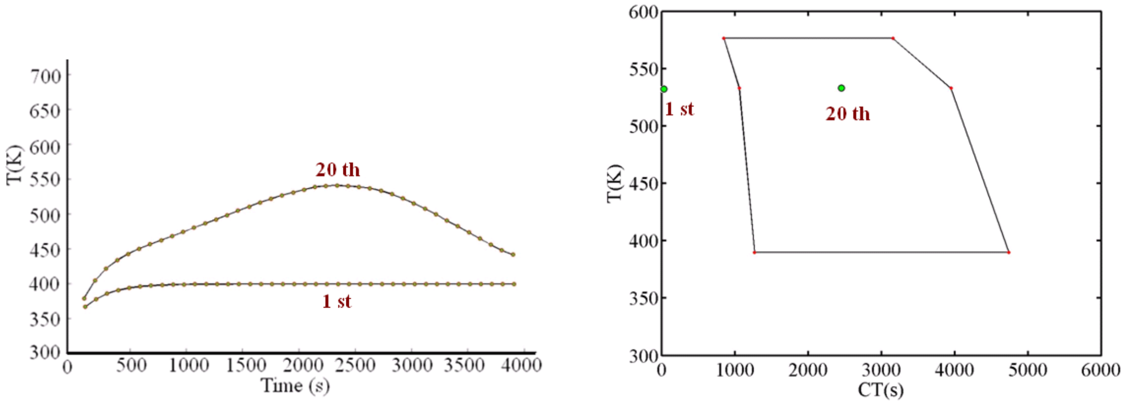


Fig6. Temperature profile of the element (e1 Fig.1) accompanied by cure window criterion at first and 20th iteration for the case of considering a single element in optimization procedure

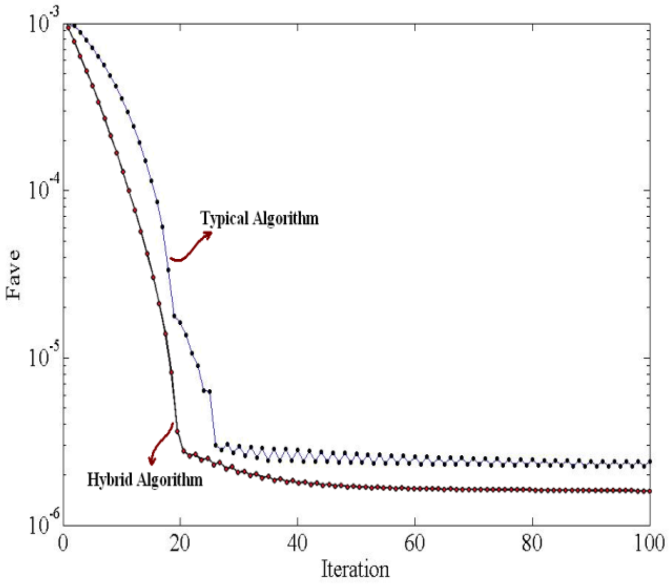
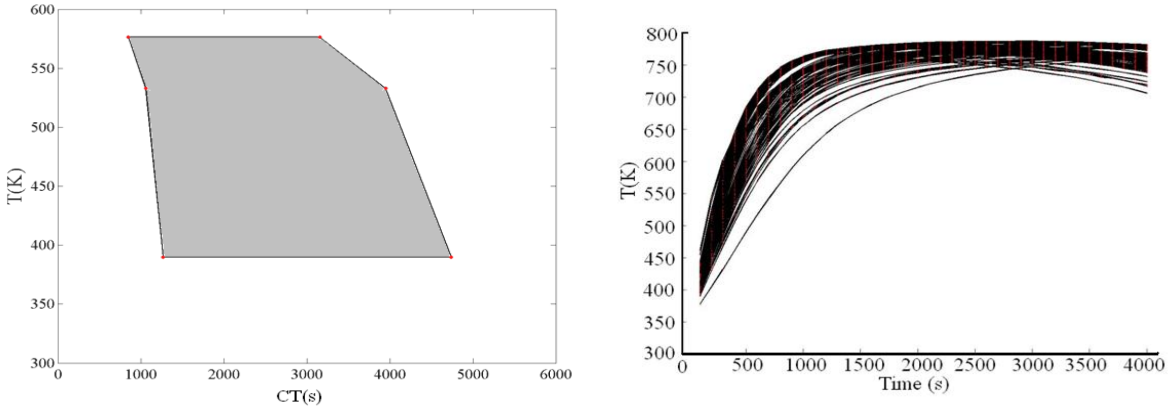
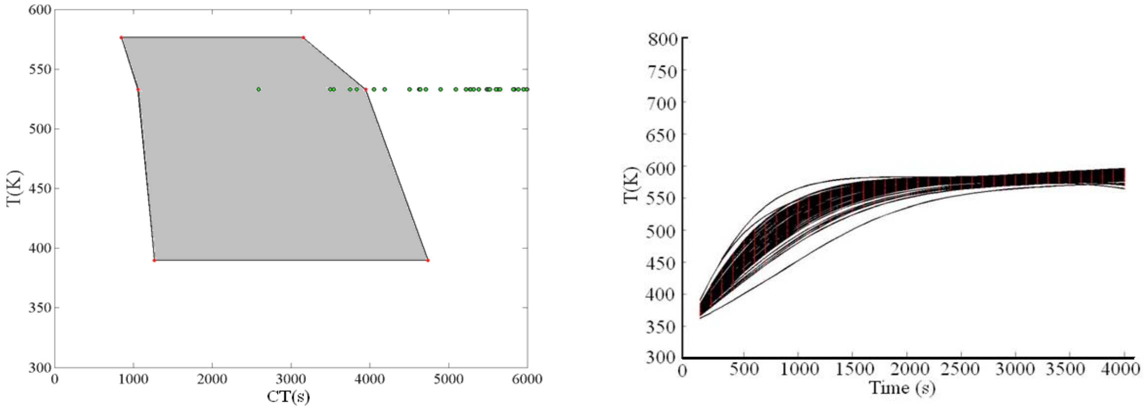


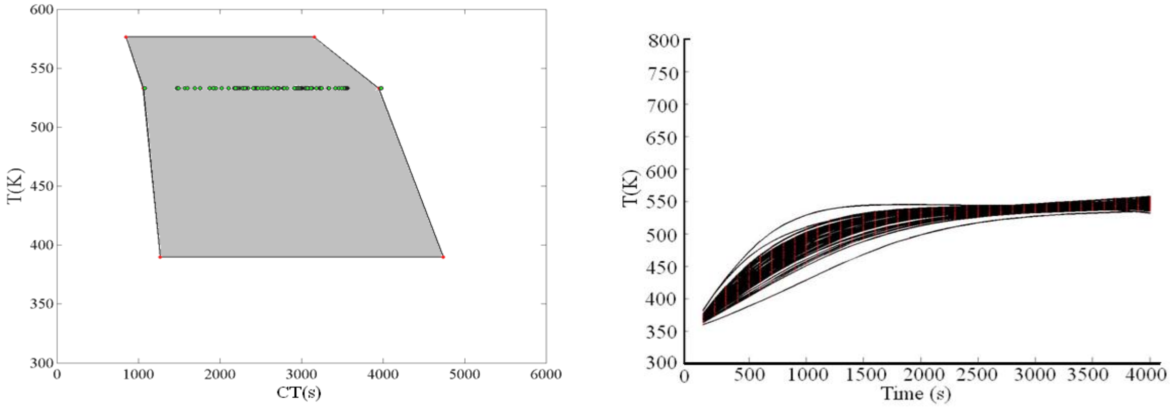
Fig7. Comparison between the performance of usual method with the hybrid algorithm (Variations of the objective function versus the optimization iterations)



1th iteration 1th iteration



30th iteration 30th iteration



60th iteration 60th iteration

Fig8. Profile of the cure criterion and temperature profile of the nodes on the curing body for a,b) first iteration, c,d) 30th iteration e,f) 60th iteration

4.Evaluation of the Model Performance

As mentioned in previous section, the objective function is defined based on the equivalent temperature. This objective function is applied for designing the considered oven. Four elements that are shown in Fig.1 are applied for defining the objective function. Evaluation of the present model in this study is accomplished using the similar technique applied in [28].

In order to evaluate the performance of the present model, an initial guess that is far from the final solution is employed for heaters' temperature. In this regard temperature of 1200K is set as initial condition of all heaters. Temperature history and paint cure criterion are demonstrated respectively in Fig. 8.

At the end of design procedure, the design criterion becomes minimum and it means that for all the elements, that the design criterion is imposed on, a suitable cure has been achieved.

It can be found from the figures that the method is able to obtain heater's temperature profile in a way that paint cure criterion is satisfied and the solution approaches the NCP. Fig. 9 shows, respectively, the optimum heater temperatures.

A brief comparison between the proposed methods and Hybrid method, as well as influences of number of elements is demonstrated in Table 1.

A question may arise here about the number of elements on the geometry. The best number of elements is achieved when no dependence found between the solution of modeling part and the number of elements. As demonstrated at the third column of Table 1, for 367 elements there is no dependence between solution and number of elements. Further increasing number of elements increases computation costs and in some conditions (1305 elements) deteriorate optimization procedure.

To reveal the above claim, obtained heater arrangement for different cases shown at Table 1 are implemented for the geometry of automotive body with 1305 elements and then the magnitude of the objective function or in other words measure of cure for each element is calculated. By employing the last column data for comparison, a fare judgments is governed as in this column all cases are exerted on similar number of elements.

As can be found from Table.1, if obtained heaters arrangement from the 143-element model is exerted on the model with high number of elements, significant magnitude of the objective function will result that in turn represents weak curing condition.

The best performance is reported for the 568-element geometry but when effects of computation costs comes through, the 367-element geometry is recommended as the obtained precision due to increasing number of elements to 568 is not as worth to endure such computation costs. It should be noted that the computation costs reported in Table. 1 are based on the time consumed for running of each method on a specified computer and the objective is just to compare the methods performance.

From what discussed above it can be concluded that the required condition to achieve a proper design for all considered methods is the mesh dependency in the modeling part.

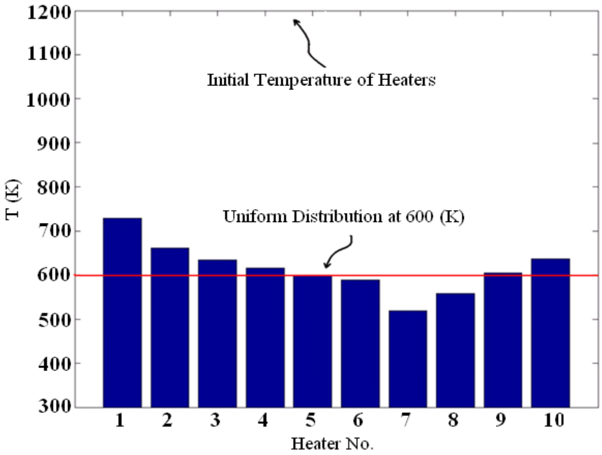


Fig9. Heaters temperature at the end of optimization procedure

Table 1. Devoted to the Hybrid method

Number of elements on the geometry (vehicle body)	143	367	568	1305	367	367	367	367
Number of employed elements in optimization procedure	entire elements	entire elements	entire elements	entire elements	Hybrid method, starting with 4 elements	Hybrid method, starting with 8 elements	hybrid method, starting with 16 elements	Hybrid method, starting with 16 elements all from the ceiling
Temperature of element e1 (applying heaters of)$1200^{\circ}C$)	720.2	744.3	745.3	745.5	744.3	744.3	744.3	744.3
Number of optimization stages until the objective function reaches the value of $5*10^{-6}$	22	24	27	26	19	21	21	14
Computation time (s) until the objective function reaches the value of $5*10^{-6}$	153	2175	7943	80789	1713	1930	1963	1370
Magnitude of the objective function at the end of 100th iteration of optimization	$3.1*10^{-6}$	$3.2*10^{-6}$	$3.7*10^{-6}$	$4.1*10^{-6}$	$2.3*10^{-6}$	$2.4*10^{-6}$	$2.3*10^{-6}$	$1.1*10^{-6}$
Magnitude of the objective function (heater arrangement is implemented for the 1305-element geometry)	$5.3*10^{-6}$	$3.6*10^{-6}$	$3.4*10^{-6}$	$4.1*10^{-6}$	$2.8*10^{-6}$	$2.9*10^{-6}$	$2.8*10^{-6}$	$8.6*10^{-6}$

The last four rows of Table 1.Is devoted to the Hybrid method. It should be noted as can be found from the table that classification of the elements is more important than the number of applied elements. If the classified zones are not picked out properly, increasing number of elements in next step may not be effective. For instance at the last row all the considered elements to build the objective function are selected from one zone (ceiling). Although the magnitude of the calculated objective function is low, the desired curing condition for the entire elements of the geometry has not been achieved.

5. 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 Mehdippour et al. [28]. It has been demonstrated that the form of the objective function significantly influences the design procedure. The concept of equivalent isothermal temperature is presented in this study to be utilized for achieving the best form of the objective function.

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