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Simulation Analysis of Temperature Field and Its Influence Factors of the New Structure Ladle

Bowen Luo[1], *Gongfa Li*[1,2,*], *Jianyi Kong*[1,2], *Guozhang Jiang*[1,2], *Ying Sun*[1,2], *Ze Liu*[1], *Wenjun Chang*[2] *and Honghai Liu*[3]

[1] Key Laboratory of Metallurgical Equipment and Control Technology, Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China.
[2] Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan 430081, China .
[3] Intelligent Systems and Biomedical Robotics Group, School of Computing, University of Ports-mouth, Portsmouth, PO1 3HE, China

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Abstract: In order to develop a ladle with excellent thermal insulation properties, a new structure ladle with a heat insulation nano-material lining was proposed and with it as the research object. The temperature field of new structure ladle and traditional ladle under two different working conditions of ladle baking and steel holding were analyzed by ANSYS after the establishment of ladle three-dimensional finite element model. The analysis results show that the temperature distribution of new structure ladle is better than that of traditional ladle under two different working conditions, and the heat loss of the new structure ladle is less than the traditional ladle, this indicates that the thermal insulation property of new structure ladle is superior to the traditional ladle. Then the influence factors of the new structure ladle temperature field was analyzed based on the analysis results of the new structure ladle temperature field. The analysis results show that, when the nano-materials thermal conductivity coefficient reduced by 80%, the temperature distribution of the new structure ladle is more balanced, and the maximum temperature of the new structure ladle is further reduced, namely, the heat loss of new structure ladle becomes smaller, which means that the thermal insulation property of the new structure ladle has been further improved.

Keywords: New Structure Ladle, Finite Element Model, Heat Insulation Nano-Material, Temperature Field, Thermal Conductivity Coefficient,Simulation Analysis

1 INTRODUCTION

In the process of steelmaking, ladle with excellent thermal insulation property is of great significance to reduce the tapping temperature and the heat loss of ladle shell, improve the quality of continuous casting billet, extend the service life of ladle lining, optimize production process and reduce the production cost. The existing research show that the temperature of the ladle shell is still too high, and the thermal insulation property of the ladle can be further enhanced.

Ladle always bears the gravity and great thermal shock of molten steel in actual production, which will cause corrosion of ladle lining material, seriously, also result in shedding of the lining material. With the widespread adoption of the continuous casting process, the working condition of ladle is deteriorating, refractory erosion is serious and the temperature of ladle shell is too high, which lead to the increase of molten steel heat loss. The heat of molten steel dissipated from ladle inner layer to the outer layer, and more heat loss will cause ladle shell overheating. Under high temperature for a long time, the creep resistance performance deterioration of ladle shell material, which result in failure of the shell strength, it has become an important factor to restrict the service life of the ladle[1,2,3].

During this period, the temperature distribution of traditional ladle was studied by scholars and experts in various countries. Sarmiento G.S[4] developed an analysis software TEMPCU, which could be very well applied to the analysis of ladle temperature field. The theoretical basis of the software was the finite element method, and the ladle temperature field under different working conditions could be analyzed by this software

* Corresponding author e-mail: ligongfa@wust.edu.cn

after the establishment of ladle model. Schalk W.P[5] analyzed the heat transfer performance of ladles with different materials lining structure. The lining temperature gradient and temperature distribution of three kinds of ladle were analyzed by taking the two dimensional section of ladles as the analysis object, the three kinds of ladle were standard ladle, thermal insulation ladle and low thermal conductivity ladle. The research results showed that: the overall temperature level of the thermal insulation ladle was higher than that of the standard ladle, and the heat of the thermal insulation ladle and standard ladle under the working condition of ladle steel holding was basically same.

Although the field tests for traditional ladle temperature has verified the accuracy and efficiency of the relevant models, and the numerical simulation analysis of the ladle temperature field also has made a fruitful contribution to the design and manufacture of the ladle, the current research still have a great challenge, the temperature of traditional ladle shell is too high and the thermal insulation property is not good. In recent years, many foreign scholars and domestic researchers have done a lot of work on the ladles with new material lining structure, and made some achievements. mario[6] studied on the temperature drop process of molten steel in standard ladle and thermal insulation material ladle, it could be found that the temperature drop rate of molten steel in the thermal insulation material ladle was lower 1.9$^\circ C$/min than that of the standard ladle, and 10.5% electric energy could be saved. Chen Y.F., et.al[7] proposed a new ladle lining structure, and analyzed the insulation performance of the new ladle and traditional ladle. The results showed that new ladle shell temperature lower 4$^\circ C$ than that of traditional ladle, The average rate of molten steel temperature drop reduced 0.27$^\circ C$/min, the insulation performance of the new ladle better than traditional ladle. Liu Z.Y, et.al[8] chose a new WDS micro-porous insulation nanometer materials for solving the problem of heat loss of molten steel in ladle during the steelmaking production. Under the condition that the service life of the refractory material was not affected, the heat storage capacity of the steel making equipment was improved, and the purpose of saving energy and reducing consumption was achieved.

The above results show that the temperature distribution and the thermal insulation property of the ladle are not very good at the control of ladle shell temperature and the influence of different lining materials on ladle temperature distribution. In recent years, the ladle with the heat insulation nano-material was studied by some manufacturers, compared with the traditional ladle, this ladle have an advantage of lower shell temperature and lower heat consumption. But this structure ladle was difficult to be popularized and applied, because the using temperature range of nano-materials was limited. Therefore, the thermal analysis theory and temperature field of the ladle with heat insulation nano-material should be further studied.

In order to optimize the lining structure and further improve the thermal insulation property of the ladle, with a new structure ladle with heat insulation nano-material lining as the research object, the 3D finite element model was established, and the temperature field of the new structure and traditional ladles were analyzed by ANSYS under the working conditions of ladle baking and steel holding. The influence of thermal conductivity of heat insulation nano-material on the new structure ladle was also studied. The establishment of the finite element model of the new structure ladle is described in Section 2. The numerical simulation of the new structure ladle temperature field under the typical working conditions is described in Section 3. The influence of thermal conductivity of heat insulation nano-material on the new structure ladle is described in Section 4, and the conclusion is presented in Section 5.

2 ESTABLISHMENT OF THE FINITE ELEMENT MODEL OF NEW STRUCTURE LADLE

2.1 Lining structure of new structure ladle

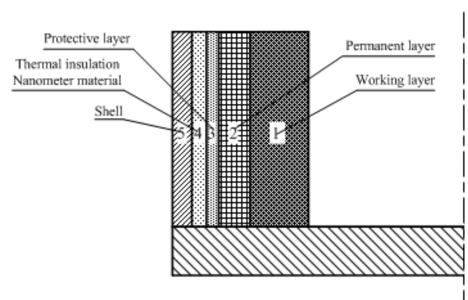

Fig.1. Lining structure of new structure ladle

Lining structure of the new structure ladle is shown in Figure 1. Lining structure of the traditional ladle includes working layer, permanent layer and shell. Different from the traditional ladle, lining structure of the new structure ladle comprises five layers, a heat insulation nano-material layer and protective layer are added in the new structure ladle between the permanent layer and ladle shell. Among them, the heat insulation nano-material layer uses the nano micro-porous materials, which is prepared by the gas phase oxidation silicon and calcium silicate, and the thermal insulation property of this kind of nano-material are very good [9,10,11] The protective layer is welded by 5mm thick steel plate, and is added between the permanent layer and the heat insulation nano-material layer to protect the expensive heat insulation nano-material layer. The material and thickness of each lining layer in barrel body and ladle bottom of the new structure ladle as shown in Table 1.

Table 1: Material and thickness of each lining layer in barrel body and ladle bottom of the new structure ladle

LAYER	*MATERIAL*	THICKNESS IN LADLE BODY(mm)	THICKNESS IN LADLE BOTTOM(mm)
working layer	aluminum magnesium carbon	170	240
permanent layer	high alumina	105	155
Protective layer	Q345	5	5
heat insulation nano-material	gas phase oxidation silicon	20	20
Shell	Q345B	32	32

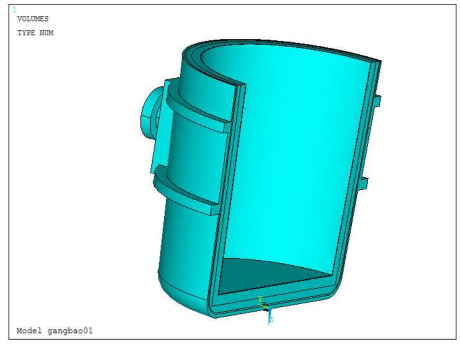

Fig. 2. 3D model of new structure ladle

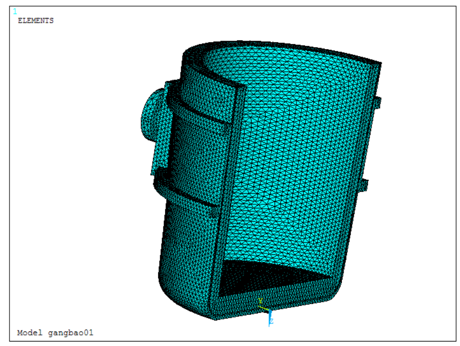

Fig.3. Finite element model of new structure ladle

2.2 Establishment of the finite element model of new structure ladle and mesh generation

The ladle model was established by ANSYS command stream. In the process of modeling, the modeling size (unit: m) was determined, and according to the ratio of 1:1 to establish model, then the 3D model of the new structure ladle as shown in Figure 2. In the process of the finite element mesh generation, the SOLID70 unit of ANSYS13.0 was selected, and the grid was divided by the way of free division, the unit size was 0.1, and it could obtain 112706 grids and 23957 nodes after mesh division. The finite element model of the new structure ladle as shown in Figure 3.

2.3 Boundary conditions, material parameters and simulation method

The inner surface temperature of ladle lining was respectively set to 1000$^{\circ}C$. and 1600$^{\circ}C$. under the working conditions of baking and steel holding, and the environment temperature was set to 30$^{\circ}C$; the comprehensive convective heat transfer coefficient of ladle was 16.234 $W/\left(m^2 \cdot K\right)$ [12,14]; the material physical properties parameters of each lining layer of ladle as shown in Table 2[12], and the thermal conductivity of each lining layer of ladle at different temperatures as shown in Table 3; the temperature distribution of the each lining layer of ladle was simulated by the steady state analysis method[15].

Table 2: Material physical properties parameters of each lining layer of ladle

PHYSICAL PARAMETERS	MODULUS OF ELASTICITY E(GPa)	POISSON'S RATIO μ	COEFFICIENT OFTHERMAL EXPANSION $\alpha\left(10^{-6}K^{-1}\right)$	DENSITY $\rho\left(kg/m^{-3}\right)$
working layer	6.3	0.21	8.5	2950
permanent layer	5.7	0.21	5.8	2800
Protective layer	206	0.3	13	7800
heat insulation nano-material	2	0.01	1.2	400
Shell	206	0.3	13	7800

Table 3: Thermal conductivity of each lining layer of the new structure ladle at different temperatures

LAYER	TEMPERATURE()			
	20	400	800	1200
working layer	1.15	1.3	1.51	1.6
permanent layer	0.5	0.63	0.75	0.9
Protective layer	54	42	31	31
heat insulation nano-material	0.023	0.028	0.034	0.038
shell	54	42	31	31

3 PARALLEL PROVING ALGORITHM BASED ON SEMI-EXTENSION RULE

Under the conditions of same grid cell type and boundary conditions, the temperature field of the new structure and traditional ladle were simulated under the working conditions of baking and steel holding

3.1 Temperature distribution of new structure ladle under the working condition of baking

The overall temperature distribution of the new structure and traditional ladle after baking as shown in Figure 4 and Figure 5, respectively. It can be seen from Figure 4 and Figure 5 that the overall temperature distribution of two types ladle is uniform, the temperature of ladle shell is relatively low, and the temperature of the new structure ladle lining gradually decreased from the inside to outside.

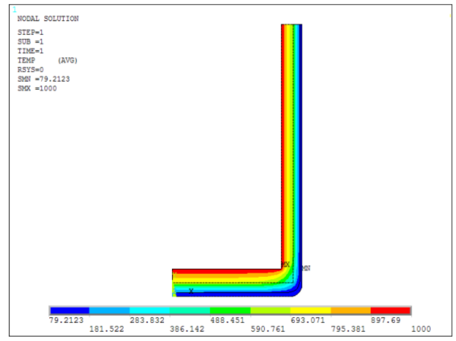

Fig.4. Overall temperature distribution of new structure ladle after baking

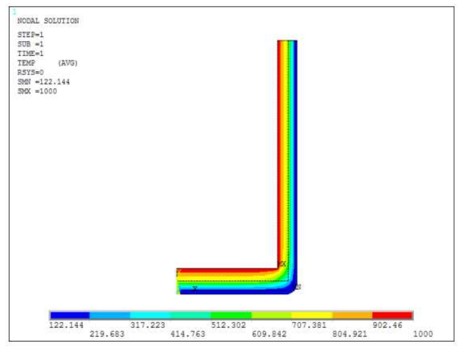

Fig.5. Overall temperature distribution of traditional ladle after baking

In order to more intuitively compare the each lining layer temperature distribution of new structure and traditional ladles after baking, the temperature data of new structure and traditional ladles after baking was presented. The temperature distribution of each lining layer of the new structure and traditional ladles after baking as shown in Table 4 and Table 5, respectively.

Table 4: Temperature distribution of each lining layer of the new structure ladle after baking

TEMPERATURE / LAYER	MOST AREAS	MAXIMUM	MINIMUM	TEMPERATURE DIFFERENCE
working layer	677~935	1000	419	258
permanent layer	249~656	748	187	407
protective layer	252~360	382	187	108
heat insulation nano-material layer	165~350	381	103	185
shell	122~186	202	58	64

Table 5: Table 5 Temperature distribution of each lining layer of the traditional ladle after baking

TEMPERATURE / LAYER	MOST AREAS	MAXIMUM	MINIMUM	TEMPERATURE DIFFERENCE
working layer	661∼932	1000	391	271
permanent layer	231∼664	726	169	433
shell	246∼269	316	106	116

It can be seen from Table 4 and Table 5 that the new structure and traditional ladles have little difference in the temperature distribution of the working layer and the permanent layer under the working condition of baking. The maximum temperature of the shell of new structure ladle with a heat insulation nano-material layer is 202°*C*., but that of traditional ladle is up to 316°*C*.. Compared with the traditional ladle, the maximum temperature of the shell of new structure ladle decreased by 114°*C*., it is obviously decreased, and the temperature of most areas of new structure ladle shell is lower than that of the traditional ladle. This indicates that a lot of heat was blocked inside the heat insulation nano-material layer, it can not be transferred to the shell, so that heat loss is small, which is the key of thermal insulation, and it showed that the heat insulation nano-material layer has excellent thermal insulation property[16]. Meanwhile, the improvement of the thermal insulation property of new structure ladle also means the reduction of heat loss, which is of great significance for energy-saving and emission reduction.

3.2 *Temperature distribution of new structure ladle under the working condition of steel holding*

The overall temperature distribution of the new structure ladle under the working condition of steel holding as shown in Figure 6. It can be seen from Figure 6 that the overall temperature distribution of new structure ladle under the condition of steel holding is similar to that of new structure ladle under the condition of baking[17]. Also, the overall temperature distribution of new structure ladle is uniform, the temperature of the new structure ladle lining gradually decreased from the inside to outside, and the temperature of ladle shell is relatively low under the condition of steel holding.

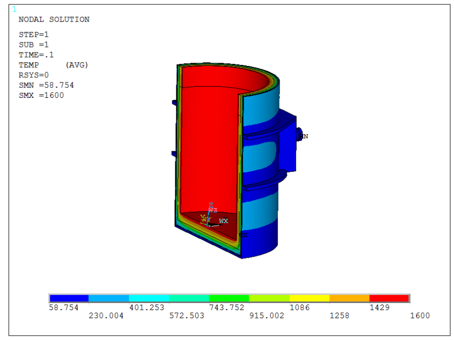

Fig.6. Overall temperature distribution of new structure ladle during steel holding

The working layer temperature distribution of new structure and traditional ladles under the working condition of steel holding as shown in Figure 7 and Figure 8. It can be seen from Figure 7 and Figure 8 that the working layer temperature distribution of new structure ladle under the working condition of steel holding is similar to that of traditional ladle[18], the minimum temperature of working layer of new structure and traditional ladles is 633°*C*. and 623°*C*., respectively. This shows that the heat loss of working layer of new structure ladle is lower than that of traditional ladle.

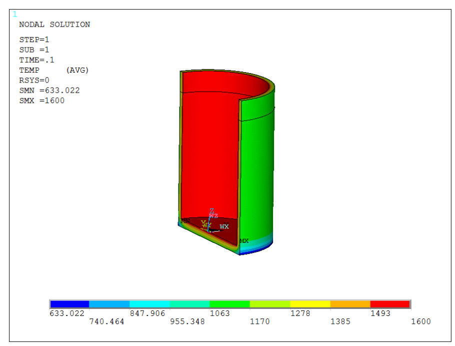

Fig.7. Working layer temperature distribution of new structure ladle during steel holding

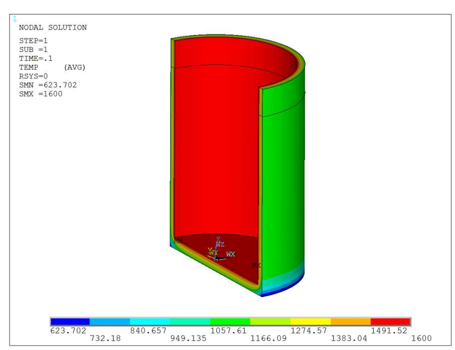

Fig.8. Working layer temperature distribution of traditional ladle during steel holding

The permanent layer temperature distribution of new structure and traditional ladles under the working condition of steel holding as shown in Figure 9 and Figure 10. It can be seen from Figure 9 and Figure 10 that the permanent layer temperature distribution of two kinds of ladle is approximately same under the condition of steel holding, but the permanent layer temperature distribution of new structure ladle is more uniform than that of traditional ladle[19].

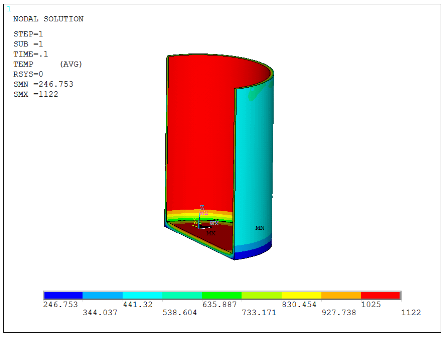

Fig.9. Permanent layer temperature distribution of new structure ladle during steel holding

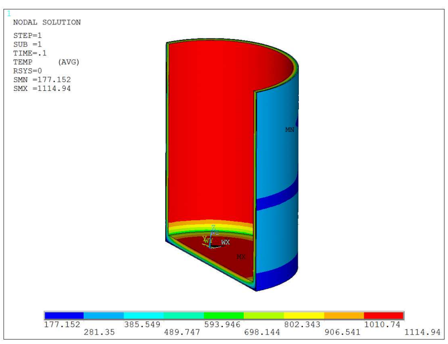

Fig.10. Permanent layer temperature distribution of traditional ladle during steel holding

The temperature distribution of protective layer and heat insulation nano-material layer of new structure ladle under the working condition of steel holding as shown in Figure 11 and Figure 12,respectively. It can be seen from Figure 11 that the maximum temperature of protective layer is 543°C, and the temperature distribution is in a high level[20]. And it can be seen from Figure 12 that the maximum temperature of heat insulation nano-material layer is 542°C. and the minimum temperature is only 129°C, the temperature difference between the inner and outer surface of heat insulation nano-material layer reaches 275°C. It shows that a large number of heat which transfer from the protective layer was also blocked inside the heat insulation nano-material layer, namely, the heat insulation nano-material layer have played a good thermal insulation effect[21].

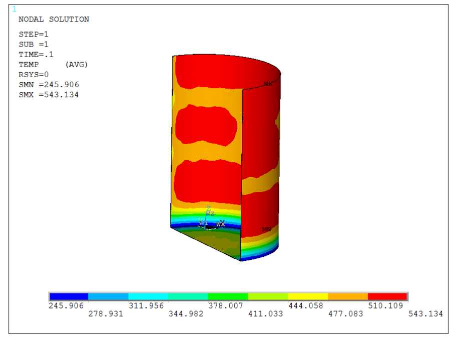

Fig.11. Protective layer temperature distribution of new structure ladle during steel holding

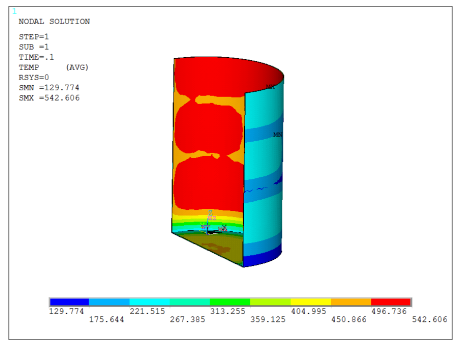

Fig.12. heat insulation nano-material layer temperature distribution of new structure ladle during steel holding

The shell temperature distribution of new structure and traditional ladles under the working condition of steel holding as shown in Figure 13 and Figure 14, respectively. It can be seen from Figure 13 that the temperature of most areas of new structure ladle shell in the range of 143 228°C the maximum temperature is 250°C. which appeared in the inner wall of the shell, and the temperature difference between the inner and outer surface of the shell is 85°C And it can be seen from Figure 14 that the appeared area of the maximum and minimum temperature of traditional ladle shell are similar to that of new structure ladle[22], but the maximum temperature of the shell is up to 359°C and the temperature difference between the inner and outer surface of the shell is 91°C.The maximum temperature of new structure ladle shell is lower 109°C than that of traditional ladle. It shows that the heat loss of new structure ladle with a heat insulation nano-material layer is fewer than that of traditional ladle even under the working condition of steel holding[23].

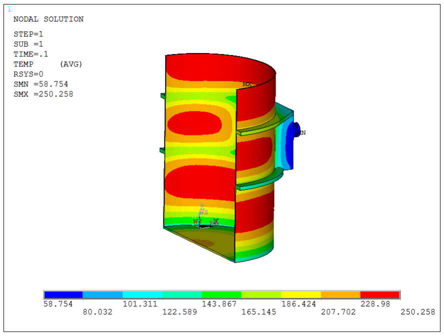

Fig.13. Shell temperature distribution of new structure ladle during steel holding

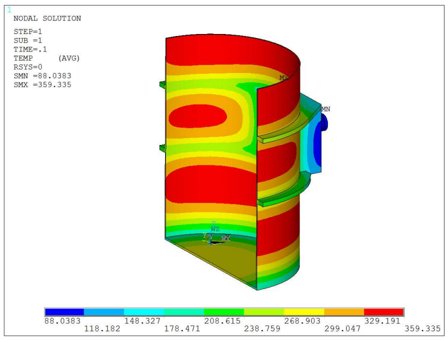

Fig.14. Shell temperature distribution of traditional ladle during steel holding

In order to more intuitively compare the each lining layer temperature distribution of new structure and traditional ladles during steel holding[24], the temperature data of new structure and traditional ladles during steel holding was also presented. The temperature distribution of each lining layer of the new structure and traditional ladles during steel holding as shown in Table 6 and Table 7, respectively.

Table 6: Temperature distribution of each lining layer of the new structure ladle during steel holding

TEMPERATURE / LAYER	MOST AREAS	MAXIMUM	MINIMUM	TEMPERATURE DIFFERENCE
working layer	1063~1493	1600	633	430
permanent layer	441~1025	1122	246	584
protective layer	378~510	543	245	330
heat insulation nano-material layer	313~496	542	129	275
shell	143~228	250	58	85

Table 7: Temperature distribution of each lining layer of the traditional ladle during steel holding

TEMPERATURE / LAYER	MOST AREAS	MAXIMUM	MINIMUM	TEMPERATURE DIFFERENCE
working layer	1057~1491	1600	623	434
permanent layer	385~1010	1114	177	625
shell	238~329	359	88	91

It can be seen from Table 6 and Table 7 that the working layer and the permanent layer temperature distribution of two kinds of ladles also have little difference under the working condition of steel holding, but for the new structure ladle with a heat insulation nano-material layer, the overall temperature of the ladle shell is significantly lower than that of traditional ladle, and the maximum temperature and minimum temperature of the shell are obviously decreased[25]. This indicates that even under the working condition of steel holding, a lot of heat was also blocked inside the heat insulation nano-material layer and can not be transferred to the shell, so that the heat loss is small. Therefore, the new structure ladle also has excellent thermal insulation property under the working condition of steel holding.

4 EFFECT OF NANO-MATERIAL THERMAL CONDUCTIVITY ON THE TEMPERATURE FIELD OF NEW STRUCTURE LADLE

It can be seen from analysis results of new structure ladle temperature field that the temperature distribution of new structure ladle can be further optimized to further improve the thermal insulation property. Since the new structure ladle using the heat insulation nano-material, it is necessary to investigate the effect of heat insulation nano-material physical properties parameters new structure ladle temperature field. According to existing research found that the influence of the thermal conductivity on the temperature field is larger than other parameters in the heat insulation nano-material physical properties parameters, and the thermal conductivity becomes smaller with the continuous decrease of the thermal conductivity coefficient[26]. Therefore, the thermal conductivity coefficient can be as the research object of new structure ladle temperature influence factors.

At the same time, due to the new structure ladle with the heat insulation nano-material lining have displayed the excellent thermal insulation property under two working conditions of baking and steel holding, and the most intuitive part is that the shell temperature of new structure ladle is lower than that of traditional ladle. Therefore, the ladle shell can be as a carrier for evaluating the overall thermal insulation property of new structure ladle[27]. Also, it can more really display the temperature distribution of new structure ladle under the working condition of steel holding.

Above all, the influence of thermal conductivity coefficient of heat insulation nano-material on the new structure ladle shell temperature under the working condition of steel holding was researched[28].

Due to the thermal conductivity becomes smaller with the continuous decrease of the thermal conductivity coefficient, the thermal conductivity of heat insulation nano-material layer after heat insulation nano-material thermal conductivity coefficient decreased as shown in Table 8. Therefore, the temperature distribution of new structure ladle shell when the thermal conductivity coefficient decreased by 20%, 40%, 60% and 80% were analyzed, and the simulation results as shown in Figure 15-18.

Table 8: Thermal conductivity of heat insulation nano-material layer after heat insulation nano-material thermal conductivity coefficient decreased

THERMAL CONDUCTIVITY COEFFICIENT REDUCTION RATIO	THERMAL CONDUCTIVITY UNDER DIFFERENT TEMPERATURES(Wm-1K-1)			
	20	400	800	1200
unchanged	0.02	0.028	0.038	0.041
20%	0.016	0.0224	0.304	0.0328
40%	0.012	0.0168	0.0228	0.0246
60%	0.008	0.0112	0.0152	0.0164
80%	0.004	0.0056	0.0076	0.0082

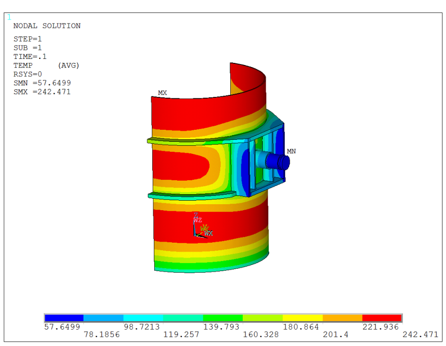

Fig.15. Shell temperature distribution when the thermal conductivity coefficient of heat insulation nano-material decreased by 20%

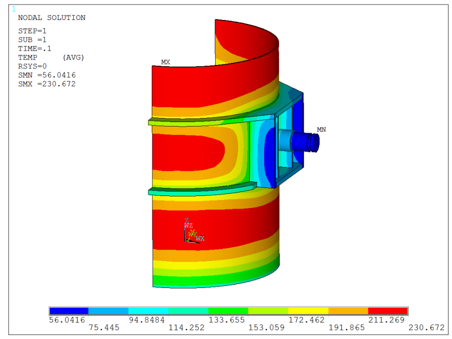

Fig.16. Shell temperature distribution when the thermal conductivity coefficient of heat insulation nano-material decreased by 40%

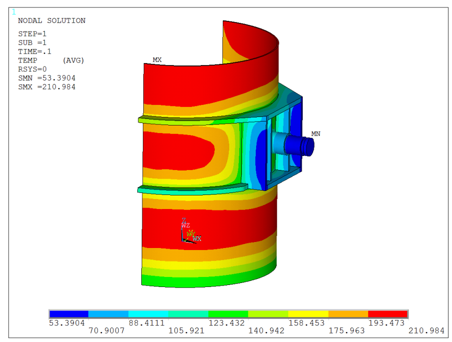

Fig.17. Shell temperature distribution when the thermal conductivity coefficient of heat insulation nano-material decreased by 60%

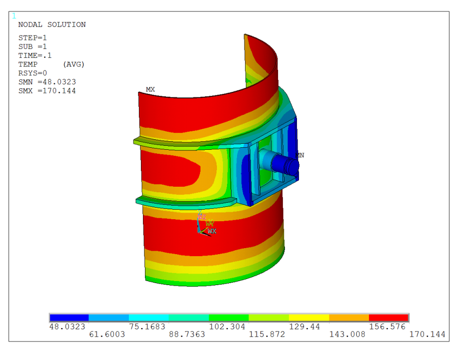

Fig.18. Shell temperature distribution when the thermal conductivity coefficient of heat insulation nano-material decreased by 80%

It can be seen from Figure 15-18 that when the thermal conductivity coefficient of heat insulation nano-material has not changed, the maximum temperature of heat insulation nano-material layer is 542°C. and the minimum temperature is 129°C, meanwhile, the maximum temperature of shell is 250°C. and the minimum temperature is 58°C.In order to more intuitive compare shell temperature distribution when the thermal conductivity coefficient of heat insulation nano-material decreased by 20%, 40%, 60% and 80%, respectively, the temperature data of shell after the thermal conductivity coefficient heat insulation nano-material decreased are listed in Table 9.

Table 9: Shell temperature distribution after the thermal conductivity coefficient heat insulation nano-material decreased

THERMAL CONDUCTIVITY COEFFICIENT REDUCTION RATIO	SHELL TEMPERATURE($^{\circ}C$)		
	MIN-IMUM	MAX-IMUM	MOST AREAS
unchanged	58	250	143∼228
20%	57	242	119∼221
40%	56	230	133∼191
60%	53	210	123∼193
80%	48	170	102∼156

It can be seen from Table 9, when the thermal conductivity coefficient of heat insulation nano-material decreased by 20%, 40%, 60% and 80%, respectively, compared with the condition of thermal conductivity coefficient of heat insulation nano-material decreased has not changed, the minimum temperature of shell decreased by 1, 2, 5 and 10$^{\circ}C$., respectively; and the maximum temperature of shell decreased by 8, 20, 40 and 80$^{\circ}C$. respectively; meanwhile, the most areas temperature of shell is lower. This indicates that, in a certain range, the shell temperature of the new structure ladle decreases linearly with the continuous decrease of the thermal conductivity coefficient of heat insulation nano-material. This is because, according to the heat transfer theory, thermal conduction in solid material, when the thermal conductivity coefficient decreased and wall thickness unchanged, the thermal resistance will increase[29]. Therefore, the essence of the thermal conductivity coefficient decreased is the thermal resistance increased of thermal insulation nanometer material, so that the heat which go through the heat insulation nano-material layer in unit time have reduced, and heat loss is small, at last, the heat which can be transfer to the shell is less, result in the shell temperature is relatively low. It also can be seen from Table 9, when the thermal conductivity coefficient of heat insulation nano-material decreased by 80%, the maximum temperature of new structure ladle shell have a biggest drop, and the most areas temperature of shell is low and the temperature difference is small. This indicates that when the thermal conductivity coefficient of thermal insulation nanometer material decreased by 80%, the temperature distribution of new structure ladle shell is more balanced, the heat loss is small, and the thermal insulation property of the new structure ladle is further enhanced[30].

5 CONCLUSIONS

(1) The temperature distribution of new structure ladle with a heat insulation nano-material is obviously superior to that of traditional ladle. Under two working conditions of baking and steel holding, the maximum temperature of new ladle shell are lower 114 and 109 than that of traditional ladle, respectively. The heat loss of new structure ladle significantly reduced, and the thermal insulation property more excellent than traditional ladle. (2) In a certain range,the shell temperature of the new structure ladle decreases linearly with the continuous decrease of the thermal conductivity coefficient of heat insulation nano-material. When the thermal conductivity coefficient of heat insulation nano-material decreased by 80%, the maximum temperature of new structure ladle shell have a biggest drop, the temperature distribution of new structure ladle shell is more balanced, the heat loss is small, and the thermal insulation property of the new structure ladle is further enhanced.

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B.W.Luo received the B.S. degree in mechanical engineering and automation from Wuhan University of Science and Technology,WuHan,China.He is currently occupied in his M.S.degree in mechanical design and theory at Wuhan University of Science and Technology. His current research interests include mechanical CAD/CAE, signal analysis and processing.

G.F.Li received the Ph.D. degree in Wuhan University of Science and Technology, Wuhan, China. He is currently a professor in Wuhan University of Science and Technology. His major research interests are computer aided engineering, mechanical CAD/CAE, modelling and optimal control of complex industrial process.

J.Y.Kong received the Ph.D. degree in Helmut Schmidt Universitat, Germany. He is currently a professor in Wuhan University of Science and Technology. His research interests are intelligent machine and controlled mechanism, mechanical and dynamic design and fault diagnosis of electrical system, mechanical CAD/CAE, intelligent design and control.

G.Z.Jiang received the Ph.D. degree in Wuhan University of Science and Technology, China. He is currently a professor in Wuhan University of Science and Technology. His research interests are computer aided engineering, mechanical CAD/CAE and industrial engineering and management system.

Y.Sun is currently an associate professor in Wuhan University of Science and Technology. Her major research focuses on teaching research in Mechanical Engineering.

Z.Liu received the B.S. degree in mechanical engineering and automation from Wuhan Institute of Bioengineering, Wuhan, China, in2013. He is currently occupied in his M.S. degree in mechanical design and theory at WuhanUniversity of Science and Technology. His current research interests include mechanical CAD/CAE,signal analysis and processing.

W.J.Chang was born in Hubei province, P. R. China, in 1991. He received B.S. degree in mechanical engineering and automation from Donghu college of Wuhan University, Wuhan, China, in 2015. He is currently occupied in his M.S. degree in mechanical design and theory at Wuhan University of Science and Technology. His current research interests include mechanical CAD/CAE, signal analysis and processing.

H.H.Liu received the Ph.D. degree in intelligent robotics from Kings College, University of London, London, U.K. He is currently a professor of School of Mechanical Engineering in Shanghai Jiao Tong University, Shanghai, China and a Professor of Intelligent Systems in Portsmouth University, Portsmouth, UK. His research interests are approximate computation, pattern recognition, multi-sensor based information fusion and analytics, human machine systems, advanced control, intelligent robotics and their practical applications.