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GAS MIXING AND CHEMICAL HOMOGENIZATION OF STEEL IN 100 T LADLE FURNACE

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The article presents numerical simulations of fluid flow and chemical homogenization of liquid steel in gas-stirred ladle with two asymmetric porous plugs. In this study mixing time is analyzed as a function of porous plug location. All calculations were carried out by commercial computer program Fluent using *k*-ε turbulence model. Results show the velocity vectors of liquid steel and tracer concentration field after alloy addition. Numerical calculations were used to get the mixing time of liquid steel as a function of gas flow rate and porous plugs location.

Key words: *steel, ladle, mixing time, mathematical modeling, fluid dynamics*

Miješanje i kemijska homogenizacija taline čelika u 100-tonskom livnom loncu. Članak predstavlja numeričke simulacije tijeka tekućine i kemijske homogenizacije tekućeg čelika u loncu s miješanjem plina pomoću asimetrično postavljenih poroznih čepova. U ovoj se studiji vrijeme miješanja analizira kao funkcija položaja poroznog čepa. Svi su izračuni provedeni pomoću komercijalnog računalskog programa Fluent koristeći *k*- ε modele turbulencije. Rezultati pokazuju vektore brzine tekućeg čelika i polje koncentracije obilježenih indikatora nakon dodavanja legure. Numerički su proračuni upotrijebljeni za dobivanje vremena miješanja tekućeg čelika kao funkcije brzine toka plina i položaja poroznog čepa.

Ključne riječi: *čelik, livni lonac, vrijeme miješanja, matematičko modeliranje, dinamika fluida*

INTRODUCTION

The presented paper describes the results of numerical simulations of gas injection to the metal bath during the ladle process and the dissipation of the marker after the introduction of the alloy addition. The distribution of the vectors of liquid steel velocities in the ladle furnace has been presented, and then marker mixing time has been determined. The simulations of alloy addition dissipation were carried out for two cases corresponding exactly to the conditions of industrial experiments carried out. The industrial tests were carried out on the ladle furnace using an identical mass of the alloy addition, but two different argon flow rates. The gas was blown through an asymmetrical porous block incorporated in the ladle bottom. The facility under investigation is a 100 ton ladle furnace. The furnace is supplied by a 15 MVA-power transformer.

MATHEMATICAL MODEL

The model of steel motion in the ladle relies on the system of differential equations [1, 2].

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As the flow examined is a turbulent flow, its description in the classical turbulence modeling (RANS) formulation includes a stress tensor encompassing the stresses resulting from molecular viscosity and the turbulent stresses - Reynold's stresses. Reynold's stresses cannot be expressed in a strict manner as a function of averaged flow parameters and require to be modeled. In the performed computation, the *k*-ε turbulence model was employed, which is widely used in engineering problems. The coefficient of turbulent viscosity, μ_T, is defined by two functions: the kinetic energy of turbulence and the rate of turbulence energy dissipation according to relationship [3]:

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon}, \tag{1}$$

where:

k - kinetic turbulent energy,
ε - dissipation rate.

INITIAL AND BOUNDARY CONDITIONS

The argon injected to the steel takes on the form of gas bubbles, whose motion in the liquid is described by the discrete phase model (DPM) [4].

The boundary conditions of the model applied are shown in Figure 1.

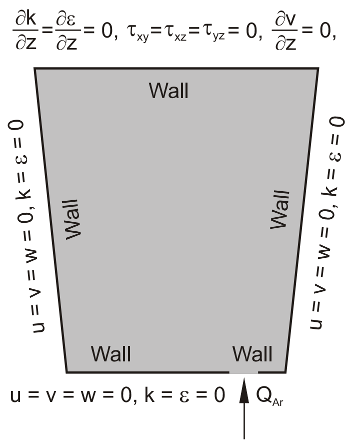


Figure 1. **Boundary conditions of the mathematical model**
Slika 1. **Granični uvjeti matematičkog modela**

The computations were performed using the Fluent commercial code relying on the control volumes method.

Table 1. **Value and location of heat losses allowed for in computation**
Tablica 1. **Vrijednost i područja toplinskih gubitaka koji su dopušteni pri proračunu**

Loss location	Heat transfer mode	Value of lost heat flux / $kW \cdot m^{-2}$
Metal table	radiation	12,5
Ladle walls	conduction	5,0
Ladle bottom	conduction	5,0

COMPUTATION RESULTS

Determination of the distribution of velocity and temperature vectors

The numerical computation of the distribution of steel velocity vectors were performed for two cases: with and without argon injection, respectively. Guide by the data recommended in references [5 - 7], the heat flux values were set as the boundary conditions, respectively for particular ladle planes. These values are given in Table 1.

When considering Case 1 - without argon injection, it can be seen that the main role in forming the bath movement is played by natural convection currents.

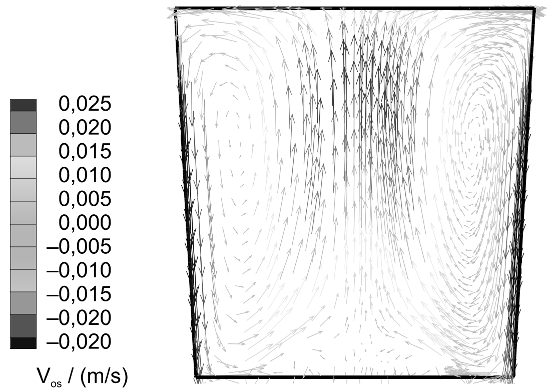


Figure 2. **Distribution of steel velocity in the ladle after 5 minutes of "holding" the ladle [8]**
Slika 2. **Raspored brzine čelika u livnom loncu nakon 5 minuta "držanja" lonca [8]**

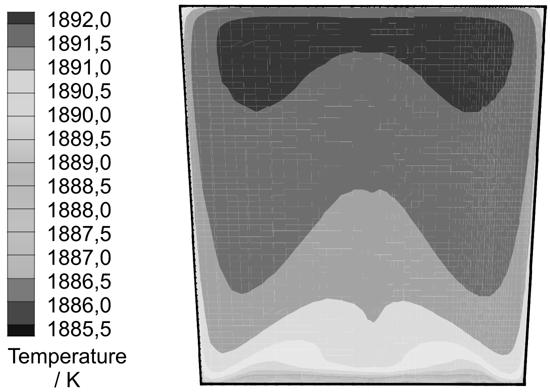


Figure 3. **Steel temperature field after 5 minutes of "holding" the ladle [8]**
Slika 3. **Polje temperature čelika nakon 5 minuta "držanja" lonca [8]**

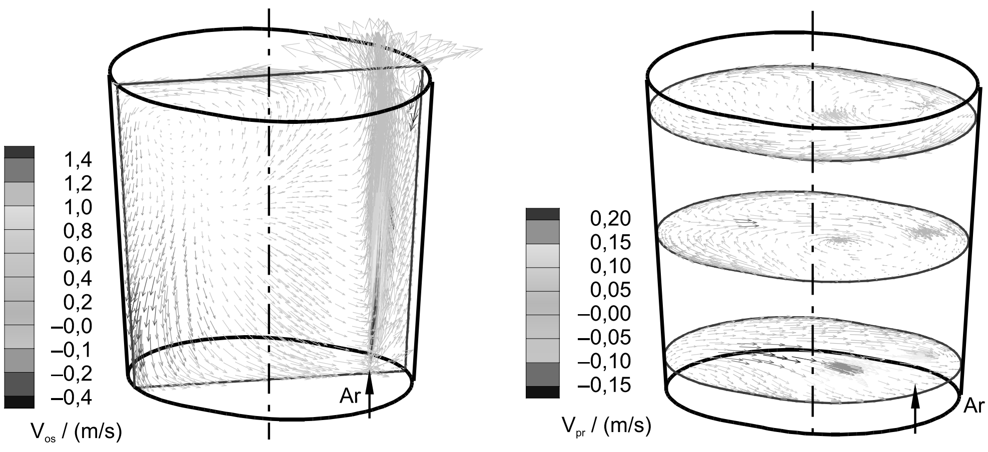


Figure 4. **Distribution of velocity vectors on selected planes of the ladle in a steady state (Q_{Ar} = 330 dm^3/min) [8]**
Slika 4. **Raspored vektora brzine na odabranim ravninama lonca u statičnom stanju (Q_{Ar} = 330 dm^3/min) [8]**

The liquid steel movement is induced by temperature gradients occurring in the bath. Figure 2. shows the metal velocity distribution that will establish after 5 minutes of "holding" the ladle. Figure 3., on the other hand, illustrates the temperature field corresponding to this situation.

Table 2. **Conditions of simulations carried out**
Tablica 2. **Uvjeti provedenih simulacija**

Simulation	Ar flow rate / $dm^3 \cdot min^{-1}$	Marker	Mass of the marker / kg
S1	330	Cr	858
S2	500		

Table 3. **Properties of the media adopted in the simulation computation on the basis of [9]**
Tablica 3. **Svojstva materijala prilagođenog u simulaciji izračunatoj na bazi [9]**

Medium at a temperature / K		Density σ / $kg \cdot m^{-3}$	Specific heat C_p / $J \cdot kg^{-1} \cdot K$	Thermal conductivity λ / $W \cdot m^{-1} \cdot K$
Liquid steel	1860	6898,7	824,50	39,80
	1895	6868,4	824,62	39,39
Liquid FeCr	1860	6320,0	918,86	59,96
	1895	6294,7	930,66	59,53
Ar	298	1,6341	520,64	0,0158

The steel of higher temperature is raised by convection currents formed, whereas the cooled steel "flows" down the ladle walls towards the ladle bottom. This causes a gradual "cooling down" of the steel in the vicinity of the bottom and the formation of a characteristic, layered distribution

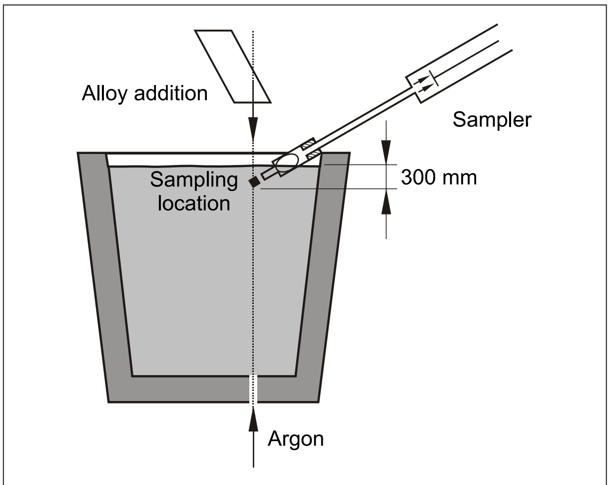


Figure 5. **Illustration of the method of introducing the addition and taking samples for chemical analyses**
Slika 5. **Prikaz metode uvođenja dodavanja i uzimanja uzoraka za kemijske analize**

of bath temperature, as can be seen in Figure 3. The deformation of the layers in the axial zone is the confirmation of the existence of a convection mechanism of movement of the bath in a stagnant condition.

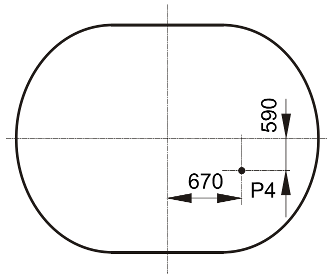


Figure 6. **Probe point localization**
Slika 6. **Područja uzimanja proba**

A different situation is in Case 2. Here, when the metal movement is forced by injecting argon to the bath, forced convection caused by the circulatory motion of the steel starts to pre-

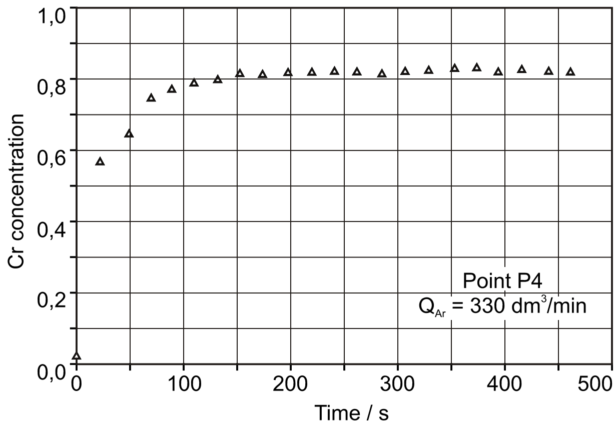


Figure 7. **Cr concentration in the metal bath during agitation with argon [8]**
Slika 7. **Koncentracija Cr u metalnoj kupki tijekom propuhivanja argonom [8]**

dominate, changing the distribution of temperature. This becomes uniform within almost entire facility, with any differences observed being negligible. The distribution of

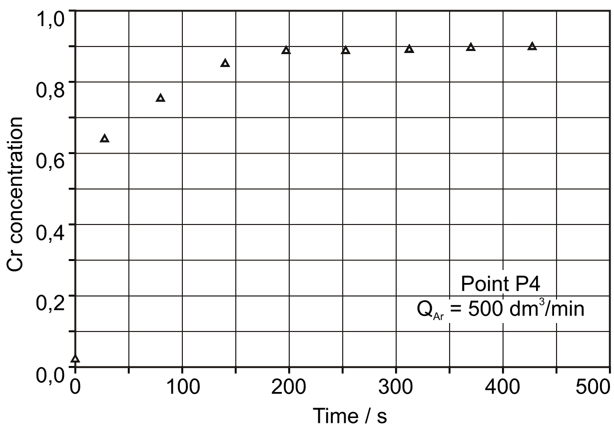
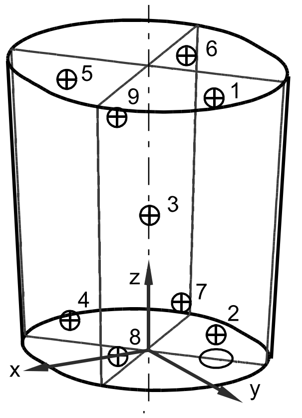


Figure 8. **Cr concentration in the metal bath during agitation with argon [8]**
Slika 8. **Koncentracija Cr u metalnoj kupki tijekom propuhivanja argonom [8]**



Nr	Localisation (x, y, z) / mm
1	(–590; 670; 2530)
2	(–590; 670; 300)
3	(0, 0, 1415)
4	(590; –670; 300)
5	(590; –670; 2530)
6	(–670; –590; 2530)
7	(–670; –590; 300)
8	(670; 590; 300)
9	(670; 590; 2530)

Figure 9. **Monitors localizations**
Slika 9. **Postavljanje monitora**

steel velocity vectors, as the steel is blown with argon at a rate of 330 dm^3/min, is illustrated in Figure 4.

Determination of the distribution of marker concentration and the time of metal bath homogenization

The next stage was to perform numerical simulations corresponding to the industrial experiments carried out. In the tests, an attempt was made to determine the mixing time (τ_m) for the marker after introducing the alloy addition to the steel, by recording its variations in time.

The values of the basic parameters of the performed simulations and the physicochemical properties of fluid applied in industrial tests are given in Tables 2. and 3.

In the industrial experiments, variations in the concentration of the marker introduced to the steel were monitored by recording chemical composition of steel in specified time intervals. As the dissipation of the marker added is spatial in character, it is important for (numerical) verification to accurately identify the location of introducing the alloy addition and the sampling location. The diagrams below (Figures 5. and 6.) indicate the locations of introducing the alloy addition and taking metal samples.

The role of the marker was performed by chromium introduced with ferrochromium. The average sampling interval was approx. 22 s. The sampling frequency and probe immersion depth were accomplished in a comparable and rhythmical manner owing to the mechanical drive of the probe. The results obtained from the experiments carried out are shown in Figures 7. and 8. Part of the tests has

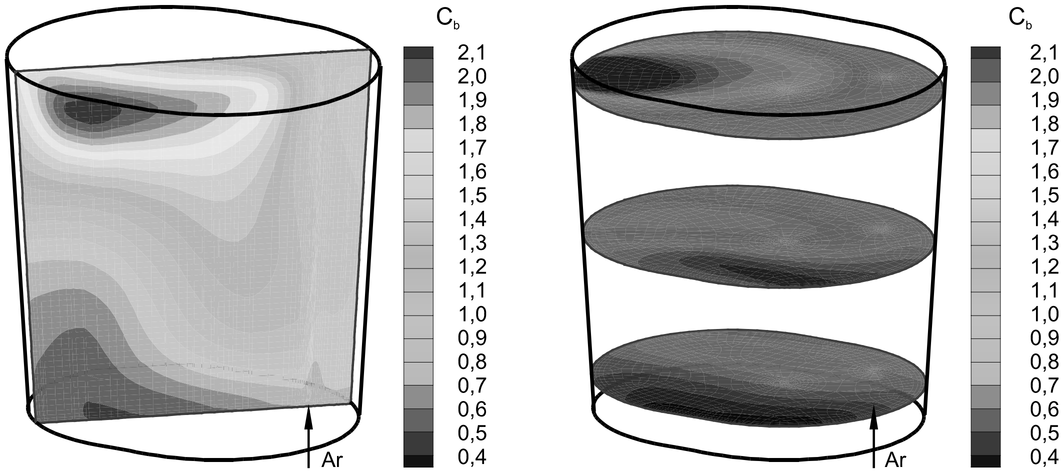


Figure 10. **Contour-line map of dimensionless chromium concentration after 80 sec. from addition introduction (Q_{Ar} = 330 dm^3/min) [8]**
Slika 10. **Mapa konturnih linija bezdimenzijske koncentracije kroma 80 sekundi od uvođenja dodatka (Q_{Ar} = 330 dm^3/min) [8]**

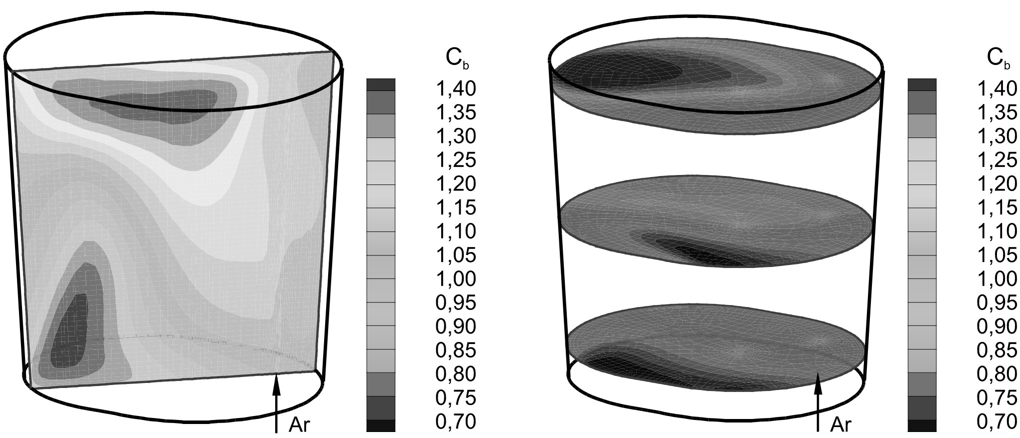


Figure 11. **Contour-line map of dimensionless chromium concentration after 120 sec. from addition introduction (Q_{Ar} = 330 dm^3/min) [8]**
Slika 11. **Mapa konturnih linija bezdimenzijske koncentracije kroma 120 sekundi od uvođenja dodatka (Q_{Ar} = 330 dm^3/min) [8]**

already been the subject of publication [10]. The zero time represents the time of ending the addition introduction.

For the numerical simulation of the ladle process, further 8 monitors were applied (in addition to the experimental monitoring point), which were positioned both in the regions of expected high velocity gradients, and in the so called dead regions of the ladle. The arrangement of monitors, together with their coordinates, is shown in Figure 9.

For the transient conditions of bath movement, computations were done, which allowed the evaluation of variations in marker concentration in the steel during its blowing with argon. The computations were carried out with a time step of 0.1 sec. The computations were carried out on a double-processor (2 × 2,0 GHz) server.

Figures 10. - 12. show the obtained distributions of chromium concentration in the ladle blown with argon at a rate of 330 dm^3/min for respective times.

Two steel bath homogenization levels, resulting from the metallurgical experience, were adopted: the first level - 95 % ($C_b \in \langle 0,95; 1,05 \rangle$) for mass-usage steels, and the second level - 99.5 % ($C_b \in \langle 0,995; 1,005 \rangle$) for quality steels. When using this criterion, we will find that the dissipation of chromium in the conditions, as shown in Figures 10. - 12., cannot be regarded as preliminary completed after 180 seconds, since we notice regions in Figure 12., which correspond to the conditions $C_b < 0,95$ and $C_b > 1,05$.

Figures 13. and 14. indicate that the time of homogenization depends clearly on the monitoring location. The

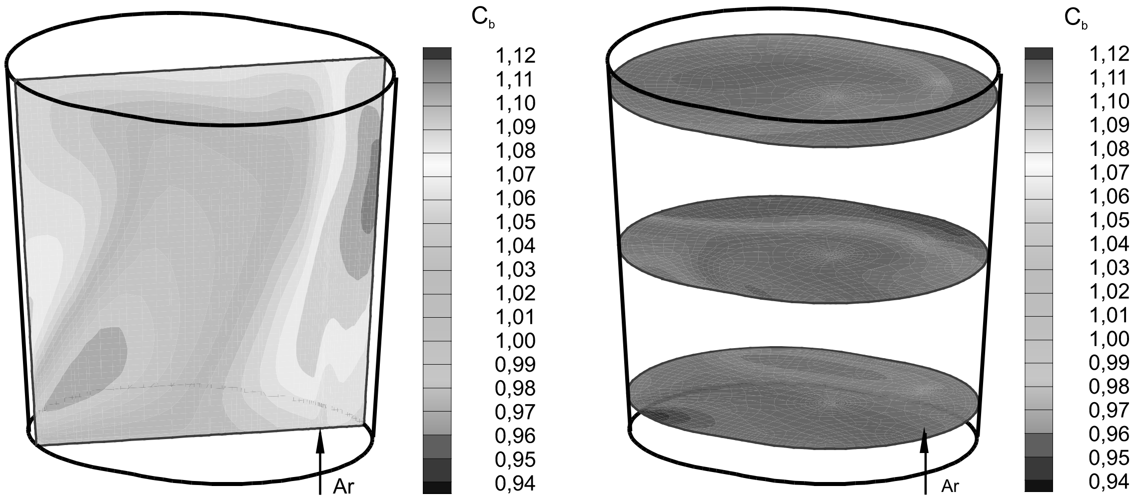


Figure 12. **Contour-line map of dimensionless chromium concentration after 180 sec. from addition introduction (Q_{Ar} = 330 dm^3/min) [8]**

Slika 12. **Mapa konturnih linija bezdimenzijske koncentracije kroma 180 sekundi od uvođenja dodatka (Q_{Ar} = 330 dm^3/min) [8]**

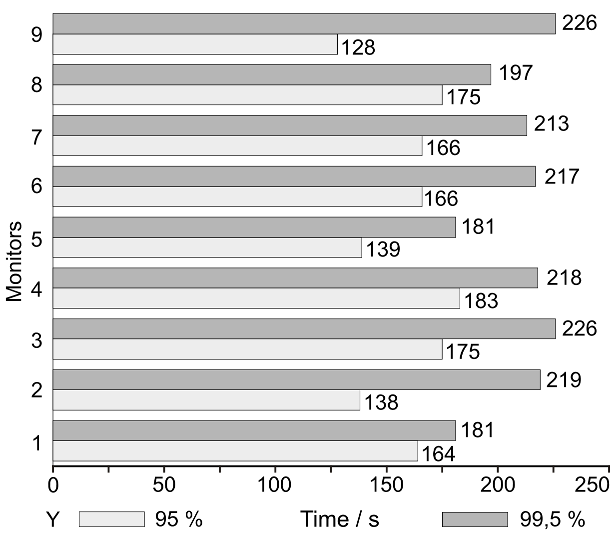


Figure 13. **Mixing time for different monitors - simulation S1 [8]**

Slika 13. **Vrijeme miješanja za različite monitore - simulacije S1 [8]**

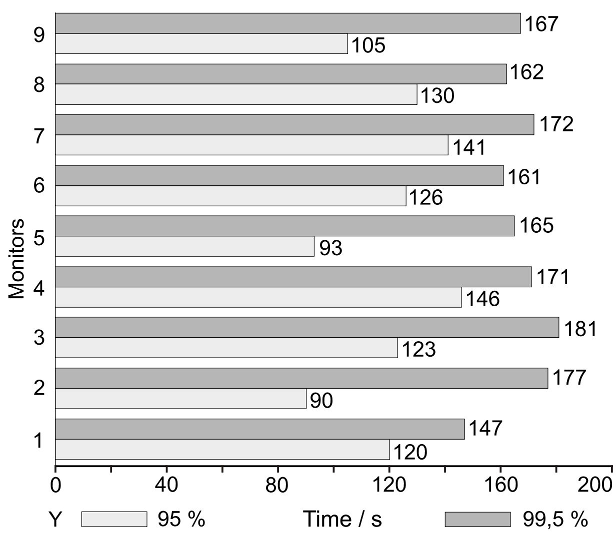


Figure 14. **Mixing time for different monitors - simulation S2 [8]**

Slika 14. **Vrijeme miješanja za različite monitore - simulacije S2 [8]** monitoring point (1), corresponding to the sampling location in the industrial facility, is not representative for the determination of the steel homogenization time. For the determination of this time, the longer of the times should be taken. For both simulations, the time of homogenization in the entire ladle was determined. Time difference, in relation to the longest time from 9 monitors, was below 20 seconds for both cases.

CONCLUSIONS

Numerical modeling applied to the determination of temperature distribution in liquid steel yields very precise results, owing to which it can be used for the identification of the technical parameters of the ladle.

The mathematical model makes it possible, with little time expenditure, to determine the distribution of steel velocity vectors, the distribution of steel temperatures and homogenization time.

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