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MODEL BASED DIAGNOSIS OF LADLE REFRACTORY LINING

DIJAGNOSTIKA VATROSTALNE OBLOGE LIVAČKOG LONCA NA BAZI MODELA

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- thermal modelling
- numerical modelling
- service life

Ključne reči
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- termičko modeliranje
- numeričko modeliranje
- radni vek

Abstract

Knowledge of the condition and properties of refractory brick on the roof and sidewalls is essential when assessing the stability and integrity of furnace. Nondestructive testing and monitoring of the refractory lining would lead to better safety, longer service life of the vessels, controlled maintenance and increased production. The equipment surface temperature appears to be a reliable indicator of the refractory condition.

Infrared cameras are a perfect solution for a contactless monitoring during operation. Visual evaluation, thermal modelling based on thermal couple readings and mathematical simulations and infrared thermography are used for thermal insulator thickness estimation. Non-destructive testing techniques are the preferable methods to provide details about the condition of existing structures.

As a step towards predictive maintenance procedure realisation of high temperature equipment, mathematical modelling of heat transfer in refractory lining has been undertaken. A numerical model is used for prediction of the wall temperature fields during the operation depending on wear thickness and used materials. The calculated lining temperature fields in combination with the results of temperature measurements can be used to analyse the wear rates of the equipment.

Izvod

Poznavanje stanja i osobina vatrostalne cigle na krovu i zidu (ozid) je od velikog značaja kod procene stabilnosti i integriteta peći. Ispitivanje bez razaranja i praćenje vatrostalne obloge pružilo bi veću sigurnost, produžilo radni vek posuda, omogućilo bi kontrolisano održavanje i povećalo proizvodnju. Temperatura površine opreme se pokazuje kao pouzdani indikator stanja vatrostalnosti obloge.

Infracrvene kamere su odlično rešenje za beskontaktno praćenje u toku rada. Vizuelna ocena, termičko modeliranje na bazi očitavanja termoparova, matematičke simulacije i infracrvena termografija se koriste za procenu debljine izolacije. Metode ispitivanja bez razaranja su preporučene metode kojima se dobija detaljan uvid u stanje postojećih konstrukcija.

Kao korak ka realizovanju procedura u predviđanju održavanja visokotemperaturske opreme, izvedeno je matematičko modeliranje prenosa toplote u vatrostalnim oblogama. Primenjen je numerički model za predviđanje temperaturskih polja u zidu u uslovima rada, u zavisnosti od istrošenosti debljine i korišćenih materijala. Proračunata temperaturska polja obloge u kombinaciji sa rezultatima izmerenih temperatura se mogu upotrebiti za analizu brzine trošenja opreme.

INTRODUCTION

The processes in industrial furnaces require extremely high temperatures for processing their products. Depending on the process, temperatures can reach up to 1650°C or higher in some cases. Industrial processes such as steel making and silicate manufacturing all involve extremely high temperatures in their process. Refractory and castable linings are used in construction of industrial furnaces, ladles and vessels as building materials and thermal insulators in order to protect the integrity of the vessels.

Refractory linings in metallurgical furnaces undergo deterioration and wearing with time caused mainly by thermal stress and chemical attack resulting in loss of heat transfer capability. Failure of the lining is dangerous and could affect the structural integrity of the furnace.

Knowledge of refractory thickness and lining condition is crucial in operation and maintenance decisions. Visual evaluations, thermal modelling based on thermal couple drilling readings or on the mathematical modelling of heat transfer in combination with infrared thermography measurements can be used for thermal insulator thickness estimations. Non-destructive testing techniques are preferable methods to provide details on the condition of existing structures.

Liquid steel, the production of which starts in a converter or an electric furnace, is tapped into a ladle through a furnace gate. Further refinement and chemistry of molten steel required to produce a high-grade steel, such as a vacuum treatment of the liquid steel takes place exclusively in the ladle. After passing the ladle's secondary metallurgy process, the ladle's content is sent to a continuous casting machine. Then the hot steel is casted from the tundish to the continuous casting machine moulds, channelled through tundish slide gate valves which assure an accurate level control of the moulds for the steel.

Ladles are huge containers used in steelworks to transport the molten steel to other production stages. The ladles are covered by refractory materials that are needed to withstand molten metal temperatures during the casting process. Their quality and performance features are vital to a clean and safe production process. Refractory materials are heat proof, but also thermal shock-sensitive. If they are not exchanged timely, the ladle will burst and all quantity liquid steel will gush out in the foundry. The ladle's surface temperature appears to be a reliable indicator of the refractory's condition. Consequently, infrared cameras are a perfect solution for a contactless monitoring of the ladle during operation.

Finding hot spots is one thing, but assessing them is another issue; inspection results have to be classified and put into some kind of formal structure to allow a decision about how - and especially when - to take corrective action. In the practice the following severity criteria for industrial installations are suggested:

- Class "A" – A very serious anomaly that requires immediate attention.
- Class "B" – A serious anomaly that requires attention as soon as possible.
- Class "C" – An anomaly that requires monitoring and a check-up at the earliest convenient time.

Nondestructive testing and contactless monitoring of the refractory lining in combination with suitable corrective events would lead to better safety, longer service life of the vessels, controlled maintenance and increased production.

The diagnostic system and including the infrared surveys can aid to fulfil these requirements. For example the predictive maintenance is one of the many possibilities for saving investments, spare parts and manpower. Therefore, condition monitoring aiding predictive maintenance based on complex diagnostic system (online and offline –routes - complex analysis based on mathematical models) has also become more and more important within the last years. Thus, the system not only enhances operational safety, but also optimizes refractory exchange while minimizing costs: a built-in trending function calculates the expected thermal performance and consequently the life cycle of the refractory material.

MATHEMATICAL MODEL

As a step of towards predictive maintenance procedure realisation, a mathematical modelling of heat transfer in refractory lining has been undertaken. In this paper a numerical model is used for prediction of the 120 t ladle wall temperature fields during the operation, depending on wear thickness and used materials.

According to thermal conditions, mathematical models can be classified in three groups:

- steady-sate thermal models /2/;
- transient thermal models /3, 4/;
- thermal models based on experimental analytical equations /5/.

The present model has been developed in two stages. In the first step, a model based on steady-state thermal conduction is developed, followed by a second model based on transient thermal conduction for charged ladles.

In the mathematical model, the ladle work is subdivided into different working periods:

- drying and preheating of the ladle after relining,
- break between preheating and charged state (5 min),
- charging with liquid steel (5 min),
- period of charged ladle with casting (120 min),
- empty state (30 min),
- intermediate preheating (60 min).

The ladle lining consists of inner refractory lining of high-alumina mass (0.215 m), heat insulating lining of fireclay (0.065 m), and steel shell (0.02 m), Fig. 1.

The lining wear has been simulated for three depths, as they are presented in Fig. 2:

- Lining wear with depth h_1 = 0.100 m – liquid steel is in contact with the high-alumina mass. This case corresponds with Class "C" from the above-indicated criteria – an anomaly that requires monitoring and a check-up at the earliest convenient time.
- Lining wear with depth h_2 = 0.15 m – liquid steel is in contact with the high-alumina mass but after casting, the ladle have to be repaired. This case corresponds with Class "B" – a serious anomaly that requires attention as soon as possible.
- Lining wear with depth h_3 = 0.2 m – liquid steel is still in contact with the high-alumina mass but the ladle have to be changed immediately. This case corresponds with Class "A" – a very serious anomaly that requires immediate attention.

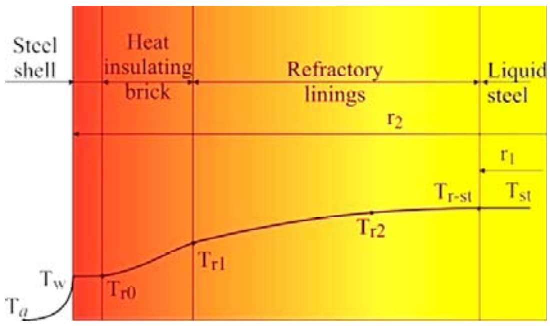


Figure1. Scheme of the ladle lining in steady-state thermal conditions.
Slika 1. Šema obloge lonca u uslovima stacionarnog termičkog stanja.

In Fig. 2, $T_w(h_1)$, $T_w(h_2)$ and $T_w(h_3)$ are the outer surface temperatures in the field of lining wear with depths h_1, h_2, h_3, respectively, and T_w is the outer surface temperature in the fields without wear.

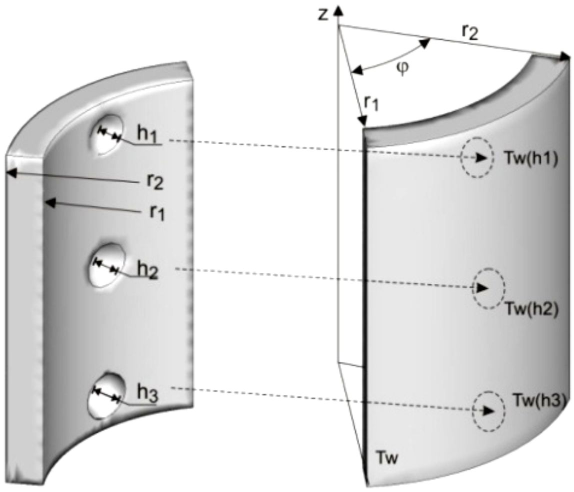


Figure 2. Scheme of ladle lining wears.
Slika 2. Šema istrošenosti obloge lonca.

The transient heat transfer can be described by the Fourier differential equation:

$$\rho c\frac{\partial T}{\partial \tau}=\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(\lambda\frac{\partial T}{\partial \phi}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right), \quad (1)$$

where: T is temperature (°C); λ is heat conductivity (W/mK); c is specific heat (kJ/kgK); ρ is density (kg/m^3); r is the radius (m); z, r and φ are coordinates; τ is time (s).

The transient thermal model has been developed using the following boundary conditions:

1. For the inner lining wall:

$$T(z,\phi,\tau)\big|_{r=r_1}=T_{r-st}(\tau) \quad (2)$$

where: $T_{r-st} = f(\tau)$ is the temperature of the contact area between the inner wall of refractory lining and liquid steel (°C); r_1 is the radius of inner lining area (m).

2. For the outer wall to the environment:

$$\lambda\left(T\right) gradT(z,\phi)\big|_{r=r_2}=\alpha_\Sigma\left(T_w-T_a\right) \quad (3)$$

$$\alpha_\Sigma=\alpha_c+\alpha_r \quad (4)$$

where: r_2 is the radius of outer surface (m); T_a is the temperature of the environment (°C); α_Σ is the heat transfer coefficient from the outer surface to the environment (W/m^{2}K); α_c and α_r are convective and radiant components of the heat transfer coefficient, $\alpha_r = q_r/(T_w - T_a)$; q_r is the resultant heat flow from the outer surface to the environment (W/m^2).

In the numerical model, T_{r-st} is a function of time. Levels of this temperature during the time and according to ladle work and different working periods are presented in Fig. 3.

The solutions of the differential equations at the applied boundary conditions were obtained using the finite element method. The transient thermal model is used for calculations and predictions of temperature distribution for abovementioned wear values and heat losses in the ladle, depending on the number of charges.

INVESTIGATION

The calculation of temperature distribution was made simultaneously using a steady-state model and transient model. Steady-state thermal conditions are found in the ladle lining, when the melted steel remains in the ladle over an extended period and when the ladle is exposed to preheating or intermediate preheating over an extended period. Therefore the steady-state thermal model is used to determine the initial conditions.

The steady-state thermal ladle model can be used for calculations and predictions of temperature distribution in the ladle lining at the end of the charged state /4/. But the temperature distribution during the technological operations in the ladle, as function of time, cannot be calculated from the steady-state thermal ladle model. The real heat flux in the ladle lining is unsteady and changes with time, and the thermal ladle model has to be based on transient thermal conduction.

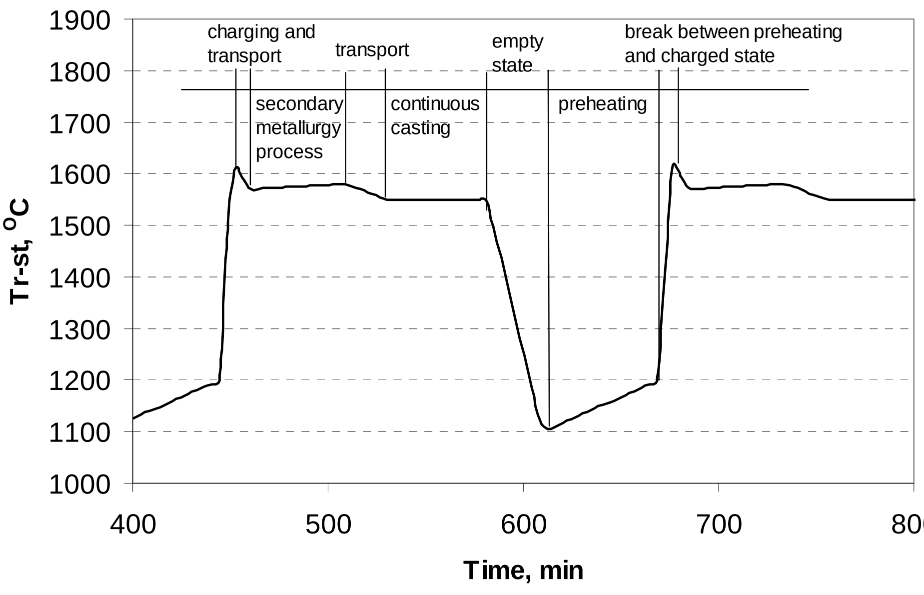


Figure 3. Temperature variation during the technological cycle.
Slika 3. Temperaturne varijacije u tehnološkom ciklusu.

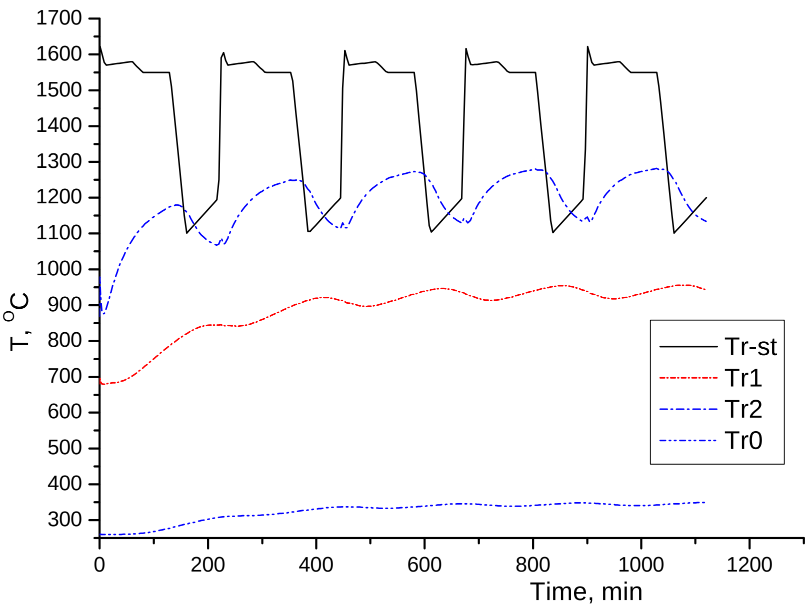


Figure 4. Temperature distribution of ladle wall during first five charges of the ladle. Distance from inner wall surface: T_{r0} (280 mm); T_{r1} (215 mm); T_{r2} (100 mm).
Slika 4. Temperaturna raspodela zida lonca tokom prvih pet punjenja. Rastojanje od unutrašnje površine zida: T_{r0} (280 mm); T_{r1} (215 mm); T_{r2} (100 mm).

The calculated temperature distribution from the transient model is presented in Fig. 4, whereas the temperature symbols are presented in Figs. 1 and 2. The temperature field of the ladle wall is illustrated by T_{r0}, T_{r1}, and T_{r2} for different distances from the inner wall surface. The calculated temperature variation of the outer surface in the fields of different depths of wear is presented in Fig. 5. The temperature redistribution on the outer surface at 396 and 896 min is presented in Fig. 6.

From Figs. 4 and 5 it is obvious that the maximal heat accumulation is observed during the first four charges and after that temperature variations are in a constant boundary.

Figure 4 shows that the temperature field changes in a lining layer of a thickness of about 220 mm.

It can be seen from Fig. 5, that during the continuous casting, the outer surface temperature in the fields of the wear with depth $h_1 = 0.20$ m is above 410°C. These values for wears with depths $h_2 = 0.15$ m and $h_3 = 0.1$ m are 365°C and 350°C, respectively, and for the fields without wear, $h = h_0 = 0$, the outer temperature T_w is higher than 336°C. These values and predicted for the temperature of steel $T_{st} =$ 1560°C and $T_{st} = 1570$°C are summarized in Table 1, where $\Delta T = T_w(h_i) - T_w$.

Obviously at temperature differences on the surface, $\Delta T > 74$°C, the ladle must be changed immediately.

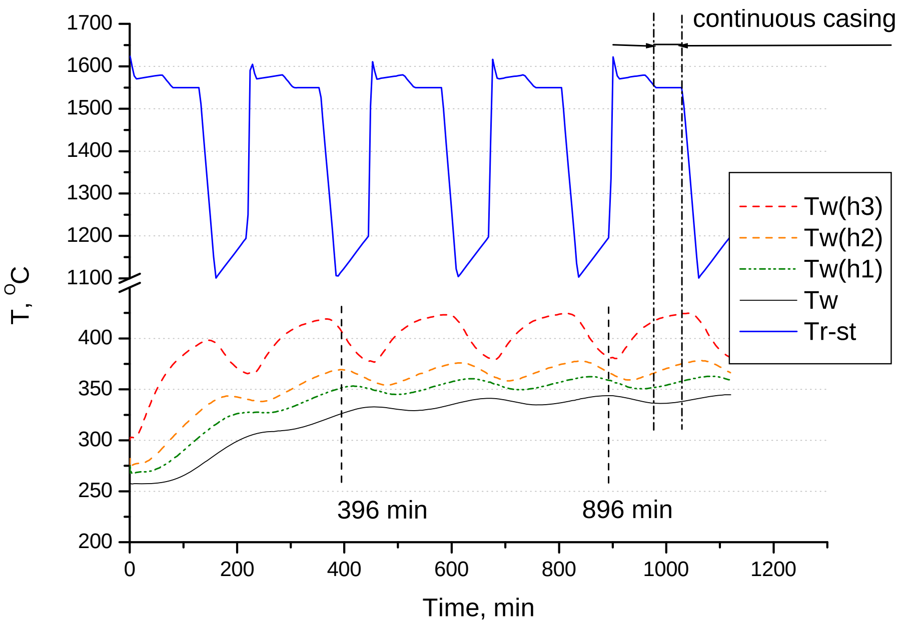
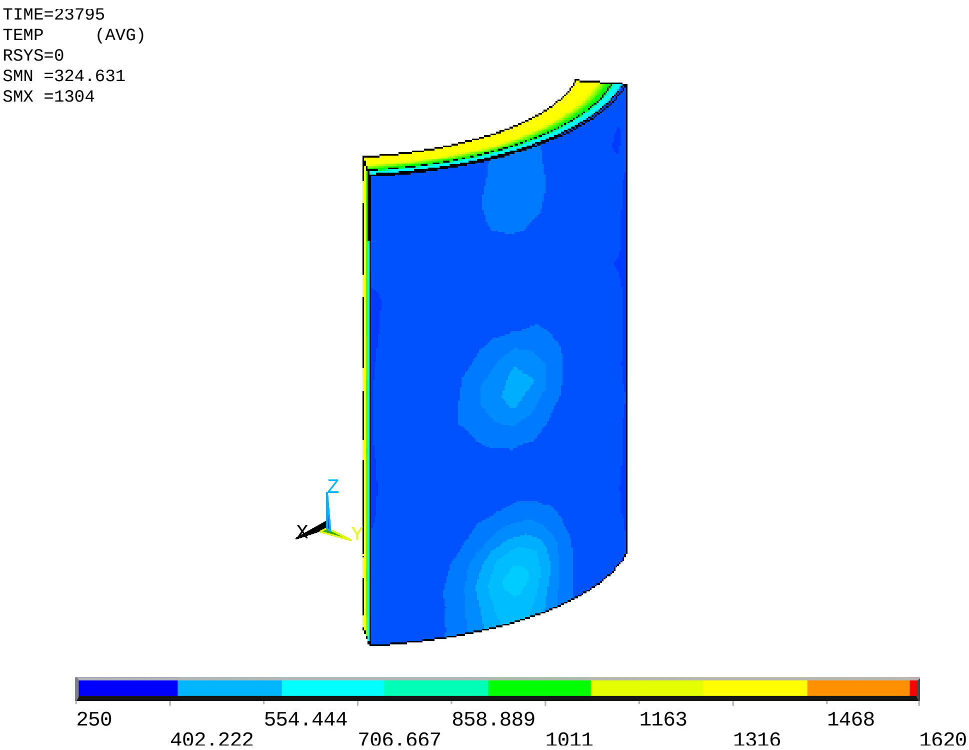


Figure 5. Temperature variation for different points of the surface.
Slika 5. Promena temperature za različite tačke na površini.

a.



b.

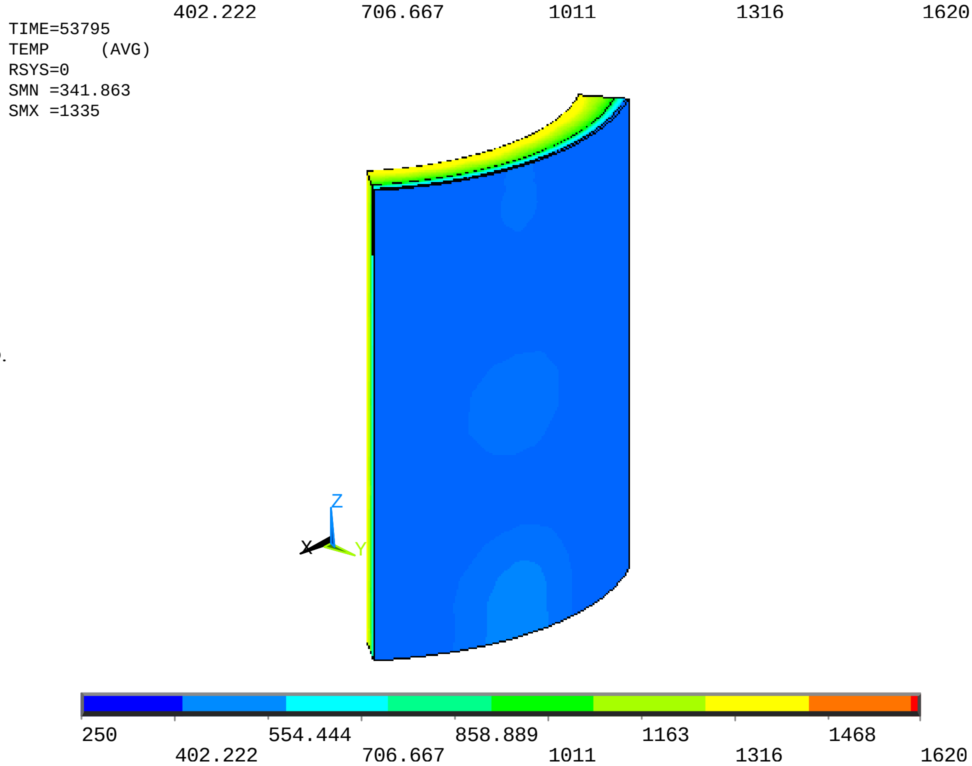


Figure 6. Temperature fields of the outer surface at: a) 396 min; b) 896 min.
Slika 6. Temperaturna polja na spoljašnjoj površini posle: a) 396 min.; b) 896 min.

Table 1. Temperature of the surface during continuous casting.
Tabela 1. Temperatura površine tokom kontinualnog livenja.

	i	h_i (m)	Criteria for corrective action	T (°C)					
				T_{st} = 1550°C		T_{st} = 1560°C		T_{st} = 1570°C	
			Class	$T_w(h_i)$	ΔT	$T_w(h_i)$	ΔT	$T_w(h_i)$	ΔT
T_w	0	0	–	336		338		340	
$T_w(h_1)$	1	0.1	“C”	350	14	353	15	356	16
$T_w(h_2)$	2	0.15	“B”	365	29	367	29	369	29
$T_w(h_3)$	3	0.2	“A”	410	74	418	80	420	80

The aggressive chemical and mechanical environment causes deterioration and wearing of the thermal insulators. The possibilities to assess the refractory thickness and lining condition are essential for maintenance decisions. It is very important to know the residual inner lining thickness. This residual inner lining thickness can be predicted from the steel shell temperature at the end of the charged state from the stationary thermal ladle model or in the process of continuous casting from transient thermal model after the fourth period. Results for the residual inner lining thickness *d*, for different temperatures of the steel, as a function of surface temperature from transient investigation are presented in Fig. 7.

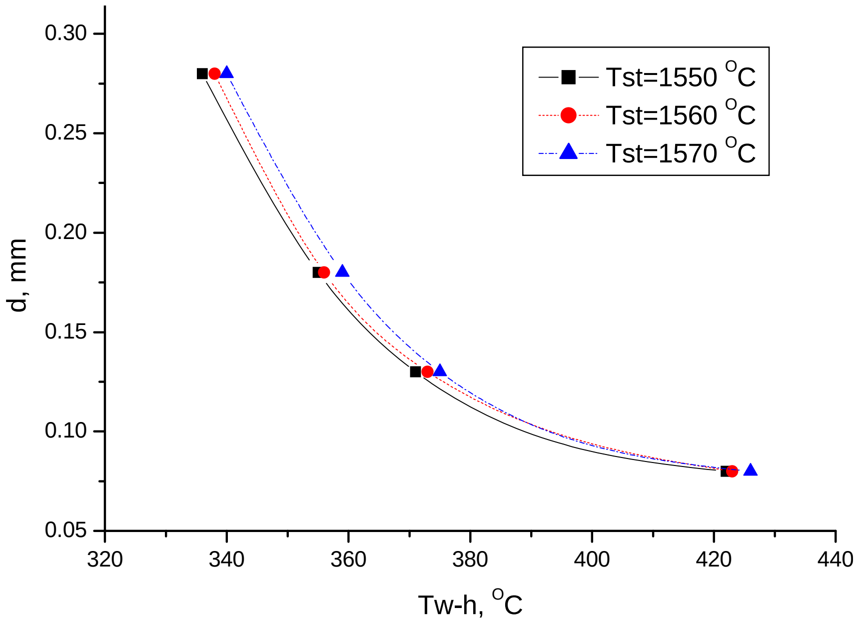


Figure 7. Residual inner lining thickness as a function of surface temperature.
Slika 7. Preostala debljina unutrašnje obloge kao funkcija temperature površine.

CONCLUSIONS

From the results the following conclusions are drawn:

- During the ladle operation, the maximal heat accumulation is observed during first four charges and afterwards the temperature variations are in a constant boundary.
- The ladle surface temperature can be measured at the end of the charged state during the process of continuous casting after the fourth working cycle.
- At the temperature differences of the surface, $\Delta T > 74$°C, the ladle must be changed immediately.

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