Thermal stress modeling for radiation heating of refractory ceramics

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Abstract — A radiation heating of refractory bodies was investigated with mathematical methods. Both: temperature and stress fields were used for analysis. Finite elements method was used for temperature field calculations. Mathematics model, considering connections of material thermal growth with appearing mechanical strain was used for stress calculation and destruction possibility fixing. As an example of method usage one of metallurgical installations (casting ladle cover of cell degasser) was chosen. Results of stress calculations correspond with real destruction picture and the moment of its beginning.

Keywords — computer simulation, finite elements method, mathematics modeling, thermal shock, refractory lining, metallurgy, degasser.

1 Introduction

Radiation heating of refractory materials is a specific situation, taking place especially at covers or walls above process zone of high-temperature installations. Formally, refractory material feels different ways of heating, because in common situation it has close contact with heat-carrier (hot metal, for example). For pure radiation heat exchange the process need to take place in vacuum, what is nearly impossible in conditions of real metallurgy. Present paper describes heating and temperature field development for casting ladle cover – refractory element, which has no contact with liquid metal. Heat exchange for this item take place with radiation and air convection. High temperature of ladle walls and bottom in the case of empty hot ladle covering or slag/metal surface in another situation is cause of the fact, that main scheme of heat exchange for this system is radiation. Calculations show, that energy, given to the cover with radiation is about 20 – 30 times greater, than given with air convection.

Material for casting ladle covers is based formally on aluminia-silicate fiber, but sometimes these items are made of corundum concrete. Concrete covers are made often for degassing installations, because while their usage there is a possibility of metal or slag impact to the item lower surface.

The present paper is devoted to thermal stability analysis of corundum concrete casting ladle cover while its preheating. Ladle cover preheating is held for technological water evaporation and finish of concrete hardening. This process needs treatment with temperatures between 100 and 800 ºC. The main way of heat exchange in this case is radiation heating, because heating is held with usage of hot casting ladle energy, while its cooling (concrete cover is simply put above ladle). Two examples of heating (one with emergency finish) would be discussed in the paper.

A finite element method was used as a calculation instrument [1]. Recently this is most widely used approach for solving problems of non stationary processes of heat or mass exchange. This algorithm could be realized in all: linear, plain or volume types. But, for most of technological tasks usage of linear or, in rear cases, plain type is enough. In the whole, number of calculating directions must be equal to number of heating axes.

So, the task of heat exchange for ladle cover can be solved as a linear problem, because heat stream direction is single: from lower to upper surface of the item.

2 Object and method description

An object of present investigation is a refractory cover of casting ladle. This item can have two methods
of manufacturing – of ceramic fiber or refractory concrete. A cover made of fiber has very low heat conductivity and Young modulus, as a consequence – high thermal stability. Equilibrium temperature field of such cover consists of very hot thin layer, turned inside the ladle, and relatively cold rest part of the item. Because of high strength of individual fiber and a great part of pores (gaseous phase), cracks appearance and thermal destruction of such cover is nearly impossible in working conditions of radiation heating.

At the case of concrete ladle cover we have an opposite situation: refractory concrete is a brittle material with high heat conductivity. Equilibrium temperature field of concrete cover does not have such sharp temperature changes at the area, close to the working surface, but Young modulus of concrete is remarkably higher and thermal stresses are higher too. Such cover has high resistance against mechanical impact of liquid metal or slag, but could be destroyed by thermal stress.

So, the material for ladle cover must be chosen, according to probability of mechanical impact, while its using. That is why fiber covers are often used for protecting of empty hot ladles from contact with cold atmospheric air and concrete covers – for metal heat treatment, combined with blowing off with argon or degassing in camera degassers.

Cover heating take place while two stages of its usage: preheating process for technological water removing and finishing of concrete strength increasing (organized as cover placing above hot empty ladle) and while metal treating process. In both cases heat energy mostly come with radiation from hot ladle wall and bottom or from metal melt surface. The scheme of heat exchange is shown at fig. 1.

Heat streams Q1 and Q2 are conditional on cooling of ladles lining: Q1 goes inside system and Q2 – outside it. Q1 is used for cover heating and heat loses with inner air, penetrating between ladle casing and cover. Q3 – is equal to heat loses from upper surface of the ladle cover. In the case of ladle, containing metal melt, Q1 transforms into heat streams sum: from metal surface and lining walls above it. At fig. 1 it would be equal to lifting of the bottom surface up to the upper melt level.

Coefficient of radiation of heat exchange (1) is necessary for fixing of covers lower surface temperature:

\[ \alpha_r = 5.67 \cdot 10^{-8} C_s \frac{T_a^4 - T_s^4}{T_a - T_s} \]  

\[ Q \] – heat stream inside cover lining, \[ dT_s \] – covers lower surface temperature change.

Approximation of heat stream value inside refractory lining of the cover can be obtained according to the following equation, using difference between systems

\[ \alpha_r = 5.67 \cdot 10^{-8} C_s \frac{T_a^4 - T_s^4}{T_a - T_s} \]  

\[ \alpha_r \] – radiation coefficient of heat exchange, \[ T_r \] – temperature of cover lower surface, \[ T_a \] – ladle lining or metal surface temperature, \[ C_s \] – coefficient of mutual radiation of ladle lining and cover.

Fig. 1. Heat streams in the system “casting ladle – cover”.

Coefficient of mutual radiation depends on areas of emitting and accepting surfaces, their blackness, orientation and distance between them. In the case, than surfaces are parallel and have same area and blackness, this coefficient is equal to 1. Calculation of this coefficient is a complicated task, which can be solved with analysis of system [2] or found in special tables for several widespread cases [3].
inner and outer temperature and heat conductivity of cover material:

\[ Q = \frac{T_{a1} - T_{a2}}{\sum \frac{\delta}{\lambda} + \frac{1}{\alpha_i} + \frac{1}{\alpha_o}} , \]  

(3)

\( T_{a1} \) and \( T_{a2} \) – temperatures inside and outside our system, \( \delta \) and \( \lambda \) – thicknesses and heat conductivities of cover lining layers, \( \alpha_i \) and \( \alpha_o \) – coefficients of heat exchange for inner and outer surfaces. Inner heat exchange coefficient can be obtained with expression (1), outer coefficient is an arithmetic sum of radiation and convection coefficient for upper cover surface. Methods of convection coefficients fixing are given in [3].

Heat exchange inside ladle lining or cover depends on heat conductivity of material. Temperature calculation inside lining can be realized according to the following equation:

\[ dT = \frac{\lambda}{\delta} dQ , \]  

(4)

\( dT \) - temperature change in the lining or cover layer [4].

With equations (1) – (4) usage, a special software was prepared for systems “dynamic temperature field” (a matrix, containing temperature values for any point of the system at any moment) calculations. Temperature changes in different points of the system were transformed into field of mechanical stress by a simply mathematics operations:

\[ \sigma_0 = \Delta T \cdot \alpha \cdot E , \]  

(5)

\( \sigma_0 \) – stress in material, \( \Delta T \) – temperature change of material element, \( \alpha \) – coefficient of material linear thermal expansion, \( E \) – modulus of material elasticity (Young modulus).

However, a slow temperature change does not give an effect of thermal stress growth, because of stress relaxation effect [5]. Stress in material disappears with the course of time, according to the following [6]:

\[ \sigma = \sigma_0 \cdot \left[ 1 - \frac{\tau E}{K_1} \right] , \]  

(6)

\( \sigma \) – real material stress, \( \sigma_0 \) – stress in material without relaxation consideration (5), \( \tau \) – time, passed after relaxation beginning, \( K_1 \) – a variable, which characterizes relaxation rate, depending on materials viscosity. This variable for refractory materials differs from \( 10^{15} \) at room temperature down to \( 10^7 \) – \( 10^9 \) at working temperature (up to 1550 – 1700 °C) [7].

Comparing of the stress values, obtained with equation (6) and mechanical strength of material, would show if conditions of construction usage are dangerous. Also, these results can help to predict places of cracks appearance and potential sizes of these cracks [8, 9].

3 Results and discussion

The special software, based on finite elements method was prepared and used for computer simulation of temperature and stress field in casting ladle cover. Simulation was applied for preheating of two different covers. It is necessary to mention, that one of the preheating processes was over with emergency.

In both cases heating and drying of ladle cover was held by putting it above several casting ladles with different lining temperatures. In this system we needed to consider both temperature fields: for ladle lining and for the cover.

The first drying of the cover was done, using four ladles with lining surface temperature from 200 up to 800 °C. Temperature changes of ladle lining working surface and cover lower surface are shown at fig. 2 and fig. 3 respectively.

Fig. 2. Temperature of ladle lining surface: 1, 2 – maximal and minimal measured values respectively; 3 – calculated values.

Fig. 2 illustrates temperature changes of four ladle linings, used for cover heating process. Moments of ladle change could be fixed by temperature jumps at fig. 2. Measurements were taken in several points of lining surface and their maximal and minimal values for each moment of time are shown at fig. 2 with red and black line respectively. Green line means the results of calculations, done with our special model of heat exchange at the system “ladle – cover”. As we can
see, calculation results are always situated between measurements or equal to the highest measurement result.

A special character of temperature changes at the last stage (measured temperature falls faster, than its calculated value) could be explained with a different ladle history: for example, first three ladles were taken after metal treating and cooling down to needed temperature and last ladle was specially preheated for the process. So, inner energy of the last ladle was lower, then for the previous ladles and its cooling was remarkably faster.

![Fig. 3. Temperature change for the cover lower surface. Designations are the same as for fig. 2.](image)

At fig. 3 we can see a result of ladle cover radiation heating. Also, we can see, that calculating results are valid according to the measurements. It means, that a model of heat exchange in our system was chosen correctly and it could be used for modeling of temperature fields.

Further, this model was applied for analysis of emergency, occurred while drying of one serial concrete ladle cover. Equations (5) – (6) were used for transformation of covers temperature field into mechanical stress field.

It was planned, that four hot ladles with different lining temperature would be used for ladle cover drying. The accident occurred while second stage of the process, 5 hours later after second ladle was set up. As an accident result we had a cover dividing in horizontal plane with through crack and destruction of upper part to relatively small pieces.

The first ladle was preheated with burning gas up to 375 °C before using, and the second was cooled after metal treating down to 500 °C.

Modeling was held with the following sequence:

1. simultaneous building of ladle lining and cover temperature field and the next stage – transformation of cover temperature field into stress matrix and its analysis.

Temperature and stress fields of the ladle cover for the second stage are presented at fig. 4 and fig. 5 respectively as 3-dimention graphs.

![Fig. 4. 3D temperature field of ladle cover. Axes are: time in seconds, distance from hot surface in centimeters and vertical – temperature, Celsius degrees.](image)

We can see, that at the stage beginning lower surface temperature lifting is rather fast and after 10000 s (about 3 hours) hot surface receive equilibrium state and its temperature become constant.

![Fig. 5. 3D stress field of ladle cover. Axes are: time in seconds, distance from hot surface in centimeters and vertical – stress, MPa.](image)

At fig. 5 we can see that at first period stress grows up according to temperature growth and then, after temperature stabilization, begin to fall down because of stress relaxation effect. The highest level of stress was found close to the hot surface of the cover. Destruction of cover occurred 18000 seconds (approximately) later.
after second ladle set up. We can see, that thermal stress at this moment was not at its highest value as for the whole item and for the layer, where destruction took place. A special stress value graph for the destructed layer (a plane, where destructive crack appeared and had grown up) is shown at fig. 6.

![Graph showing thermal stress time dependence for the line of ladle cover destruction.](image)

Fig. 6. Thermal stress time dependence for the line of ladle cover destruction. Thermal stress measure – Mpa, time – in seconds.

This image show, that maximal stress in this layer took place at 12000 – 13000 seconds of the second stage. At the same time the destruction occur about 5000 – 6000 seconds (1.5 hour) later. Due to this fact, a conclusion was made, that destruction reason was in item structure (some inner damage), but not in heating velocity. Another reason of such a conclusion was in crack surface character: it was plane and glossy (fig. 7) – it means, that this surface was created at the stage of cover manufacturing.

Pieces surfaces, which were not a main crack surface at the same time, have quiet different structure character: they are porous, rough and abrupt. So, the destruction reason was considered as a producer’s mistake.

### 4 Conclusion

Method of thermal stress calculation for brittle materials, such as ceramics and refractories was suggested. The method usage consists of two stages: temperature field calculation and the following transformation of this field into thermal stress matrix. This method is a combination of well-known mathematical methods, such as finite element method and knowledge about ways of heat exchange inside solid bodies and at their surfaces (theory of heat likeness). Also, connections of material thermal growth with mechanical strain were used.

![A main crack surface.](image)

A special software was prepared for one of metallurgical systems “casting ladle – ladle cover” thermal calculations. This system is widely used in steelmaking industry as a part of camera degassers.

This software was used for ladle cover drying stage modeling. The results of calculations, received with model usage were in good correlation with experimental temperature measurements.

Later, the software was used for emergency analysis. Emergency had occurred, while drying and heating of the serial new ladle cover. Both: computer simulation and fragment exploration gave the same result – the cover was broken because of the inner damage, appeared on the stage of cover producing. So, the truth of suggested model was approved for the second time.

### References


Andrew V. Zabolotsky was born in St. Petersburg, Russia in 1975. He had graduated from St. Petersburg State Institute of Technology (Technical University), department of High-Temperature Materials in 1998. He had defended a thesis about technology of silicon nitride (SiAlON) ceramics and received PhD degree in technical sciences in 2002.

After graduating he worked at JSK “Sigma-T” (2000-2002) – a producer of high-temperature testing equipment for ceramics and refractory materials as a head of heat insulation department. Between 2002 and 2004 he was a technologist at laboratory of “Refractory materials Ltd.”, a company which produced refractory concrete for iron and steel industry. At the present time he is an engineer-technologist of “Magnezit Group Ltd.” – one of the main producers of periclasse-carbon refractory materials in Russia. He is working with problems of heat exchange in refractory linings of metallurgical installations, their thermal stability and after-melt metal cooling – predicting and avoiding of ingot damages appearance. He had prepared more than 20 papers for different journals in Russia and other countries. He was a participant of several international conferences, devoted to metallurgical processes and mathematical methods usage in metallurgy (IAS Conference in 2009 at Buenos Aires, Argentina, WSEAS Conference in 2010 at Puerto de la Cruz, Spain and AIST Conference in 2011, Indianapolis, USA).