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Hydraulic Simulation of the Replacement of Submerged Nozzles in Slab Continuous Casters

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Abstract—A physical model is used to study the effect of submerged nozzles during their replacement on the trajectory of motion of the metal streams in the mold of a slag continuous caster in the course of casting. Recommendations are made to decrease the time of action of this factor on the ingot formation conditions.

Keywords: submerged nozzle, mold, metal stream, nozzle change time, manipulator system
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The velocity and the trajectory of the liquid steel streams in the space of the mold of a slab continuous caster with submerged nozzles, which shield the metal stream coming from a tundish, significantly affect the surface quality, the structure of the near-surface layer, and the number of internal defects in a forming ingot [1]. Therefore, the problem of ensuring stable steel streams in the mold in casting is challenging. To solve this problem, researchers performed investigations to search for the geometric parameters of submerged nozzles that can improve the uniformity of metal layer velocities in the liquid phase near the submerged nozzles and to develop electromagnetic systems for mixing and deceleration of melt streams in one or several mold zones [2]. Mathematical simulation and physical modeling methods were widely used in these investigations [3, 4]. However, there are no data on the effect of the perturbations induced by the replacement of submerged nozzles during continuous casting in long and very long series on the distribution of metal streams in the mold space. As follows from the results of timing, the time it takes for a used refractory article to be replaced is 1.5–2 min; that is, a slab can form under unstable hydrodynamic conditions in this time interval. Therefore, the purpose of this work is to obtain information on the trajectories of the liquid steel streams at the top of the mold in a slab continuous caster that form at various versions of replacing a used submerged nozzle. This information can be applied as initial data for calculating and designing the systems used for the replacement of a submerged nozzle in an automatic regime for the minimum time. For the investigation, we employed physical modeling on the laboratory setup shown in Fig. 1. It includes transparent plane models of tundish *5* and mold *8* fixed to metal structure *15*. The casing system of the tundish model consists of mechanism *3* of controlling the position of monoblock stopper *4*, which ensures a controlled flow of the liquid simulating a melt, and device *12* for replacing worn submerged nozzle *11* by duplicate nozzle *7* using special-purpose pusher *6*. The design of the mold in a slab continuous caster is characterized by the fact that a liquid flows from it through numerous small-diameter holes uniformly distributed in the bottom. As a result, a possible distortion of the picture of streams in the zone of submerged nozzles was eliminated. A model liquid was collected in a vessel with connecting branches *9* and was then moved by pump *10* in the channel of sliding shutter model *14* equipped with protective tube *13*. Compressor *16* and receiver *1* were used for blowing air, which imitated argon, into the outlet channel of the tundish model. The air flow rate was controlled with cock *2*.

The scale of modeling the casting of a slab with a cross section of 1000 × 250 mm pulled at a speed of 1–1.2 m/min was determined with allowance for the self-similarity with respect to the Reynolds number, which was Re = 1220.

To study the replacement of submerged nozzles, we analyzed two versions of their models, which are schematically shown in Fig. 2. One set included direct-flow nozzle models, and the other set, free-flow nozzle models with two side holes located in the lower part and separated by a dissector.

Experiments on the hydraulic model were performed in the following sequence. Submerged nozzle model *11* to be replaced was first placed in the guides of device *12* in line with the outlet channel of tundish model *5*. Tundish *5* and mold *8* were then filled with water to the given levels when monoblock stopper *4* was in the lower position and pump *10* was turned off. Monoblock stopper *4* was then lifted by mechanism *3*

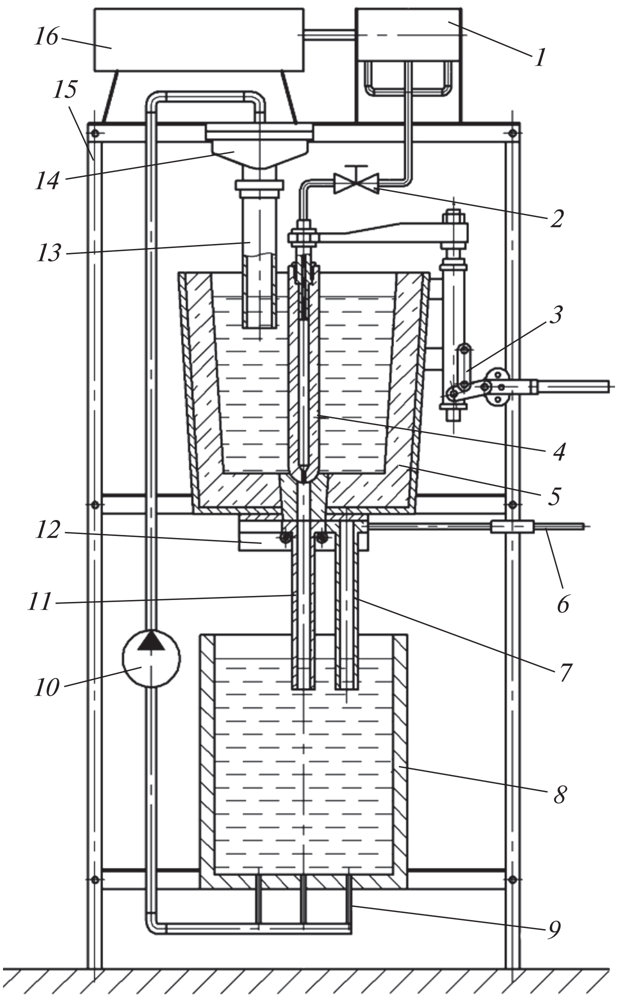

Fig. 1. Schematic diagram of the laboratory setup for modeling the replacement of submerged nozzles.

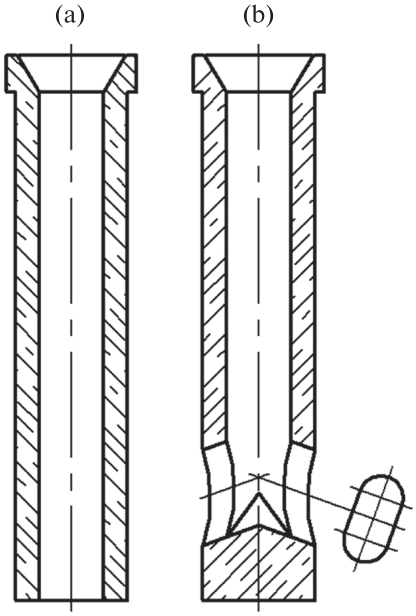

Fig. 2. Schematic diagrams of (a) direct-flow submerged nozzle and (b) free-flow closed-bottom submerged nozzle with a dissector.

and pump *10* was turned on, and constant levels of liquids in the tundish and mold models were achieved by controlling the pump rate. Compressor *16* was turned on, and air was pumped in receiver *1* and, then, in the space of monoblock stopper *4* through controlling cock *2*. Air was then trapped by the liquid stream flowing through submerged nozzle *11* into the mold model. The trajectories of the water streams trapping small bubbles were visualized due to the formation of small bubbles when pumped air reached a water stream in the mold.

The pictures of stream circulation zones were recorded using high-speed video recording and a camera placed on a support at a certain distance from the laboratory setup. The replacement of a submerged nozzle was simulated during observation. To this end, the model of a new refractory element was smoothly moved into the mold space with a special-purpose monkey and was placed in guides near the nozzle to be replaced. Using the pusher, we moved both nozzles a given distance. As a result, the new refractory element was placed in the position of casting and the used nozzle was removed from the mold space. Experiments with this sequence of operations used to replace refractory nozzles were carried out for both types of nozzles. Watching video materials under dynamic and freeze-frame conditions, we were able to detect the characteristic changes in the distributions of liquid streams in the mold model that were caused by the influence of the submerged nozzle models moved in the space to be replaced on the circulation zone of the melt imitator. The video recording frames shown in Figs. 3 and 4 illustrate the perturbations induced by the moving submerged nozzles. Some comments to these frames have to be made to understand the phenomena under study.

When a direct-flow nozzle is used under the level upon casting (Fig. 3a), the main descending current has a drop shape and a penetration depth of 300–400 mm. The ascending convective currents along the mold walls change the direction to the nozzle when the free surface of the model liquid, where no standing waves form, is reached. When the new submerged nozzle begins to move in the liquid bath of the mold model (Fig. 3b), the drop shape of the descending current changes under the action of the vortices caused by the ascending current reflected from its inclined cylindrical surface. After the new submerged nozzle is placed at the nozzle to be replaced (Fig. 3c), the symmetry of the shape of the main descending current is broken, and it shifts partly from the central vertical axis of the mold model toward its left narrow wall, which would

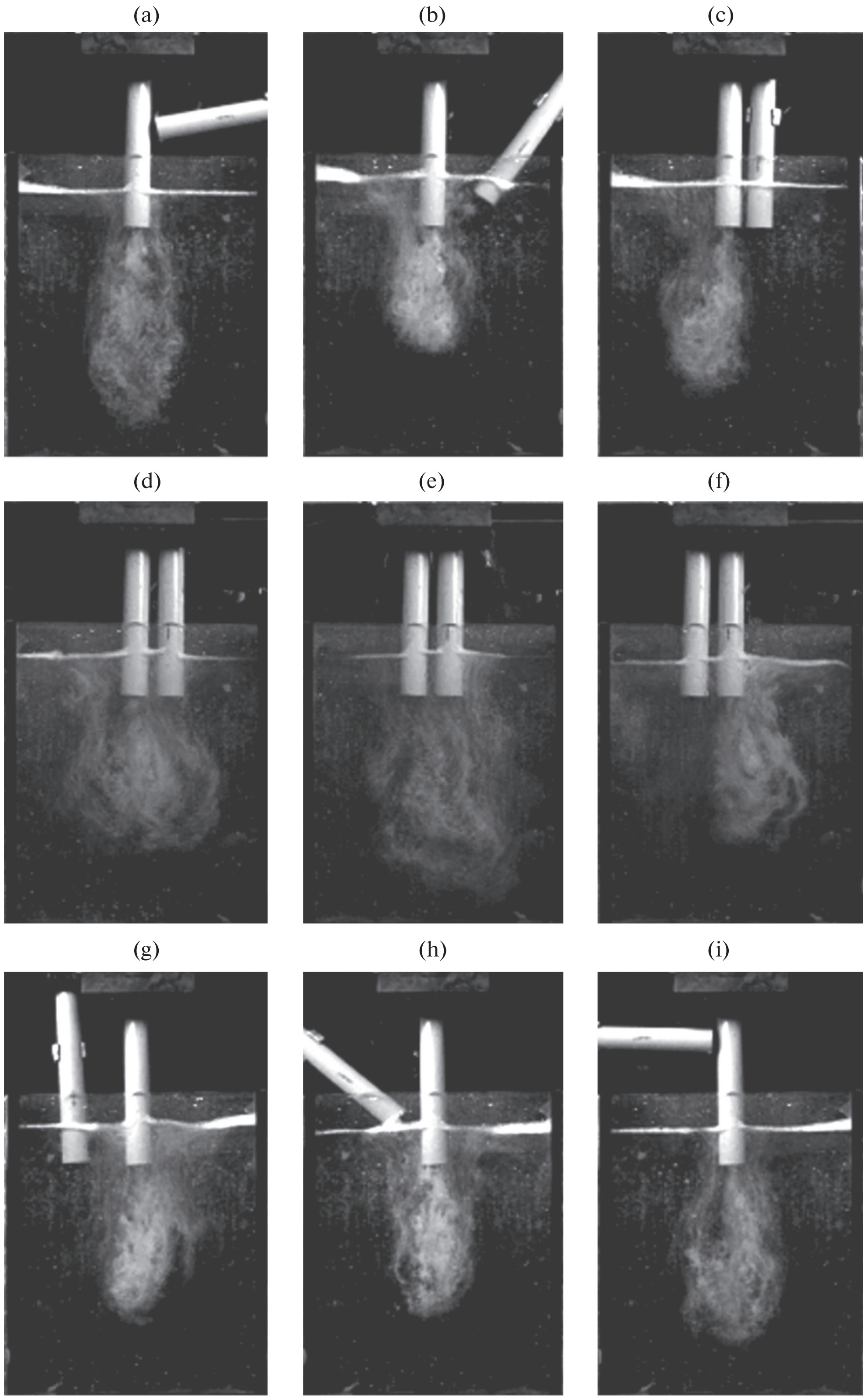

Fig. 3. Liquid stream distributions in a mold model that were observed during the replacement of a direct-flow submerged nozzle.

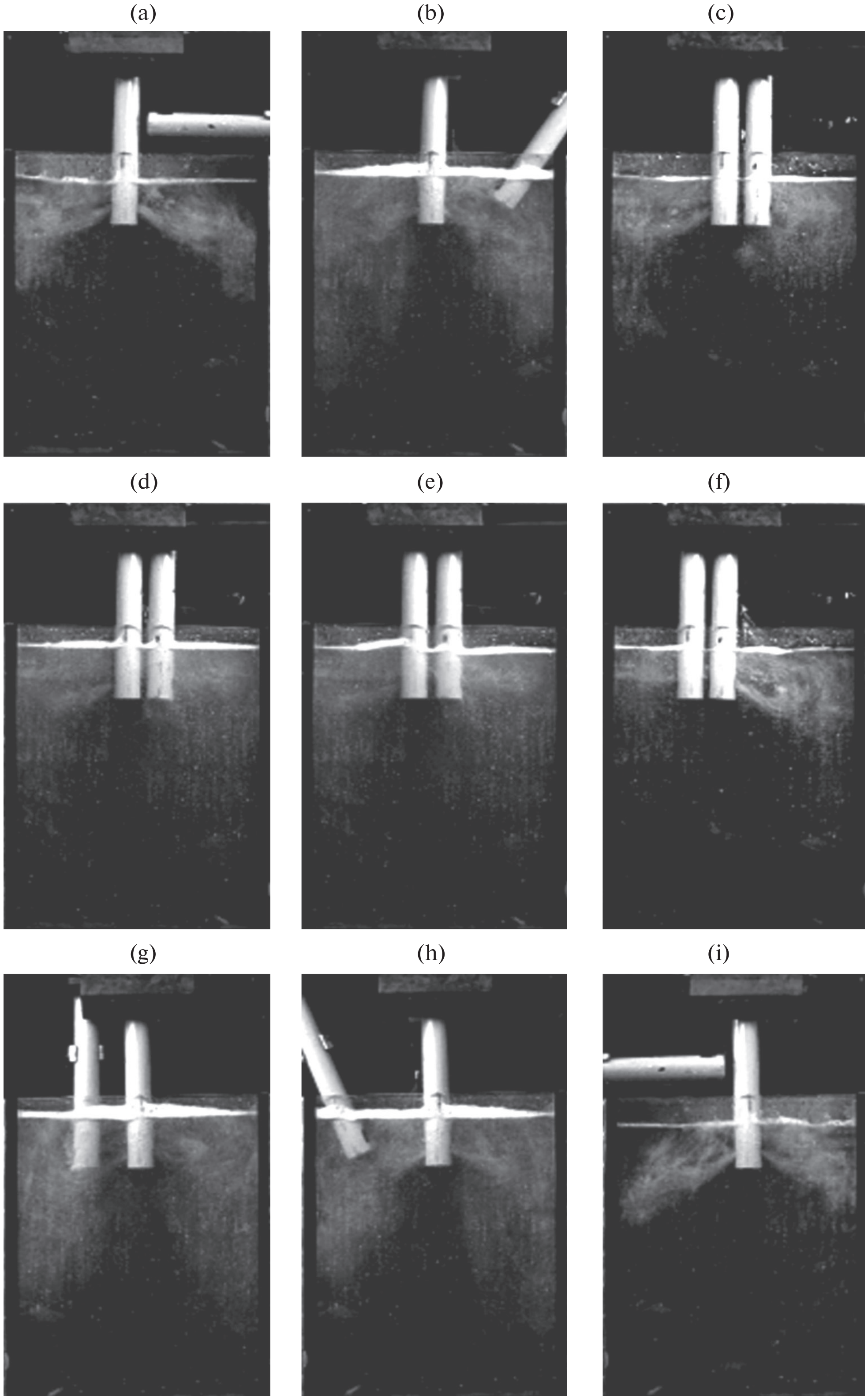

Fig. 4. Liquid stream distributions in a mold model that were observed during the replacement of a free-flow submerged nozzle with two side holes.

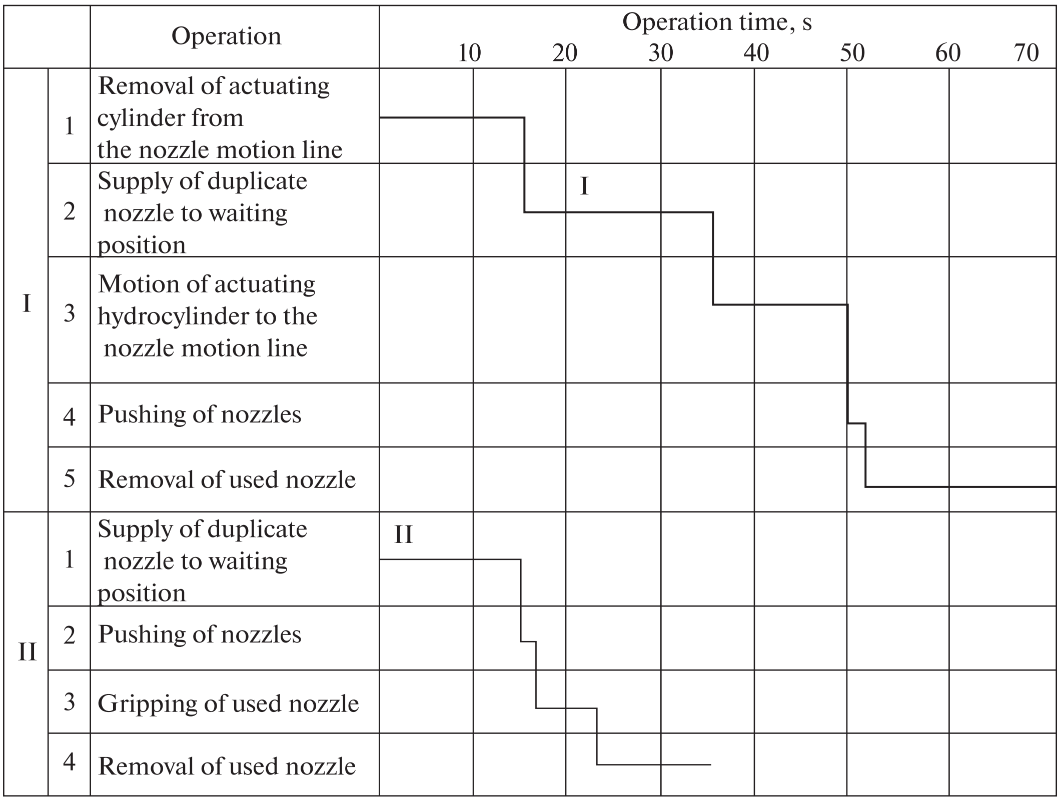

Fig. 5. Linear graphs for the rapid change of refractory submerged nozzles using (I) existing and (II) proposed systems.

destabilize the conditions of skin formation in an ingot under real conditions. At the time of the motion of the set of nozzles shown in Figs. 3d and 3e, the descending current is divided into two and standing waves form on the meniscus. The descending current has a curved trajectory within several fractions of a second.

After the new nozzle is placed in the casting position (Fig. 3f), the replaced nozzle on the left of it introduces perturbations in the circulation zone. As a result, the contour of the main descending current shifts from the central vertical axis of the mold toward its right narrow wall, and the stable conditions of skin formation in the ingot become broken. When the used submerged nozzle is moved from the mold space (Figs. 3g, 3h), the main descending current begins to restore its initial symmetry and again acquires a drop shape (Fig. 3i).

When free-flow submerged nozzles wide holes are employed, another structure of hydraulic streams is observed. This structure is caused by the existence of vortices with unidirectional oppositely directed circulations with streams along the generatrix of the cylindrical surface of the nozzle, which are located above and below the outlet holes, and by ascending streams along the narrow mold walls (Fig. 4a). The introduction of the second (duplicate) submerged nozzle in the mold space immediately breaks the symmetry of streams, since it hinders a free liquid flow from the nearest side hole in the nozzle to be replaced (Figs. 4b, 4c). In this case, the conditions of skin formation in the narrow ingot faces are noticeably different, which can influence the structure of the ingot. When the set of submerged nozzles is moved (Figs. 4d, 4e), the circulation contours near the free surface of the liquid bath disappear for a short time and standing waves form on it. After the new nozzle is displaced to the casting position, the replaced nozzle on the left of it creates obstacles to the stream flowing toward it (Fig. 4f). Under industrial conditions, this leads to nonuniform heat removal from the ingot skin that forms at the top of the mold. A similar picture of stream distribution is also observed when the replaced nozzle is removed from the mold space (Figs. 4g, 4h). Once the lower part of the used nozzle is over the free liquid surface in the mold model, the stream distribution in it becomes stable (Fig. 4i).

As follows from the aforesaid, we think that it is reasonable to change the process of changing submerged nozzles during continuous casting of slabs and to develop a new concept of systems for it implementation at the minimum time.

According to the generally accepted model of constructing a system for rapid change of submerged nozzles, it is considered as a set of interrelated and self-contained devices that ensure the following operations: the motion of a new nozzle from the position of loading on the receiving guides of the casting unit of a tundish, the pushing of this nozzle to the site of casting with simultaneous pushing of the used nozzle from the site of casting to the site of removal, and the removal of this nozzle from the working zone. The following two units are considered to be significant from the entire set of functional units: the casting unit and the pushing unit. The other units are auxiliary or are not taken into account in the manual operations of supplying a new nozzle and the removal of a used nozzle [5]. In this hierarchical model of the system of rapid change of submerged nozzles, the time auxiliary operations can be severalfold longer than that of basic operations. As a result, the time interval within which the stable steel streams in the mold of a slab continuous caster are broken and ingot formation conditions are degraded increases.

To decrease the time of residence of two submerged nozzles in the mold space during replacement, we propose to unite the casting unit of a tundish and a special-purpose manipulator so that the operations related to the motion of an actuating hydrocylinder from a working position to a parking position followed by return to the line of final motion of a used submerged nozzle are excluded (Fig. 5). In addition, a duplicate nozzle is automatically supplied, and the worn refractory elements that protect steel against secondary oxidation are automatically removed. These conditions of operation of the proposed system elements can be met if the actuating hydrocylinder is located on the manipulator rather than on the casting unit. In turn, this manipulator should be equipped with an additional grip to hold a used submerged nozzle and to impart a given motion trajectory in space to it during automatic removal from the mold space.

Thus, the results of our model studies allowed us to substantiate a new approach to creating a system for rapid change of submerged nozzles for steelmaking on a slab continuous caster in order to halve the total time of all operations and to increase the ingot-to-product yield.

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