A Heat Transfer Study of the Continuous Caster Mold Using a Finite Volume Approach Coupled With Genetic Algorithms

N. Chakraborti, K. Suresh Kumar, and G.G. Roy

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The mold region of the Continuous Caster was studied using a heat transfer formulation coupled with an optimization scheme. The pertinent transport equations were solved using a finite volume approach and the optimization calculations were conducted using biologically inspired Genetic Algorithms. The results are compared with the data available in the literature and significant improvements in terms of the casting velocity and the solidified shell thickness are observed and reported.

Keywords caster mold, genetic algorithms, heat transfer formulation

1. Introduction

The advent of Continuous Casting technology (Fig. 1) is perhaps one of the most important events influencing the processing of steel worldwide. The process was subjected earlier to rigorous heat transfer analysis[1,2] and in recent times mathematically rigorous optimization studies[3] have also been conducted. Furthermore, a number of researchers in the recent past[4-7] have used biologically inspired Genetic Algorithms (GAs) for conducting optimization studies in this area, adding a newer dimension in Continuous Casting research. The immediate advantages of using a GAs-based approach would be its high flexibility in terms of the nature of the variables, be it real, integer, discrete, or binary; its ability to adjust to a situation where a direct mathematical description of the objective function is unavailable; and its efficacy in locating the global optimum when many traditional methods fail.

In our earlier work[6,7] a heat transfer analysis of the mold region of the caster was conducted using an analytical solution for the temperature profile, which, in turn, was coupled with a Genetic Algorithm scheme to obtain the maximum casting velocity. This paper describes an alternate strategy, plus some further improvements in the methodology, where a more rigorous finite volume computation scheme[8] has replaced the approximate analytical solution based approach that was used earlier.[6,7] Consequently, during this investigation, a more elaborate and accurate optimized temperature profile could be generated for the caster. The basic methodology is described below, along with a brief outline of Genetic Algorithms.

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2. Outline of Genetic Algorithms

GAs are highly robust computing techniques that mimic the Darwinian principle of survival of the fittest, often in a context far-fetched from biology of any kind. In the most common forms of GAs, the variables are mapped on to their binary equivalents, which are concatenated together to form an *individual* and a set of individuals are generated to form a *population*. Each member of the population therefore carries a potential solution of the problem and the initial population is generated randomly. A number of genetic operators, *crossover* and *mutation* for example, then act on the population, roughly copying the similar processes in the natural world. The better individuals for the next generation are selected based on their

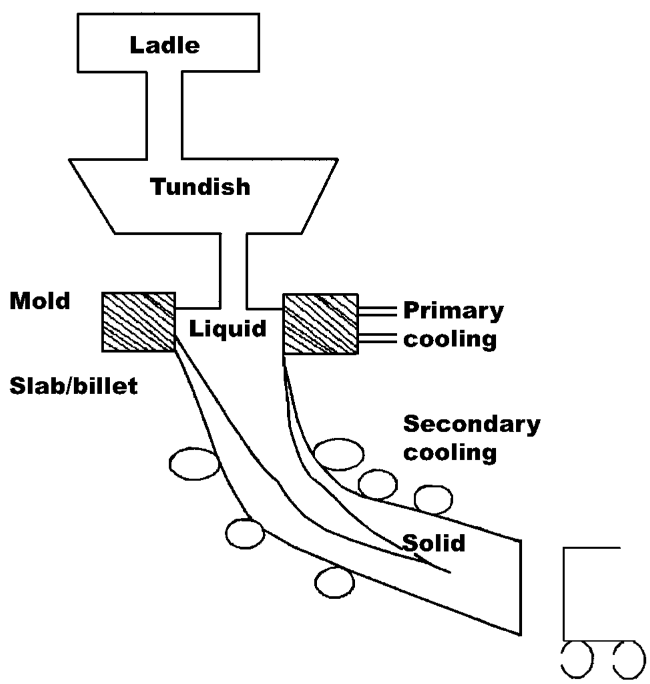

Fig. 1 Schematic diagram of Continuous Casting

respective *fitness* values—a parameter that quantifies the proximity of the individual to the actual solution. For an optimization problem, a pseudo-code for GAs can be given as:

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initialize random binary population:
    do {
    calculation of fitness;
    reproduction;
    crossover;
    mutation;} while (termination criterion not satisfied);
```

The details of the genetic operators are provided elsewhere.[9,10]

3. The Process Model and Optimization Scheme

For the efficiency of production, an optimization scheme for the continuous casting process should try to maximize the casting velocity. This, however, cannot be done unconditionally, as a number of systems constraints would tend to pull the casting velocity down. Some high casting velocity, for example, may result in a very thin solidified shell thickness at the exit of the water cooled mold, which would tend to rupture due to inadequate strength, rendering any attempts of casting at that speed totally unacceptable. Therefore, for safety, it is perhaps wise to maximize the solidified shell thickness within a required range and to accept the corresponding casting velocity as the optimum. This is the approach that we have taken in the current study. Here the casting velocity (V), negative strip time (t_N), mold oscillation frequency (f), stroke length (S), and the exit shell thickness (δ) were taken as the process variables. The fitness was calculated on the basis of δ, the thicker shells within a prescribed limit were taken as of higher fitness, and a penalty was added beyond the limit. To achieve this, binary strings consisting of t_N, f, and S were generated through GAs and the casting velocity was calculated using a well-known relationship:[1]

$$V = \pi f S \cos(\pi f t_N) \quad \text{(Eq 1)}$$

For each velocity provided by the population, the temperature profile was calculated by solving the following equation, using a finite volume approach well documented in the literature:[8]

$$\frac{DT}{Dt} = \alpha \nabla^2 T + \dot{S} \quad \text{(Eq 2)}$$

where α is the thermal diffusivity and the substantial derivative operator, D/Dt, was defined as

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + V.\nabla \quad \text{(Eq 3)}$$

The source term, $\dot{S}$, was evaluated from the latent heat of fusion and the pouring temperature at the mold, and assuming a steady state temperature profile, the transient term was neglected in Eq 3. The pouring temperature served as the boundary condition for the top surface, while the bottom surface was taken insulated, as a first approximation. Axi-symmetry was implemented along the center of the mold and heat flux continuity was implemented at the mold wall. All the calculations were performed in a Pentium (HCL, India) machine, using Microsoft FORTRAN PowerStation, Version 1.0a compiler under a Windows 98 environment.

The computing scheme adopted in this study is explained schematically in Fig. 2. The TOURNAMENT SELECTION mentioned in this figure involves choosing the better individual among two randomly selected ones.

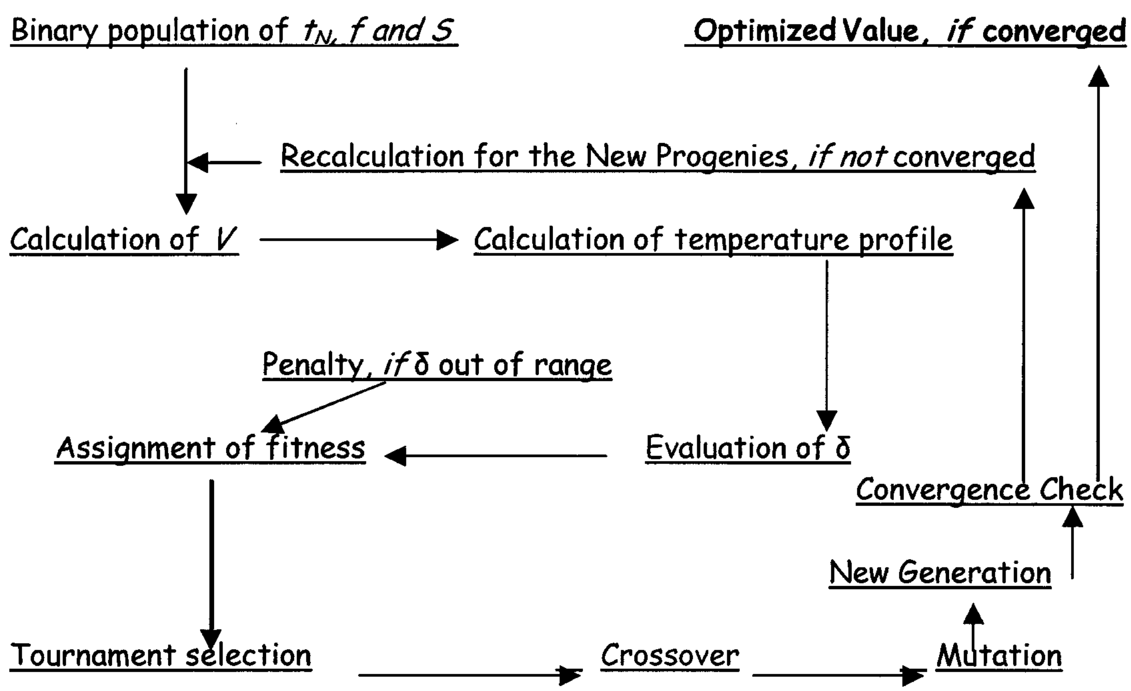

Fig. 2 Schematic diagram showing the computational procedure

Table 1 Optimized Data and Corresponding Results From Ref. 1

Calculation #	Length of the Mold × 10^2, m	Diameter of the Mold × 10^2, m	Casting Velocity, Optimized, × 10^3, m·s^{-1}	Casting Velocity From[1] 10^3, m·s^{-1}	Negative Strip Time, s	Oscillation Stroke × 10^3, m	Oscillation Frequency, s^{-1}	Exit Shell Thickness From GAs × 10^2, m	Exit Shell Thickness From[1] × 10^2, m
1	63.5	15.0	14.02	11.99	0.27	9.96	2.06	2.80	2.30
2	63.5	15.0	19.05	16.93	0.18	8.70	2.08	1.58	1.70
3	63.5	15.0	23.60	22.01	0.17	10.27	2.21	1.46	1.52
4	63.5	15.0	32.55	30.48	0.17	10.90	1.21	1.00	1.01
5	63.5	15.0	51.60	49.99	0.27	9.50	2.62	0.70	0.90
6	89.0	17.2	23.45	22.01	0.17	10.27	2.21	2.00	2.00
7	100.0	15.0	22.07	19.99	0.17	9.66	2.21	2.16	2.30
8	66.0	18.0	34.86	35.00	0.15	10.12	2.21	1.52	1.70

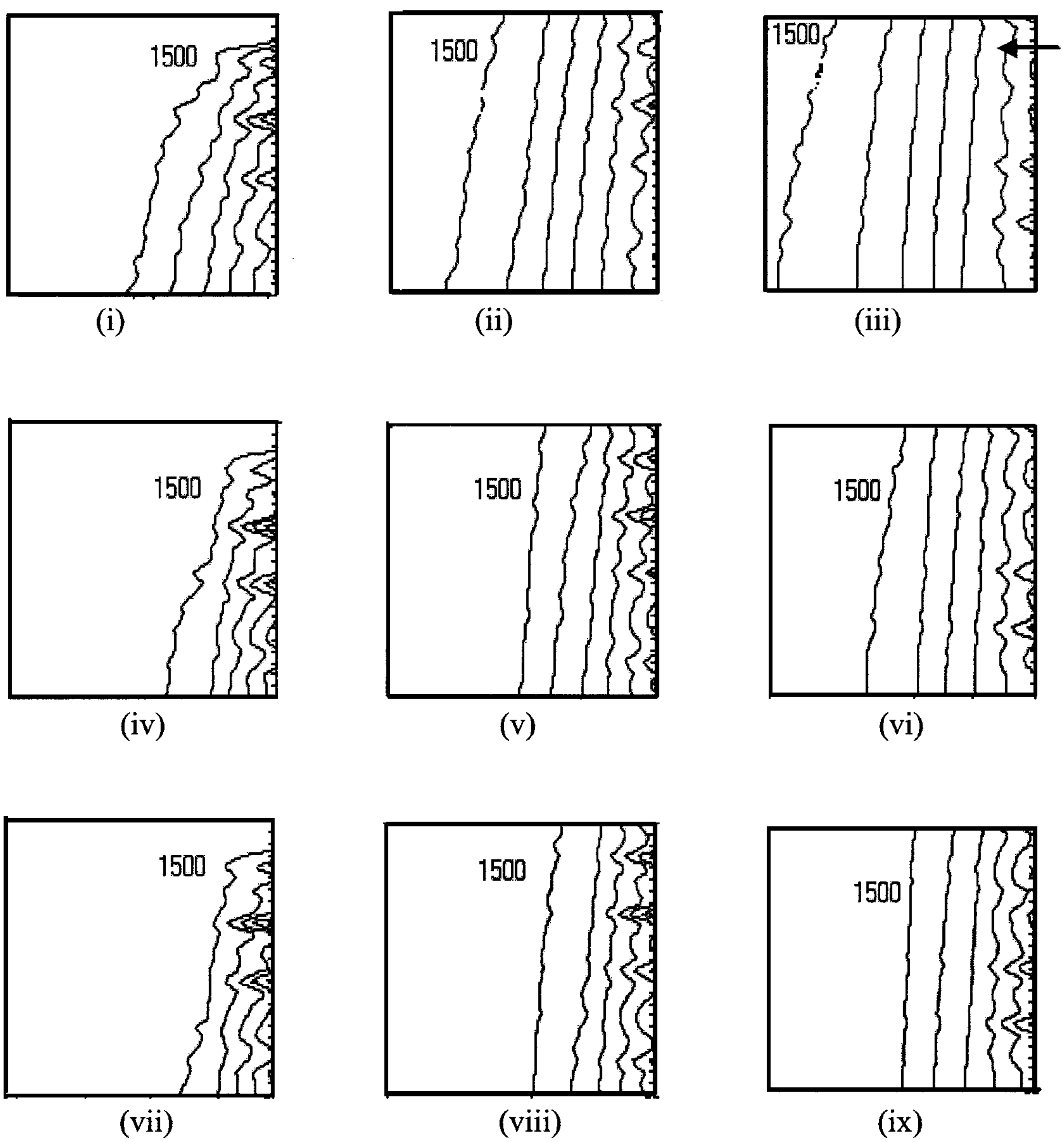

Fig. 3 Temperature profiles in the solidified shell. The isotherms are placed at an interval of 200 °C up to a maximum of 1500 °C. The arrow indicates the water-cooled exterior. (i), (ii), and (iii) denote the top (0-0.220 m), middle (0.220-0.440 m), and bottom (0.44-0.635 m) region of the shell corresponding to Calculation # 1, detailed in Table 1. (iv), (v), and (vi) denote the same for Calculation # 4. The remaining figures denote the same for Calculation # 5.

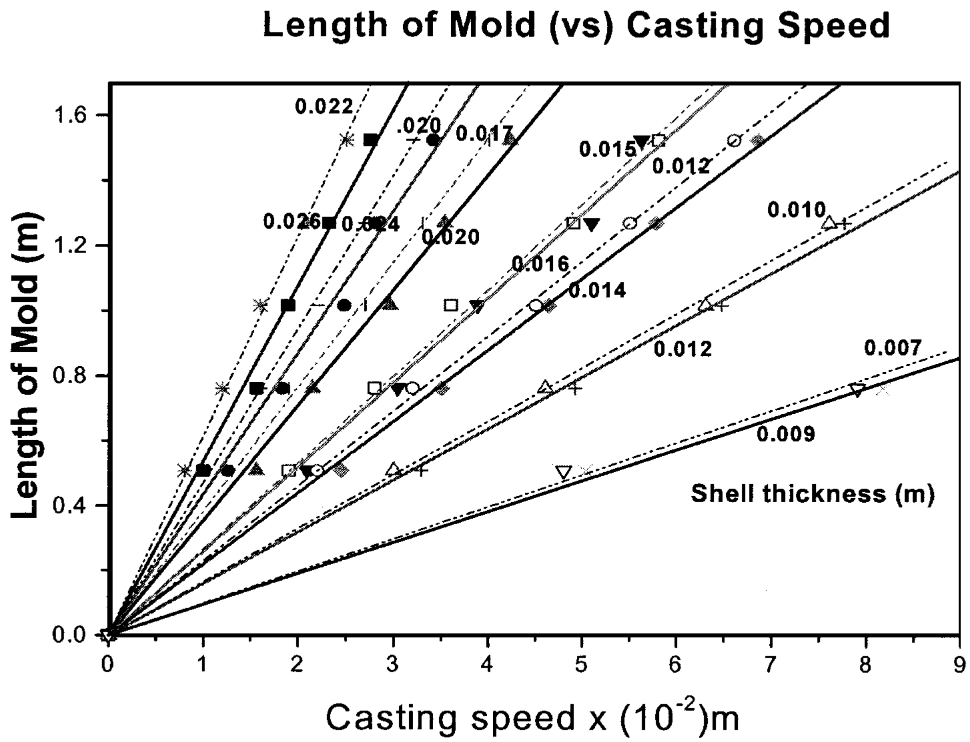

Fig. 4 Interdependence between the length of the mold, casting speed, and shell thickness. The solid lines denote the optimized data generated in this study. Previously calculated[1] un-optimized results are shown as dashed lines. The corresponding data points are also shown.

4. Results and Discussion

The optimized data obtained in the present investigation are shown in Table 1. The results are in good agreement with the data provided by Brimacombe and Samarasekera,[1] as indicated in the corresponding columns. Unlike the results obtained in this investigation, the data provided in Ref. 1 are however, not optimized for maximum casting velocity or shell thickness. The current study indicates that under optimized parameter settings, it is possible to cast at a higher speed and also to obtain a higher shell thickness at the exit. Both factors can be effectively used in an industrial scenario.

Some typical optimized temperature profiles in the solidified shell are shown in Fig. 3. All the calculations shown in this figure were performed for the same dimension of the mold. The optimized parameters, including the casting velocity, however, varied significantly. In a highly complex problem like the one in hand, the *fitness landscape*[9] becomes extremely complex. In this case the optima show a very high multi-modality, containing numerous peaks. The optimized configuration here is therefore not unique and a similar shell thickness may correspond to some alternate parameter settings. Because GAs require specifications about the upper and lower bounds of the solution space, for each simulation detailed in Table 1 we have fixed them in the vicinity of the data provided by Brimacombe and Samarasekera[1] and searched for any possible improvements. In our studies, a higher casting velocity resulted for most combinations of shell thickness and mold length (Fig. 4), where our numerical experiments are compared with the previous calculations,[1] which did not attempt any optimizations. This has a significant bearing as far as the practical applications of the continuous casting technology are concerned. An integrated steel plant operates round the clock, where even a small increase in the casting velocity adds up quickly to significantly alter the total productivity.

In this study, we have focused our attention primarily on the mold region of the caster. A comprehensive GAs-based model is yet to emerge for continuous casting, involving all the regions of the caster along with the entire set of process parameters. Our current research, however, is aimed in that direction. We have already extended this methodology to the *spray-cooling* region of the caster[11] and plan to study the *tundish* region as well. In recent times, the continuous casting technology has gone through a number of technological breakthroughs; *thin slab casting* and *strip casting* are perhaps two pertinent examples. GAs can immensely contribute to fine tune these newer technologies, provided active industrial support becomes available in this area soon.

For any attempts at applying a GAs-based analysis to the continuous casting problem, one needs to realize that the efficacy of this approach is sensitive to a judicious choice of crossover and mutation probabilities (Fig. 5 and 6). The mutation operator in Simple Genetic Algorithms essentially performs a local search. The idea is to slightly perturb the existing solution and to examine if it leads to any improvements. This operator, therefore, has to be used sparingly with a small probability value. Therefore, in this framework, excessive mutation will destroy good genes and the quality of the solution will drastically go down (Fig. 5). Here, with higher mutation probability, the average fitness of the population after a hundred genera-

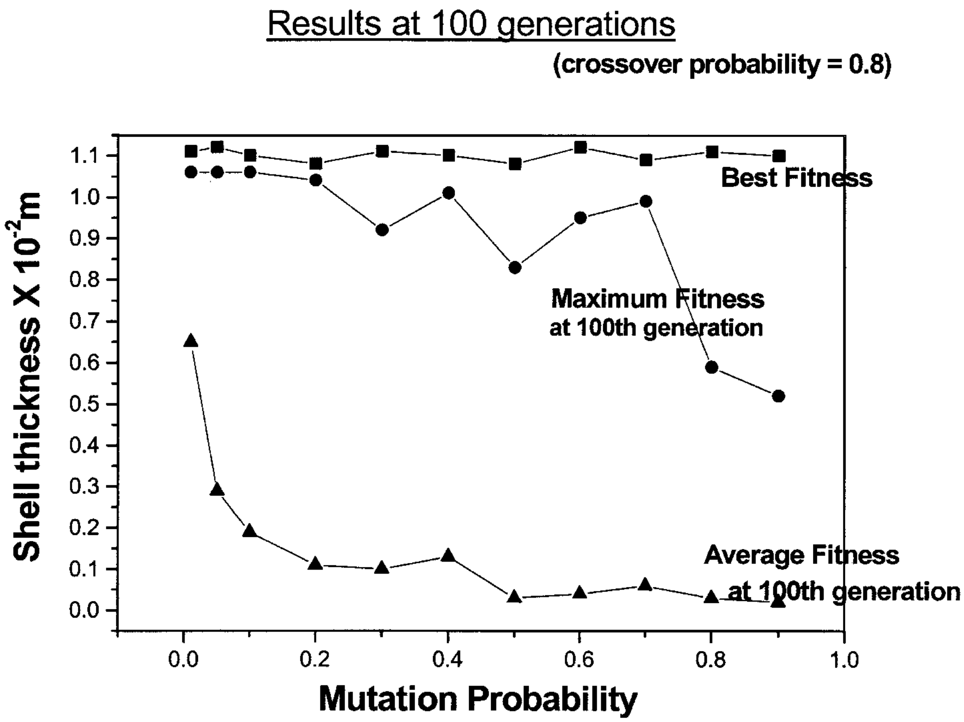

Fig. 5 Sensitivity analysis for mutation probability

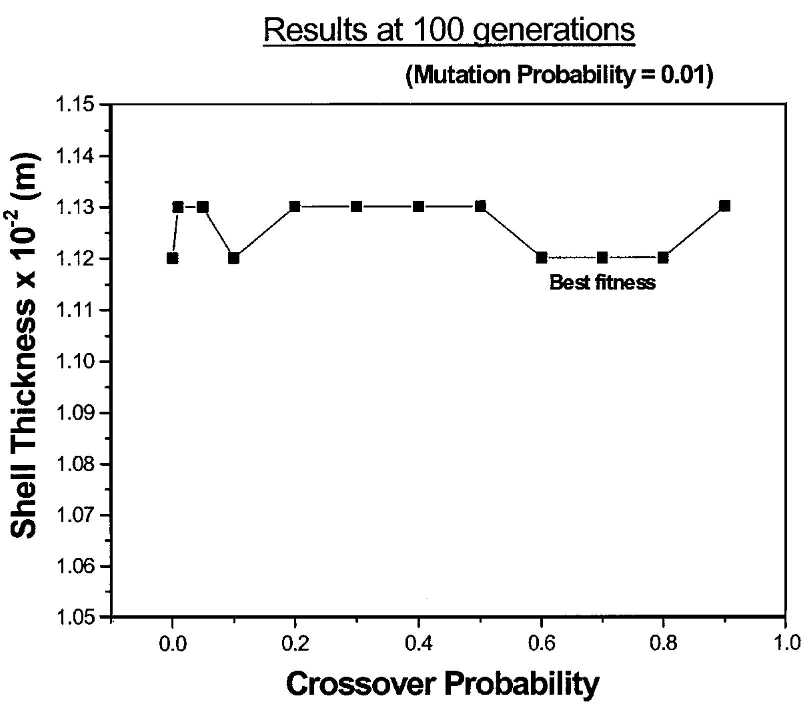

Fig. 6 Sensitivity analysis for crossover probability

tions had deteriorated to an unacceptable limit; also the maximum fitness had substantially worsened. These calculations were, however, run with an *elitist* strategy, where the best solution of the current generation was passed on to the subsequent one and the fitness of the elite was found to be somewhat insensitive to the extent of mutation. The crossover operator, on the other hand, is considered to be tailored for a global search. It combines information from the entire search space, performing an exhaustive query for the better genes in the process. Most calculations in which the binary GAs are used usually settle for a crossover probability much higher than what is usually prescribed for the mutation operator. This particular problem, however, did not show a strong dependence on the mutation probability (Fig. 6). The apparent reason for this is probably a strong multi-modality of the solution domain where the major task is to overcome the local optima, for which, ultimately it is the performance of the mutation operator that matters more.

4. Conclusions

Substantial contradictions between the operating parameters seem to exist in the continuous casting outfits worldwide.[1,6] GAs, coupled with rigorous system models, can bring order to such discrepancies. A typical methodology is demonstrated in this article, incorporating a heat transfer analysis in an evolutionary optimization scheme. The results tend to show significant improvements in terms of the allowable casting velocity for a mold of any particular length and the corresponding requirements for the solidified shell thickness. This is worthy of further exploration, particularly in an actual industrial scenario.

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