A Combined Heat Transfer and Genetic Algorithm Modeling of an Integrated Steel Plant Bloom Re-heating Furnace

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ABSTRACT: This paper presents a modeling study of preheating of blooms in a fuel fired furnace using a combined GA and heat transfer formulation. A re-heating furnace containing three asymmetrically placed burners are considered in this study, which is a typical configuration used in many integrated steel plants. This study shows that the GA is an ideally suited tool for studying such complex problems.

1 INTRODUCTION

Bloom re-heating is an integral feature of most of the integrated steel plants. An efficient design of such furnaces is an essential requirement for cost saving in this energy intensive operation. During this study a typical bloom re-heating furnace design was considered for modeling using a combined GA and heat transfer formulation. The aim of this analysis is to identify a set of properly optimized operational parameters for the furnace which would lead to the necessary temperature profile in the bloom using a minimum amount of fuel burn-off. We also wanted our modeling work not to become prohibitively complicated for actual usage by the industry, and at the same time adequate precautions were taken to ensure the engineering accuracy of the predictions. Further details of the model and the computational schemes are provided below.

2 SYSTEM DESCRIPTION

The bloom re-heating furnace considered in this study is shown schematically in Figure 1. It consisted of two

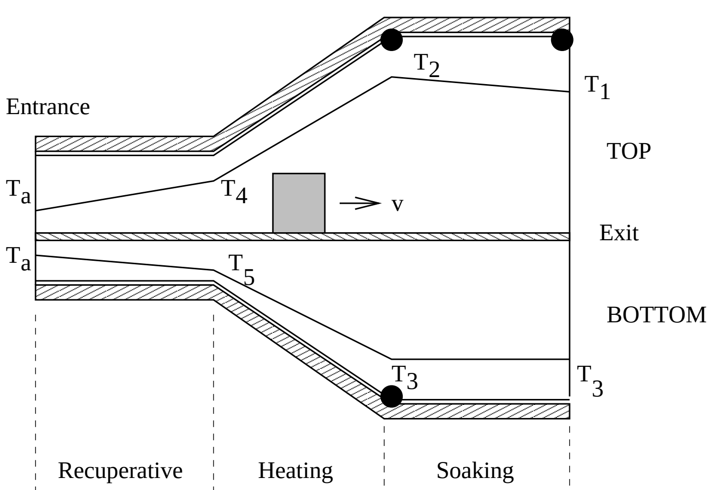

Figure 1: A schematic diagram of the re-heating furnace.

burners at some fixed locations (marked with filled circles) above and below the moving bloom, while a third burner was considered at some fixed location below it. The blooms move horizontally across the furnace, passing sequentially from a *recuperative* zone to a *heating* zone where the bloom gets heated by the first burner at the top and the burner at the bottom, and finally to a *soaking* zone where the top portion of the bloom is heated by the second burner above it, and the solid hearth below the bloom assures uniform soaking temperature. For the sake of simplicity the temperature profiles above and below the bloom were considered to be linear as shown in Figure 1. This is a typical configuration of burners known to be used by a number of integrated steel plants across the world.

3 PROCESS MODELING

A simple heat transfer model of the re-heating process was developed in this study. The top and bottom surfaces of the blooms were assumed to receive heat only through radiation, while conduction remained the only mechanism for heating the inner regions of the blooms. The small air gap between any two adjacent blooms was neglected, as they usually enter the furnace in rapid succession.

During this investigation the three burner temperatures and the velocity of the moving bloom were taken as the process variables. A simple GA approach was used to identify the optimum combination of these four variables leading to the *minimum* radiative heat flux received by the bloom surface after satisfying the various system constraints, for example:

- The average exit temperature of the bloom should be close to a prescribed dropout temperature
- Amount of scale formation (calculated using a parabolic rate expression [Geiger and Poirier 1973]) should be within a prescribed limit.

Since in this case the *fitness* evaluation for the GA selection operators is directly related to the heat flux calculation, a coupling between GA and heat transfer becomes inevitable. The basic heat transfer equation solved in this study can be stated in the vectorial notation as:

$$\frac{\boldsymbol{D}T}{\boldsymbol{D}t} = \alpha \boldsymbol{\nabla}^2 T, \tag{1}$$

where the substantial derivative operator is defined as:

$$\frac{\boldsymbol{D}}{\boldsymbol{D}t} \equiv \frac{\partial}{\partial t} + \vec{\mathrm{V}} \cdot \boldsymbol{\nabla}. \tag{2}$$

In this work equation 1 was implemented in a 2-D Cartesian co-ordinate system. The initial and the boundary conditions of the problem were taken as follows:

I.C.:	For the entire solution domain:	At $t = 0$, $T = T_a$.
B.C. 1:	For all y at $x = 0$, and $t > 0$	$T = T_a$.
B.C. 2:	For all y at $x = L$, and $t > 0$	$-\frac{\partial T}{\partial x} = 0$.
B.C. 3:	For all x at $y = 0$ and $t > 0$	$-k\frac{\partial T}{\partial y} = \sigma\left(T_l^4 - T_{ls}^4\right)$.
B.C. 4:	For all x at $y = h$ and $t > 0$	$k\frac{\partial T}{\partial y} = \sigma\left(T_u^4 - T_{us}^4\right)$.

Here the *chromosomes* of any member of the GA *population* consisted of the linearly mapped [Deb 1995] binary coded values of the system variables. A *fitness* calculation for any particular *individual* would involve corresponding adjustment of the furnace temperature profiles shown in Figure 1, followed by a numerical solution of equation 1 to yield the bloom temperature profile, from which the radiative heat flux input to the bloom could be obtained directly.

Further information on the computational scheme is provided below.

4 COMPUTATIONAL

The pertinent transient heat transfer equations were solved using a finite difference approach appropriate for such parabolic partial differential equations and the total heat flux received by the bloom surface was minimized using a rather straight forward binary Genetic Algorithm procedure involving both single point crossover and a bitwise mutation. Typically, a population size of the order of hundred was used in most of the runs. A series of GA calculations were performed using an available C code [Goldberg 1989] and for the remaining calculations a public domain FORTRAN 77 code [Carroll 1996] was utilized after several modifications. The micro-GA [Krishnakumar 1989] option built in this FORTRAN 77 code was tried out in some of the calculations and the real coded Differential Evolution strategy suggested recently [Price and Storn 1997] was also used to a limited extent, for which we had developed our own code. The constraints were incorporated in the optimization scheme through the well documented parabolic penalty function approach [Deb 1995]. For the following nonlinear programming (NLP) problem having J inequality constraints and K equality constraints, if we have to

$$\left.\begin{array}{lll} \text{minimize} & f(x) & \\ \text{subject to} & & \\ & g_j(x) \geq 0, & j = 1, 2, \ldots, J, \\ & h_k(x) = 0, & k = 1, 2, \ldots, K, \\ & x_i^{(L)} \leq x_i \leq x_i^{(U)}, & i = 1, 2, \ldots, N. \end{array}\right\} \tag{3}$$

An unconstrained penalized function is formed as follows:

$$P(x) = f(x) + \sum_{j=1}^{J} \langle g_j(x) \rangle^2 + \sum_{k=1}^{K} [h_k(x)]^2. \tag{4}$$

In the above function the bracket operator $\langle \alpha \rangle$ is equal to α if it is negative, and is equal to zero otherwise.

The 2-D heat transfer calculations were carried out using a fully implicit, line by line finite difference approach employing the popular TDMA algorithm described by [Carnahan, Luther and Wilkes 1969]. Since TDMA algorithm is actually meant for an 1-D problem, the 2-D solutions were obtained iteratively by performing a series of sequential x and y sweeps. During the x sweeps the y derivatives were absorbed in the right hand side vector, and the same was done for the x derivatives during the y sweeps. The radiation terms were quasi-linearized and appropriately absorbed in the diagonal coefficient. An appropriate relaxation parameter was chosen to ensure numerical stability.

In order to obtain quicker results several 1-D calculations using a fully explicit discretization for the heat transfer equations were also performed in this study. Since such schemes are not unconditionally stable, the discretized grid size and time steps were judiciously adjusted. The scale formation was considered in the 1-D calculations but was ignored in case of 2-D solutions in order to reduce the computational time.

5 RESULTS AND DISCUSSION

Locating the optimum solution is quite challenging here, as evident from the narrow feasible region in the typical contour plot constructed through 1-D calculations and only for two variables, as shown in Figure 2. The point marked on the diagram is a feasible solution found by GA, demonstrating efficacy of the this coupled GA and heat transfer analysis.

A typical temperature history of a moving bloom is constructed through the 1-D simulation as shown in Figure 3. A reasonably uniform dropout temperature (approximately 1200 deg C, assumed in this case) is one of the prime industrial requirements, and that seems to be quite well satisfied.

It was observed through the 2-D calculations that the furnace temperature profile reaches a steady state rather quickly. An optimized furnace temperature profile and its corresponding steady state 2-D temperature contour plot along the passage of the blooms are shown in Figures 4 and 5 respectively. The temperature profile, as expected, is highly asymmetric. We plan to extend this calculation to 3-D cases in our future work, in order to develop a better understanding of the process.

In most of our calculations a simple genetic algorithm with single point crossover and bitwise mutation worked well. Apparently, neither micro-GA nor the Differential Evolution could really enhance the computational

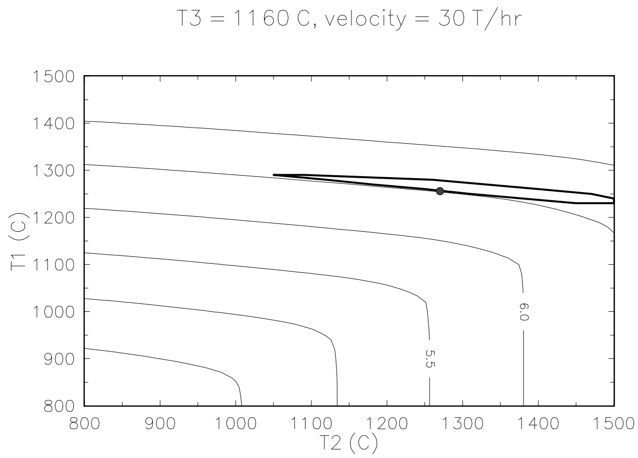

Figure 2: The feasible region and the GA-optimized solution (the solid circle) are shown. Numbers on contour lines show different heat energy values received by the bloom.

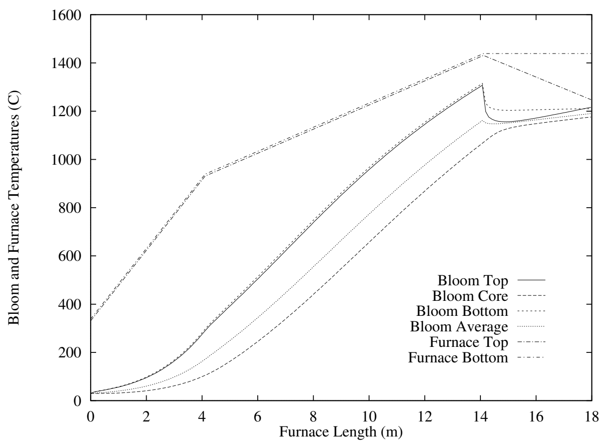

Figure 3: Bloom and furnace temperature profiles for the optimized solution. The optimal velocity is 36 Tonnes/hr.

efficiency in this case. However, we plan to investigate this aspect more thoroughly in the future. This hybrid approach of creating an interface between the transport techniques and Genetic Algorithm gave rise to a much better insight of the heating process in such industrial furnaces which so far could not be obtained using more traditional approaches.

6 ACKNOWLEDGMENTS

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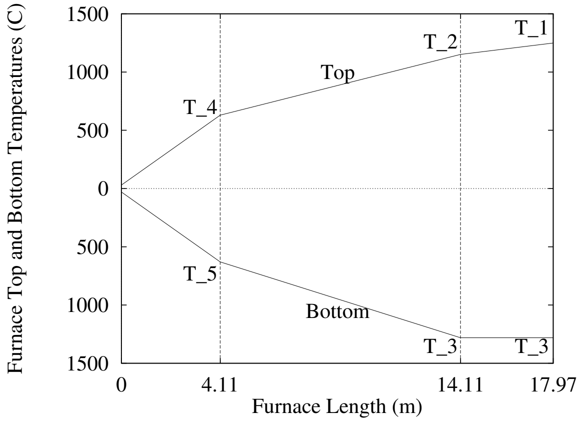

Figure 4: Furnace temperature profiles for the optimized solution of 2-D heat transfer model.

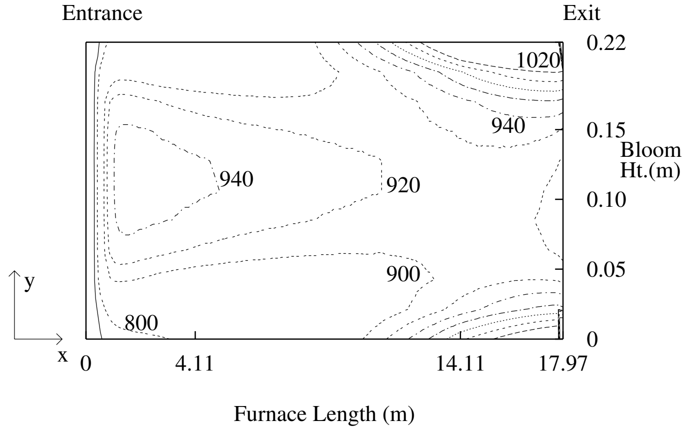

Figure 5: Bloom temperature contours for the optimized solution of 2-D heat transfer model. Velocity of bloom is 80 Tonnes/hr. Contours are shown in deg C.

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8 LIST OF SYMBOLS

$\frac{\boldsymbol{D}}{\boldsymbol{D}t}$	Substantial derivative operator
$f(x)$	Function
$g(x))$	Inequality constraint
h	Height of the bloom
L	Length of the furnace
$h(x)$	Equality constraint
$P(x)$	Penalized function
k	Thermal conductivity
T	Temperature
t	Time
V	Velocity
x, y	Cartesian coordinate

Greek symbols:

$\langle\alpha\rangle$	Bracketed penalty operator
α	Thermal Diffusivity
σ	Stefan-Boltzman constant
$\boldsymbol{\nabla}$	Vector differential operator "nabla"
$\boldsymbol{\nabla}^2$	Laplacian operator

Subscripts and superscripts:

l	Lower portion of the furnace
ls	Lower surface of the bloom
u	Upper portion of the furnace
us	Upper surface of the bloom
(L)	Lower bound of a variable
(U)	Upper bound of a variable