THE PROCESS OF AN OPTIMIZED HEAT RADIATION INTENSITY CALCULATION ON A MOULD SURFACE

Jaroslav Mlýnek
Department of Mathematics and Didactics of Mathematics
Technical University of Liberec
Studentská 2, 461 17 Liberec,
Czech Republic
E-mail: jaroslav.mlynek@tul.cz

Radek Srb
Institute of Mechatronics and Computer Engineering
Technical University of Liberec
Studentská 2, 461 17 Liberec,
Czech Republic
E-mail: radek.srb@tul.cz

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Mathematical model, heat radiation, optimization, genetic algorithm.

ABSTRACT

This article is focused on the optimization of heat radiation intensity across the surface of an aluminium mould. The mould is warmed by infrared heaters located above the mould surface, and in this way artificial leathers in the automotive industry are produced (e.g. the artificial leather on a car dashboard). This described model allows us to specify the location of infrared heaters over the mould to obtain approximately the same heat radiation intensity across the whole mould surface. In this way we can obtain a uniform material structure and colour tone across the whole surface of artificial leather. We used a genetic algorithm and the technique of “hill-climbing” during the optimization process. A computational procedure was programmed in the language Matlab.

1. INTRODUCTION

This article is focused on the problems with production technology used for artificial leathers used in car interior equipment (e.g. the artificial leather attached to the plastic surface of a car’s interior, or the leather used to upholster the interior of car doors). One successful production method is the heating of the mould surface (usually an aluminium or nickel mould is used) by infrared heaters located above the mould surface at a distance of between 5 and 30[cm]. The inside of the mould is sprinkled with special PVC powder and the outside mould surface is subsequently warmed to a temperature of 250[°C] in a few minutes. Simultaneously, it is necessary to maintain an even temperature across the mould surface at any given time during the warming process, and thereby ensure the same material structure and colour tone across the whole artificial leather surface.
Forms of different size and shape, often very rugged, are applied to production. The mould weight is approximately 300[kg]. The infrared heaters have a tubular form and their length is between 15 and 25[cm]. The infrared heater is equipped with a mirror located above the radiation tube, which reflects heat radiation in a given direction (see Figure 1). Depending on the mould size, the number of heaters is usually between 50 and 200.
It is necessary to ensure the heat radiation intensity within given tolerance on the whole mould surface through the optimization of the heaters’ location, and in this way approximately the same temperature is produced across the whole mould surface, which is essential to the production of artificial leathers.

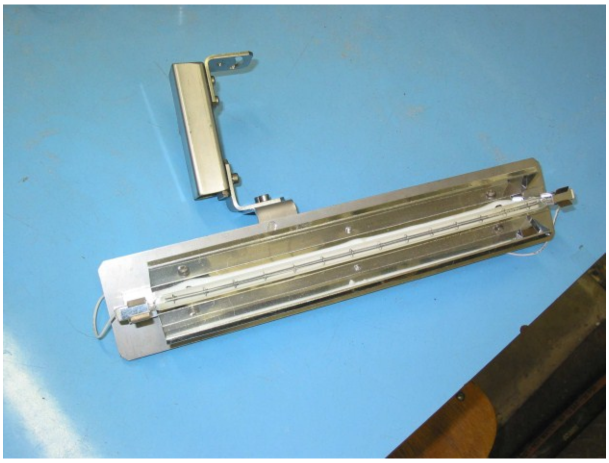

Figure 1: Philips Infrared Heater with 1000W Capacity

In the following chapters are described the heat conduction problem in the mould, the mathematical model of heat radiation on the mould, and the optimization process (a genetic algorithm and the technique “hill-climbing” were used) of the location of infrared heaters. The last chapter contains two examples with solutions. A computational procedure of the optimization process was programmed in the language Matlab.
The producer requires implementing a procedure of the optimization of the heaters’ locations at the production line (after its verification in system Matlab). Therefore, we need to know the optimization process in every detail. Hence, in order to solve the respective problem, we have not used any existing commercially available software tool designed for solution of the distributed parameter system problems.

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2. HEAT CONDUCTION IN THE MOULD

In the following chapters, the technique of optimizing the heaters' locations will be described, as well as the calculation of uniform heat radiation intensity. We are able to calculate temperature T on the mould surface during warming on the basis of knowing the heat radiation intensity I on the mould surface. We will solve the parabolic evolutionary equation of heat conduction

$$\frac{\partial T(x,t)}{\partial t} = \frac{\lambda}{c\rho} \Delta T(x,t) \qquad (1)$$

on the domain $\Omega \subset E_3$, where Ω represents the given mould, E_3 is 3-dimensional Euclidean space. In relation (1) $T(x,t)$ denotes a temperature, point $x = (x_1, x_2, x_3) \in \Omega$, time $t \in (0, \tau)$, where τ is the duration of heat radiation conducted to the mould surface by heaters; the real value λ stands for the heat conductivity of the mould material (we assume an isotropic environment and the independence of λ on x position), and real values c and ρ denote the specific heat capacity and mass density of the mould material. The symbol Δ stands for Laplace operator to space variables, i.e.

$$\Delta T(x,t) = \sum_{i=1}^{3} \frac{\partial^2 T(x,t)}{\partial x_i^2}.$$

We consider the initial condition

$$T(x,0) = T_0 \quad \forall x \in \Omega, \qquad (2)$$

where T_0 denotes the initial temperature of the mould (the mould is preheated before being warmed by the infrared heaters), boundary conditions

$$q^T \eta = -I(x) \qquad (3)$$

on the surface part $P \subset \partial\Omega$ heated by infrared heaters and

$$q^T \eta = \alpha\, (T(x,t) - T_{air}) \qquad (4)$$

on the remaining part of the mould surface $\partial\Omega - P$ (cooling of this part of the mould surface). The symbols in expressions (3) and (4) have the following meaning. The symbol q denotes the thermal flux density and it is true $q = -\lambda\, grad\, T(x,t)$, where

$$grad\, T(x,t) = \left(\frac{\partial T}{\partial x_1}, \frac{\partial T}{\partial x_2}, \frac{\partial T}{\partial x_3} \right)^T.$$

The symbol η denotes unit outward normal vector in point $x \in P$, $I(x)$ is the heat radiation intensity on P (values $I(x)$ are independent of time t), α is heat transfer coefficient, and T_{air} is the temperature of surrounding air. See more detail about the problems of heat conduction e.g. in (Cengel 2007).

The equation (1) with conditions (2) - (4) describes heat conduction in domain Ω (in the mould). No heat sources are inside the domain Ω, only the infrared heaters radiate on surface P. The equation of heat conduction (1) with the aforementioned conditions is possible to solve numerically using the software tool ANSYS through the finite element method. If values of heat radiation intensity $I(x)$ on the surface part P are within specified limit, we will obtain a numerical solution of equation (1) with conditions (2) – (4) with uniform temperature T on the surface $\partial\Omega - P$.

3. MATHEMATICAL MODEL OF HEAT RADIATION ON THE MOULD SURFACE

In this chapter will be described a simplified mathematical model of heat radiation by infrared heaters on the mould surface. The infrared heaters and mould are represented in 3-dimensional Euclidian space by the Cartesian coordinate system (O, x_1, x_2, x_3) with base vectors $e_1 = (1,0,0)$, $e_2 = (0,1,0)$, $e_3 = (0,0,1)$.

3. 1. Representation of a Heater

All heaters are of the same type (i.e. they have the same capacity and shape). A heater is represented by abscissa d in length. The location of heater is described by the following parameters: 1/ coordinates of the heater centre $S = [x_1^S, x_2^S, x_3^S]$, 2/ unit vector $u = (x_1^u, x_2^u, x_3^u)$ of heater radiation direction, component $x_3^u < 0$ (i.e. heater radiates "down"), 3/ the vector of the heater axis $r = (x_1^r, x_2^r, x_3^r)$, where the vectors u and r are orthogonal (see Figure 2).

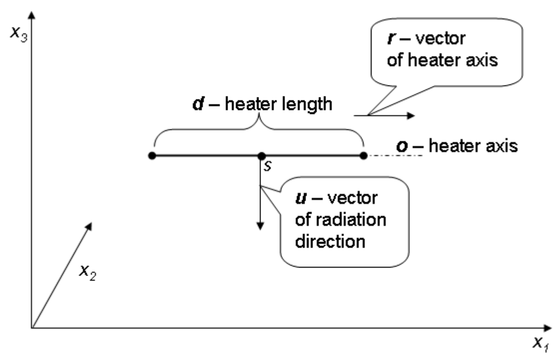

Figure 2: Representation of the Heater in the Model

The other possibility for expressing vector *r* is only by the angle φ (*u* and *r* are orthogonal) that contains the vertical projection of vector *r* to a plane given by the axes x_1 and x_2 (ground plane) and the positive part of axis x_1 ($0 \le \varphi < \pi$). The unambiguous transformation exists between these expressions. We will use the second expression in the following chapters (we need the smallest possible number of parameters to heater location determination in the genetic algorithm). The location of every infrared heater *Z* can be expressed by the following 6 parameters:

$$Z: \left(x_1^S, x_2^S, x_3^S, x_1^u, x_2^u, \varphi\right). \qquad (5)$$

In general, the location of *M* heaters is described by 6*M* parameters.

3. 2. Representation of a Mould

The thickness of an aluminium mould is uniformly 6[mm]. Therefore it suffices to define only total mould surface *P*. We will use elementary surfaces p_j, where $1 \le j \le N$ (i.e. *N* elementary surfaces) to define the mould surface. It is true $P = \bigcup_{1 \le j \le N} p_j$ and $\operatorname{int} p_i \cap \operatorname{int} p_j = \emptyset$ for $i \ne j$, $1 \le i, j \le N$. Every elementary surface is described by the following parameters: 1/ the centre of gravity $T_j = [x_1^{T_j}, x_2^{T_j}, x_3^{T_j}]$, 2/ the unit outer normal vector $v_j = \left(x_1^{v_j}, x_2^{v_j}, x_3^{v_j}\right)$ in point T_j, 3/ the area of elementary surface s_j. It is possible to unambiguously enter the vector v_j through coordinates $x_1^{v_j}, x_2^{v_j}$ (assuming the outer normal vector does not direct "down").

Every elementary surface p_j is defined therefore by 6 parameters:

$$p_j : \left(x_1^{T_j}, x_2^{T_j}, x_3^{T_j}, x_1^{v_j}, x_2^{v_j}, s_j\right). \qquad (6)$$

3.3. Experimental Measurement of Heater Radiation Intensity

We do not know the distribution function of the heat radiation intensity in the heater surroundings from the heater producer. We realized the experimental measurement of the heat radiation intensity in the surroundings of the heater by sensor. The location of the heater was *Z:* (0, 0, 0, 0, 0, 0) in accordance with relation (5), i.e. the center *S* of the heater lies in the origin, union radiation vector $u = (0, 0, -1)$ and vector of the heater axis $r = (1, 0, 0)$ in Cartesian coordinate system (O, x_1, x_2, x_3).

We will suppose the heat radiation intensity across the elementary surface p_j is the same as at centre of gravity T_j. Heat radiation intensity in T_j depends on the position of this point (determined by the first 3 parameters in relation (6)) and on direction of outer normal vector v_j in point T_j (determined by the fourth and fifth parameters in relation (6)). Thus heat radiation intensity on the elementary surface p_j depends on the first 5 parameters in relation (6). The heat radiation intensity was measured by sensor in chosen points below the heater and various deflections of the sensor (it corresponds to centre of gravity T_j location and direction of outer normal vector v_j of elementary surface p_j). We will use linear interpolation function of 5 variables to determine the heat radiation intensity in the vicinity of heater *Z*. The formula of interpolation function is described in detail e.g. in (Antia 2002).

3. 4. General Case of a Heater Location

In this paragraph will be described the process of calculating the heat radiation intensity of heater *Z* in a general position on an arbitrary elementary surface p_j of the mould. We will suppose the heat radiation intensity is the same on the whole elementary surface p_j as in the centre of gravity T_j. We transformed the previous Cartesian coordinate system (O, e_1, e_2, e_3) into a positively oriented Cartesian system $(S, r, n, -u)$, where point *S* is the centre of heater *Z*, *r* is the heater axis and vector *u* is the vector of radiation direction of heater *Z*. The vector *n* is determined by the vector product of the vectors –*u* and *r* (see more detail in (Budinký 1983)) and is defined by relation

$$n = (-u) \times r = \left(-\begin{vmatrix} x_2^u & x_3^u \\ x_2^r & x_3^r \end{vmatrix}, \begin{vmatrix} x_1^u & x_3^u \\ x_1^r & x_3^r \end{vmatrix}, -\begin{vmatrix} x_1^u & x_2^u \\ x_1^r & x_2^r \end{vmatrix} \right).$$

We assume the unit length of the vectors *r*, *n* and –*u*. Then we can define orthonormal matrix **A** (i.e. $\mathbf{A}^T \mathbf{A} = \mathbf{E}$, where **E** denotes identity matrix):

$$\mathbf{A} = \begin{pmatrix} x_1^r & x_1^n & -x_1^u \\ x_2^r & x_2^n & -x_2^u \\ x_3^r & x_3^n & -x_3^u \end{pmatrix}.$$

Let us denote $T'_j = [x_1^{T'_j}, x_2^{T'_j}, x_3^{T'_j}]$ the transformation of the centre of gravity $T_j = [x_1^{T_j}, x_2^{T_j}, x_3^{T_j}]$ of an elementary surface p_j in Cartesian coordinate system $(S, r, n, -u)$. Let the vectors $\mathbf{T}_j$, $\mathbf{T}'_j$ and **S** represent coordinates of the points T_j, T'_j and *S*. Then the transformation of the point T_j is given by relation

$$\left(\mathbf{T}'_j\right)^T = \mathbf{A}^T\left(\mathbf{T}_j - \mathbf{S}\right)^T . \qquad (7)$$

An analogy of the transformation of the outer normal vector v_j in the centre of gravity T_j of elementary surface p_j is given by relation

$$\left(\mathbf{V}'_j\right)^T = \mathbf{A}^T\mathbf{V}_j^T . \qquad (8)$$

We convert a general case of heater location on the basis of relations (7) and (8) to the case of a heater location with realized experimental measurement of the surrounding heat radiation intensity. It means we are able to calculate the heat radiation intensity of an arbitrarily located heater on centre of gravity T_j of elementary surface p_j.

3. 5. Calculation of Total Heat Radiation Intensity on an Elementary Surface

In this part of the article will be described the numerical calculation of heat radiation intensity on an elementary surface. We denote as L_j the set of all infrared heaters radiating on the *j*-th elementary surface p_j, $(1 \le j \le N)$ for the defined location of heaters, and I_{jl} for the heat radiation intensity of *l*-th infrared heater on the p_j elementary surface. Then the total heat radiation intensity I_j on the elementary surface p_j is defined by the following relation (see in more detail in (Cengel 2007))

$$I_j = \sum_{j \in L_j} I_{jl} .$$

We denote as I_{opt} the recommended heat radiation intensity across the whole mould surface by the producer. We define aberration F by relation

$$F = \frac{\sum_{j=1}^{N}\left|I_j - I_{opt}\right| s_j}{\sum_{J=1}^{N} s_j} \qquad (9)$$

and aberration $\widetilde{F}$ is determined by relation

$$\widetilde{F} = \left(\sum_{j=1}^{N}(I_j - I_{opt})^2 s_j\right)^{1/2} . \qquad (10)$$

We highlight that s_j denotes the area of the elementary surface p_j. We need to find the location of heaters such that value of aberration F (alternatively aberration $\widetilde{F}$) will be within specified tolerance.

4. OPTIMIZATION OF LOCATION OF HEATERS BY GENETIC ALGORITHM AND BY "HILL-CLIMBING" METHOD

In this chapter we will briefly describe a procedure to optimize the location of heaters. Note that we do not know the analytical expression for the function of heat radiation intensity surrounding the heater. During optimization we must test three possible collisions of heaters (one heater radiating on a second heater more than the given limit, one heater having insufficient distance from second heater, a heater has not sufficient distance from mould surface). Hence, optimization process is more complicated.

We will use a genetic algorithm for global optimization (this method is less liable to get stuck in the local minimum) and upon finding a solution we will apply the "hill-climbing" method to locally optimize the heater's location.

4. 1. Use of Genetic Algorithm

We note that the terms and relations used in this paragraph are described in more details e.g. in (Affenzeller et al. 2009). The location of every heater is defined by 6 real parameters according to relation (5). Therefore 6*M* parameters are necessary to define the location of all *M* heaters. One chromosome will represent one individual (one possible location of the heaters). Particular genes of the chromosome will represent the determining parameters of the heaters' location. The population will include *Q* individuals. Continuously generated individuals will be saved in the matrix $\mathbf{B}_{Q \times 6M}$. Every row of this matrix represents one individual. Our goal is to find an individual *y*, such that the radiation intensity on the mould surface for the corresponding location of the heaters approaches the recommended value I_{opt} provided by the producer. Thus, we will seek individual $y_{\min} \in C$ satisfactory condition

$$F(y_{\min}) = \min_{y \in C} F(y) , \qquad (11)$$

where $C \subset E_{6M}$ is searched space and function F is defined by relation (9). We often seek minimum of function $\widetilde{F}$ given by relation (10) during the process of optimizing the location (allows us to find location of heaters without extreme difference in radiation intensity from recommended intensity I_{rec} on elementary surfaces p_j, we tested other aberrations too).

4.1.1. Schematic Description of Used Genetic Algorithm

In this part we will describe the schematically particular steps of used genetic algorithm:

begin of algorithm
1/ the creation of the specimen and an initial population of individuals,
2/ the evaluation of all individuals (calculation value $F(y)$ for every individual y), sorting of all individuals y according their evaluation $F(y)$ (from the smallest value to largest value),
3/ *while* a condition of termination is not fulfilled *do*
if operation crossover is randomly chosen *then*
random selection of a pair of parents,
execution of operation crossover and
creation of two new individuals
else
random selection of an individual,
execution of operation mutation and
creation of two new individuals
end if,
integration and evaluation of new calculated individuals, sorting of all individuals in accordance with evaluations, storage of only the first Q individuals with the best evaluation for subsequent calculation
end while,
4/ output of the first row of matrix **B** - the best finding individual
end of algorithm.

The setting of the specimen y_1 (initial individual) is selected in such a way that all the centres of the heaters create nodes in a regular rectangular network, and this network lies over the mould on a plane parallel with the plane defined by axes x_1 and x_2. We generate consequently $Q-1$ remaining individuals of initial generation by random modification of genes with values of y_1. If a collision of any heater exists for any individual y during the genetic algorithm, the individual y is penalized and consequently expelled from the population. Individual selection to operation crossover or to operation mutation is accomplished on the principle of fitness-proportionate selection (see more detail in (Affenzeller at al. 2009)). During the operation crossover we do only one point crossover and modify the variants of crossover and generate two new individuals. During the operation mutation we generate two new individuals, too. This algorithm is described in more detail in (Mlýnek and Srb 2011).

4. 2. Use of "hill-climbing" Method

We will use this method to further locally optimize the solution provided by the genetic algorithm.

4.2.1. Schematic Description of Used "hill- climbing" Method

In this part we will describe the schematically particular steps of the used "hill-climbing" method:

begin of algorithm
1/ let us assign the solution provided by genetic algorithm to $\bar{y}$ and denote $\tilde{y}$ as the individual received by partial increment of $\bar{y}$,
2/ we choose suitable sizes of increments h_i, $1 \le i \le 6M$,
3/ *repeat*
*for i:=*1 *to* 6*M do begin*
we perform repeatedly an increment of *i*-th gene of individual $\bar{y}$ by value h_i (we obtain individual $\tilde{y}$) until inequality $F(\bar{y}) > F(\tilde{y})$ is true, $\bar{y} := \tilde{y}$;
$h_i := -\frac{h_i}{2}$
end
until a condition of termination is not fulfilled,
4/ output of optimized solution – individual $\bar{y}$
end of algorithm.

The final optimized solution is individual $\bar{y}$ that includes information about location of every heater in the form (5). "Hill-climbing" method is described in more details e.g. in (Chembers 2001).

5. TESTING EXAMPLE AND PRACTICAL EXAMPLE

We will describe the results of the heat radiation intensity optimisation calculations by using the mentioned methods in Chapter 4. First, we will use the genetic algorithm to globally optimize the location of the heaters and upon received solution we will apply the "hill-climbing" method for local optimization. We will focus on a testing example and a practical example. A software application was programmed in the language Matlab.

5. 1. Testing Example

One of the tested heated surfaces was a section of a spherical surface. The radius of the sphere is 0,4[m], the vertical projection of this part of surface to plane given by axes x_1 and x_2 (ground plane) is square with side length 0,5[m]. This part of the spherical surface is described by 1800 triangular elementary surfaces.

The recommended radiation intensity by a producer I_{opt} we will define as I_{opt} =68[kW/m^2].

We will use 16 heaters to provide radiation across the mould. All heaters are of the same type: producer Philips, capacity 1600W, length 0,15[m], width 0,04[m]. In the first step of genetic algorithm we will construct specimen y_1. We will create a regular rectangular network in the parallel plane ρ with the plane given by axes x_1 and x_2. The centres of the heaters will be located at network nodes. The vector of the heater axis of every heater is parallel with axis x_1. The plane ρ lies over the mould surface at distance 0,1[m] from centre of gravity T_i with the highest value $x_3^{T_i}$ from the all centres of gravity $T_j, 1 \le j \le N$. The aberration $F(y_1)$ given by relation (9) is $F(y_1) = 40{,}46$. The population will contain 30 individuals (Q =30) and we will construct an initial population of individuals by modifying the parameters of specimen y_1. We will apply the genetic algorithm described in Chapter 4. We will find the optimized individual y_{optga} after 100000 iterations (finding of $y_{\min}$ from relation (11) is not realistic in practice), $F(y_{optga}) = 4{,}00$. Now, we will apply the "hill-climbing" method described in Chapter 4 on y_{optga} and after 5000 iterations we obtain the final optimized solution y_{opt}, value $F(y_{opt}) = 3{,}86$. The values $F(y_{optga})$ and $F(y_{opt})$ depend on the number of iterations of the genetic algorithm and the "hill-climbing" method (see Figure 3).

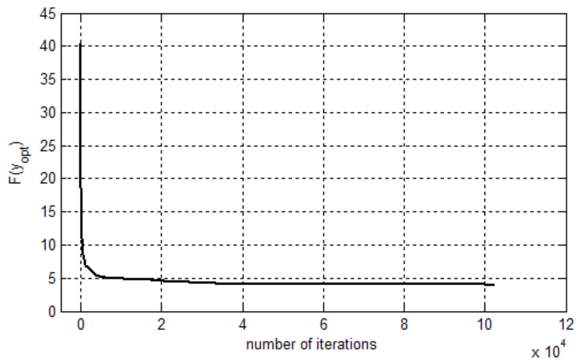

Figure 3: Testing Example - Dependence of $F(y_{optga})$ and $F(y_{opt})$ on Number of Iterations

The graphical representation of heat radiation intensity on the mould surface (levels of radiation intensity in [kW/m^2] correspond to shades of gray colour) and location of heaters corresponding to individual y_{opt} are displayed in Figure 4.

We will make an analogous calculation in the case of replacing function F with function $\widetilde{F}$ given by relation (10); we will execute the same numbers of iterations to the computation of $\widetilde{y}_{optga}$ and $\widetilde{y}_{opt}$. We get the following results:

$\widetilde{F}(y_1) = 25{,}13$; $\widetilde{F}(\widetilde{y}_{optga}) = 3{,}48$; $\widetilde{F}(\widetilde{y}_{opt}) = 3{,}34$. The choice of function $\widetilde{F}$ as the evaluation function in the genetic algorithm and in the „hill-climbing" method allows us to eliminate the parts of the mould surface with extremely high or low heat radiation intensity.

5. 2. Practical Example

Now we will describe a practical example of heat radiation on an aluminium mould surface. The size of the mould is 0,6x0,4x0,12[m^3]. This mould is used to produce the piece of artificial leather that is used to cover a car's passenger-side dashboard. The mould surface is described by 2187 triangular elementary surfaces.

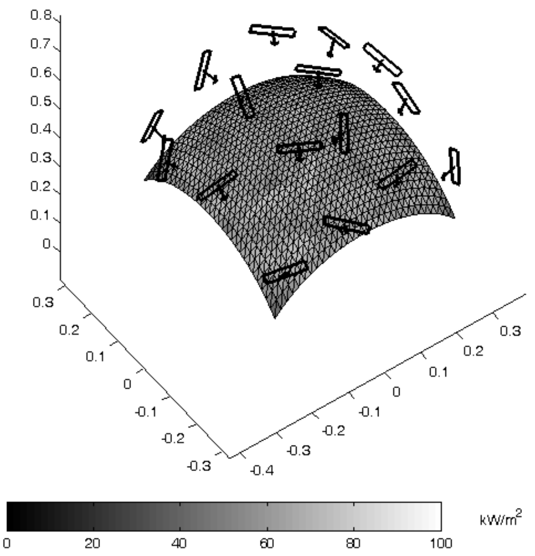

Figure 4: Testing Example - Displaying Heat Radiation Intensity ([kW/m^2]) on the Mould Surface and Location of Heaters Corresponding to Individual y_{opt}

The recommended radiation intensity from the producer is I_{opt} =50[kW/m^2]. We will use 19 heaters to heat the mould. The heaters are of the same type as in the „testing example" and we will use the same determining procedure of specimen y_1 (the distance of plane ρ from the mould surface is again 0,1[m]). Following the computing procedure the population, also analogous to the "testing example", will again contain 30 individuals. We will obtain the following results after 100000 iterations of genetic algorithm, and after 5000 iterations of „hill-climbing":

$F(y_1) = 41{,}11$; $F(y_{optga}) = 5{,}17$; $F(y_{opt}) = 5{,}12$.

The values $F(y_{optga})$ and $F(y_{opt})$ descend in dependence on the number of iterations of the genetic algorithm and the number of iterations of the "hill-climbing" algorithm (see Figure 5). The graphical representations of heat radiation intensity across the mould surface and the locations of heaters corresponding to individual y_{opt} are displayed in Figure 6. Calculation time on PC, CPU 2xAMD Athlon 2,81GHz was 20 hours. When we use function $\widetilde{F}$ given by relation (10) instead of function F during calculation, we obtain the following results:

$\widetilde{F}(y_1) = 28{,}39$, $\widetilde{F}(\widetilde{y}_{optga}) = 4{,}03$, $\widetilde{F}(\widetilde{y}_{opt}) = 3{,}96$.

These two described examples are illustrative. There are often moulds of larger sizes used, with more rugged surfaces and the value of recommended heat radiation intensity on surface I_{opt} is higher, therefore we apply a higher number of heaters to produce the radiation.

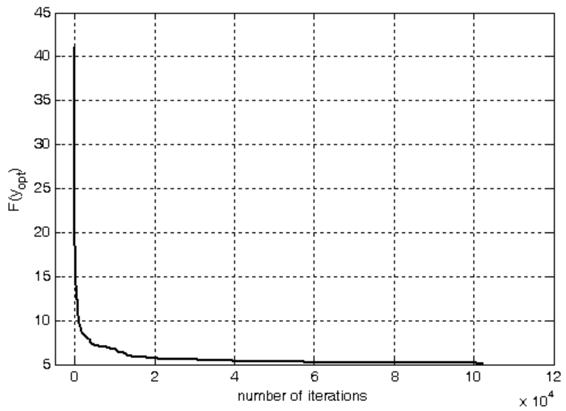

Figure 5: Practical Example - Dependence of $F(y_{optga})$ and $F(y_{opt})$ on Number of Iterations

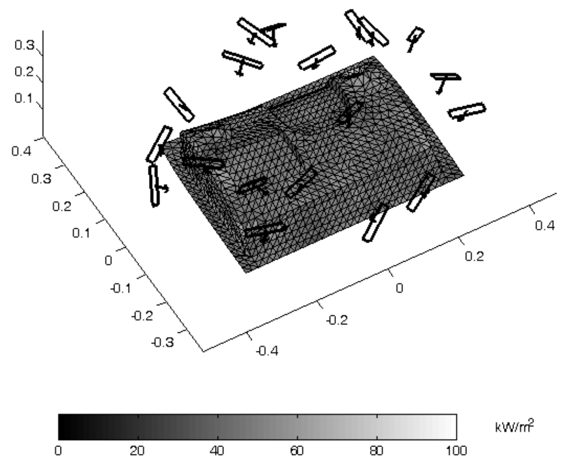

Figure 6: Practical Example - Displaying Heat Radiation Intensity ([kW/m^2]) on the Mould Surface and Location of Heaters Corresponding to Individual y_{opt}

On the basis of practical experience along with finding the optimal location of heaters through use of the genetic algorithm and "hill-climbing" method described in this article we can calculate a sufficiently precise solution for the needs of artificial leathers producer.

6. CONCLUSION

On the basis of numerical tests we get a sufficiently exact solution of the optimized location for heaters over a mould. It is necessary to ensure the temperature differences on the mould surface less than 3[°C] during the mould warming process. Heat conductivity of the mould affects the unification of different temperatures on the mould surface.

Generally, the locations of heaters determined upon the basis of the experience of technicians produce significantly worse results than ours. For various models and, as a result, the process is much more time consuming (approximately 2 week in comparison to our calculation, which usually took from 15 to 30 hours).

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AUTHOR BIOGRAPHIES

JAROSLAV MLÝNEK was born in Trnava, Czechoslovakia and went to the Charles University in Prague, where he studied numerical mathematics on Faculty of Mathematics and Physics and he graduated in 1981. He focuses in his work on the computational problems of warming and thermal losses in components of electrical machines and on mathematical models of thermal convection in electric machines. Currently he works as associate professor at the Technical University of Liberec, Czech Republic. His e-mail address is: `jaroslav.mlynek@tul.cz`.

RADEK SRB was born in Mladá Boleslav, Czech Republic and went to the Technical University in Liberec, Czech Republic, where he studied computer science and programming in the Faculty of Mechatronics. He graduated in 2005. He focuses on problems with automated control of production. He works as a teacher and he is a Ph.D. student. His e-mail address is: `radek.srb@tul.cz`.