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Restoration of the cooling conditions in a three-dimensional continuous casting process using artificial intelligence algorithms

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ABSTRACT

In this study, we propose a procedure for restoring the cooling conditions in a crystallizer and in the secondary cooling zone of a three-dimensional continuous casting process. The additional information required to solve the inverse problem is given by temperature measurements at selected points. The appropriate direct problem is solved using the alternating phase truncation method. The ant colony optimization algorithm and the artificial bee colony algorithm are used to minimize a functional that defines the error of the approximate solution. We compare usefulness of these two algorithms for solving this type of problem.

1. Introduction

Continuous casting is a widely used method for producing casts. The design of the cooling system significantly influences the quality of the casts produced. Therefore, it is very important to select appropriate cooling conditions for metal ingots. In [1], the inverse problem was considered, which involved determining the cooling strategy in the secondary cooling zone of the continuous casting process such that the interface would have the correct shape. In the formulation of the problem, the Stefan condition was omitted and the interface was identified as one of the isotherms where the temperature was equal to the solidification temperature. Results were also obtained concerning the stability of the solution and the convergence of Tikhonov regularization. The practical aspects of this method were discussed in [2]. The uniqueness and continuous dependence on the initial data during the continuous casting process for pure metals was also considered in [3], where the Stefan condition on the interface was also omitted from the formulated problem and the equivalent thermal capacity was used in the heat conduction equation instead. A method for determining the optimal cooling strategy in the secondary cooling zone of the continuous casting process with a constant casting velocity was proposed in [4], where the full two-phase inverse Stefan problem (with the Stefan condition) was solved. The same task with a variable casting velocity was considered in [5], where an optimization criterion (total solidification in the selected zone) was considered. In [6], the heat transfer coefficient in the secondary cooling zone was selected for the continuous casting process, which was described using the two-phase one-dimensional (axisymmetric) inverse Stefan problem. The optimization criterion involves achieving the given

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time for solidification and the given heat flux values, which are constant in the successive cooling zones. Evaluations of the heat transfer coefficients along the secondary cooling zone during continuous steel casting were presented in [7]. In [8], some additional criteria were added (surface temperature and the location of the interface) and the selected cooling strategy was applied in the primary and secondary cooling zones.

In addition to determining the cooling conditions for continuous casting, other parameters that describe the process should be considered. In [9], the location of the phase change front in the continuous casting process was designated by solving the inverse geometry problem. Nawrat and Skorek [10,11] used the Stefan problem to determine the thermal resistance of the interspace between the ingot and the crystallizer in a continuous casting process. The thermal resistance of the interspace between the crystallizer (or the mould) and the ingot was also identified in [12,13], whereas the coefficient of heat transfer between the ingot and the mould was determined in [14,15]. Chakraborti et al. [16,17] used a genetic algorithm to model the mould, spray, and radiation cooling regions of the caster. A genetic algorithm was also employed to model the continuous casting regions in [18–22].

Most previous studied in this area have considered two-dimensional problems, whereas very few have addressed the three-dimensional modeling of continuous casting processes. Słota [21,22] reconstructed the cooling conditions in a crystallizer and in the secondary cooling zone for two- and three-dimensional models of pure continuous metal casting. The optimization criterion was the difference between the given and the calculated temperatures at selected points in the solid phase. Later, Nowak et al. solved the inverse boundary problem [23] and the geometry problem [24] for a three-dimensional continuous casting process with aluminum alloy.

In the current study, we propose a procedure for restoring the cooling conditions in a crystallizer and in the secondary cooling zone for a three-dimensional continuous casting process. The additional information needed to solve the inverse problem is given by temperature measurements obtained from selected points in the region considered. The direct problem that corresponds to the inverse problem is solved using the alternating phase truncation method. We employ two artificial intelligence algorithms, i.e., the ant colony optimization (ACO) algorithm [25–27] and the artificial bee colony (ABC) algorithm [28–30], to minimize a functional that describes the error of the approximate solution. We also compare the two optimization algorithms to assess their usefulness for solving problems of this type. Applications of these algorithms for solving the two-dimensional inverse problem in continuous casting were also presented in [31,32].

2. Formulation of the problem

We consider the problem of pure continuous metal casting in a vertical device that operates in an undisturbed cycle. We assume that the heat flows only in the direction perpendicular to the ingot axis. This assumption is based on the fact that the amount of heat conducted in the direction of the ingot's movement is small compared with the amount of heat conducted in the direction perpendicular to the ingot's axis [33]. We consider the apparently steady field of temperature generated during the undisturbed working cycle of the continuous casting device.

In terms of heat symmetry, the investigations are reduced to a quarter of the region. We assume that the region Ω of the ingot can be considered as a three-dimensional region, which comprises two subregions: Ω_1 as the liquid phase and Ω_2 as the solid phase, which are divided by the interphase surface Γ_g (see Fig. 1). On the boundary of region $\Omega = [0, b] \times [0, d] \times [0, z^*] \subset \mathbb{R}^3$, the following subsets are separated

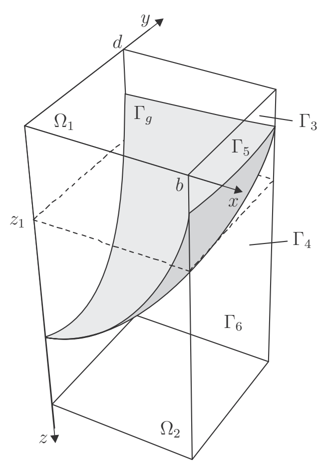

Fig. 1. Domain of the three-dimensional problem.