MODELING OF THE THERMAL STATE OF A HOT ROLLED STRIP IN AN ACCELERATED COOLING PROCESS PART 2: A CALCULATION OF THE THERMAL FIELD OF THE STRIP. RESULTS AND CONCLUSIONS

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Received 20 June 2019
Accepted 30 September 2019

ABSTRACT

The physical and mathematical model of cooling a moving steel strip by a water jet system is described in Part 1 of this paper. The temperature distribution along the steel strip motion direction and at its cross section is obtained. Two main variants of the relative position of the upper and the lower jets are considered. An analysis of the jets pattern effect on the steel strip temperature field is performed.

The validity of the heat transfer mathematical model and the program for calculating the temperature field is verified by comparing the results of the functioning Hot Rolling Mill 2000 of the Public Joint-Stock Company «Magnitogorsk Iron and Steel Works» with the calculated data referring to a specific steel grade. The transverse temperature distributions for different layouts of the jets as well as the longitudinal distributions of the maximum temperature differences of the steel strip sections are obtained.

Results referring to the steel strip temperature field calculation in view of the temperature dependence of the thermo-physical properties of low-carbon steel are presented in this communication. Conclusions on the need of considering the temperature dependence of the steel thermo-physical properties when predicting the final temperature are drawn based on these calculations.

Keywords: hot-rolled steel strip, accelerated cooling, jet system, thermal field of steel strip.

INTRODUCTION

It is possible to change the mechanical properties and the structure of steel of an identical chemical composition in a wide range by varying the temperature of the steel cooling and its rate. The cooling is usually performed both from above and below the strip aiming a more uniform metal structure but the use of jet systems causes the existence of zones of different cooling mechanisms. This kind of cooling causes a significant non-uniformity of the temperature field which largely depends on the geometrical parameters of the jet system. This paper discusses the various schemes of the mutual arrangement of the jets which allow choosing an effective cooling system for the moving steel strip.

The correct choice of a strategy of accelerated cooling of the rolling steel strip in functioning rolling mills provides an improvement of the metal quality, a decrease of the water amount used in the cooling system and also a decrease of the cost of the electricity consumed during the operation of the pumps. The use of a heat transfer physical and mathematical model at the design stage of the jet cooling systems provides also to find the optimal geometrical parameters of the system ensuring the most uniform cooling of the hot steel strip.

The compiled program for calculation of the heat transfer on the basis of a mathematical model described in the Part I of this paper provides to obtain a three-dimensional temperature distribution in the steel strip throughout the outgoing roller table of the hot rolling mill. It is possible to change the cooling scheme and the water flow rate in all parts of the given system with the application of this program to the numerical study of the heat transfer in a laminar system with given geometrical dimensions. The changes in the temperature field of the strip can be tracked by varying the flow rate of the water in each collector of the laminar cooling system as well as by changing some of its geometric features (the jet layout). This method provides to determine the optimal initial parameters determining the more efficient use of the laminar cooling system.

A JET COOLING SCHEME

Steel strip cooling systems including flat (water curtain) and round jets are widely used in the rolling industry due to their high efficiency compared to that of the spray systems. The results of calculating the steel strip temperature field using a single flat jet and flat jet systems based on the proposed physical and mathematical model of the heat transfer are described in Part I and will not be considered in this communication. The calculation of the temperature field using a system of circular cross section jets is more interesting because of the system geometry complexity and the possibility of changing the relative position of the jets.

The steel strip cooling with a system of circular jets is a very common method of heat treatment since the jet sprinkler organization is quite simple and easy to implement. A qualitative analysis of the heat transfer during the jet cooling shows that in case of an identical number of upper and lower nozzles the most intensive cooling occurs through the upper surface due to the fact that the heat sink on the upper surface of the film boiling zone exceeds essentially the heat sink on the lower surface of the air cooling zone. Obviously, this leads to a significant difference in the heat treatment regimes of the upper and the lower sides of the steel strip. An unequal number of nozzles are used in the upper and the lower jet systems aiming to avoid such unevenness. In fact, more uniform cooling of the steel strip sides is achieved when the number of the nozzles of the lower part is twice that of the nozzles of the upper irrigation system.

Two schemes of jet cooling of a steel strip (a linear and a chess scheme) which differ in the mutual arrangement of the jets are discussed in this paper.

Fig. 1(a) shows the linear arrangement of the jets. The name of the scheme is conventionally accepted because the centers of the stagnation zones of the lower and the upper jets in the direction of the steel strip movement are located along a single line. In the chess scheme the centers of the upper jets stagnation zones are oriented to the lower jets in a chess pattern (Fig. 1(b)). The top nozzles in these schemes are arranged in a chess pattern for more uniform cooling of the upper part of the steel strip.

The symmetry condition referring to the jets location in respect to the steel strip movement direction provides to select the longitudinal lines of heat fluxes absence in the transverse direction. In this case a small section can

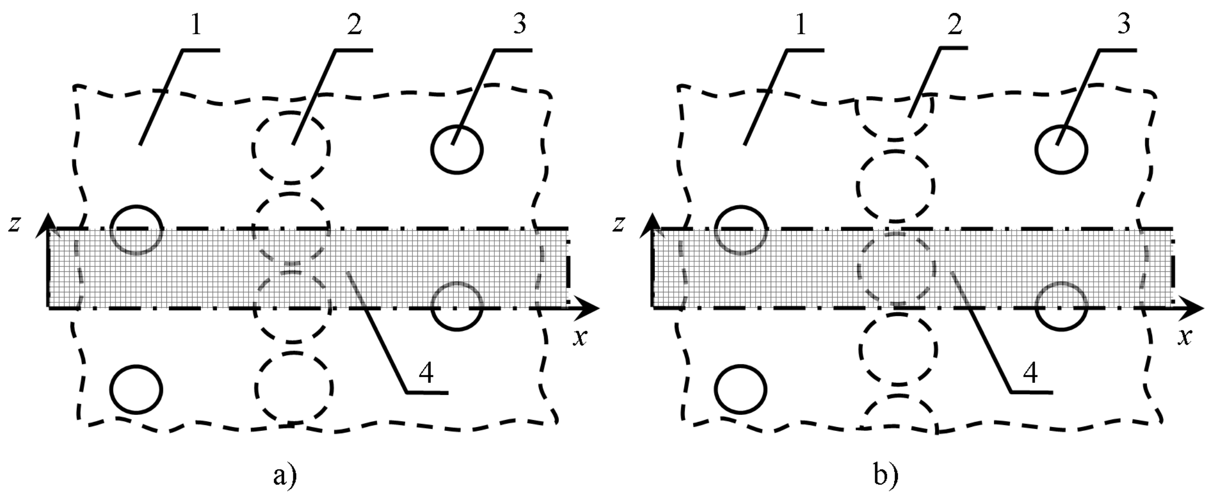

Fig. 1. A linear (a) and a chess pattern (a) diagram of the mutual arrangement of circular jets: 1 - a steel strip, 2 – a zone of the lower jet stagnation, 3 - a zone of the upper jet stagnation, 4 - a calculated area.

be selected for a computational area compared with the transverse dimensions of the steel strip (highlighted by hatching in Fig. 1), which in turn decreases significantly the number of the operations and the calculation time of the numerical research program. It should be noted that part of the heat in the extreme of the transverse direction areas will go through the end of the strip. Thus, the heat transfer in the outer areas will differ from the heat exchange in the inner one. However, such a difference can be neglected taking into account that the strip thickness is much smaller (by several orders of magnitude) than its width.

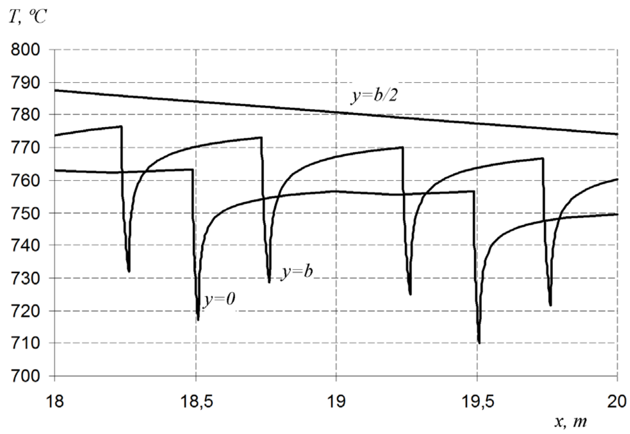

Fig. 2. A temperature distribution in the direction of the steel strip movement (a linear pattern, a strip thickness of 4 mm, a movement velocity of 10 m s^{-1}).

THE JETS LAYOUT EFFECT ON THE TEMPERATURE FIELD OF THE STEEL STRIP

The geometrical parameters of the jet system and the steel strip thickness are varied in a numerical study of the heat transfer during the strip cooling with a system of circular cross section jets. These parameters affect most significantly the cooling rate and the temperature field. At the same time, the initial temperature of the steel strip and its properties do not qualitatively change the temperature field, therefore, they are not changed in this series of numerical experiments, but are fixed to the values that are characteristic of the real conditions of steel strip accelerated cooling in the rolling industry.

The heat transfer in a 20 m long zone is studied in this communication. The placement there of up to 40 transverse rows of jets on each side is simulated. Moreover, the distance between the transverse rows of jets and the distance between the jets in a row can be chosen arbitrarily. However, in order to preserve the peculiarities of the circular jets system, the distance between the jets of the lower row is chosen so that the impingement regions do not overlap or the overlap zone is insignificant. The last condition referring to a partial small overlap of the impingement regions by the lower jets is chosen as a limiting case due to the fact that the cooling modes of the underside of the steel strip are closer to the top. It is worth adding that the convergence

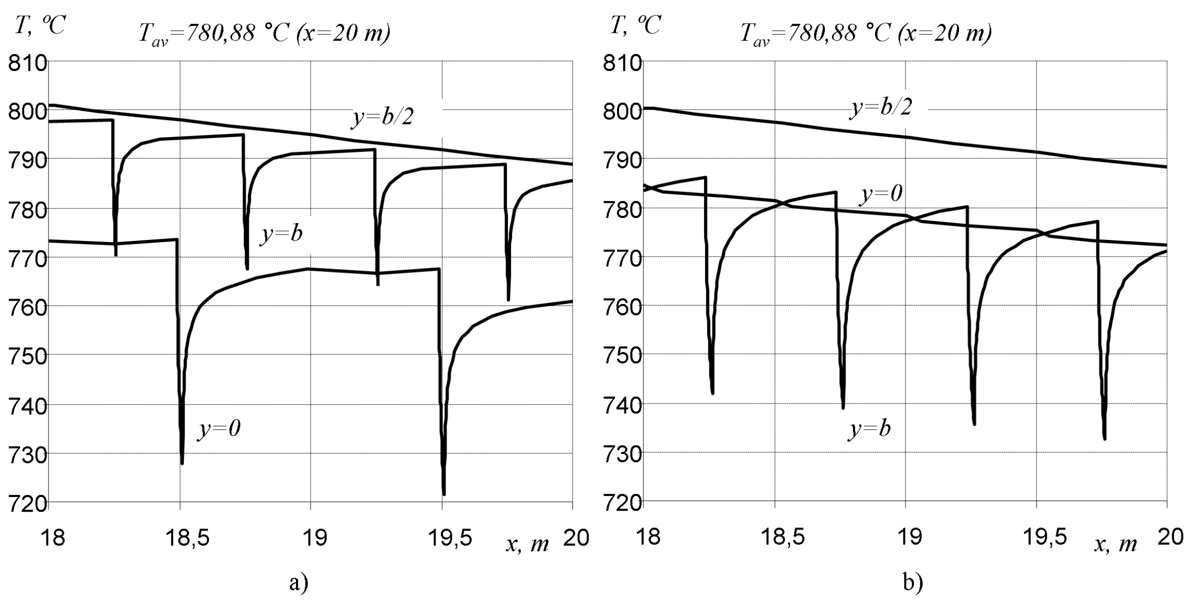

Fig. 3. A temperature distribution in the direction of the steel strip movement (a chess pattern, a strip thickness of 4 mm, a movement velocity of 10 m·s^{-1}): (a) z = 0; (b) z = L_z/2.

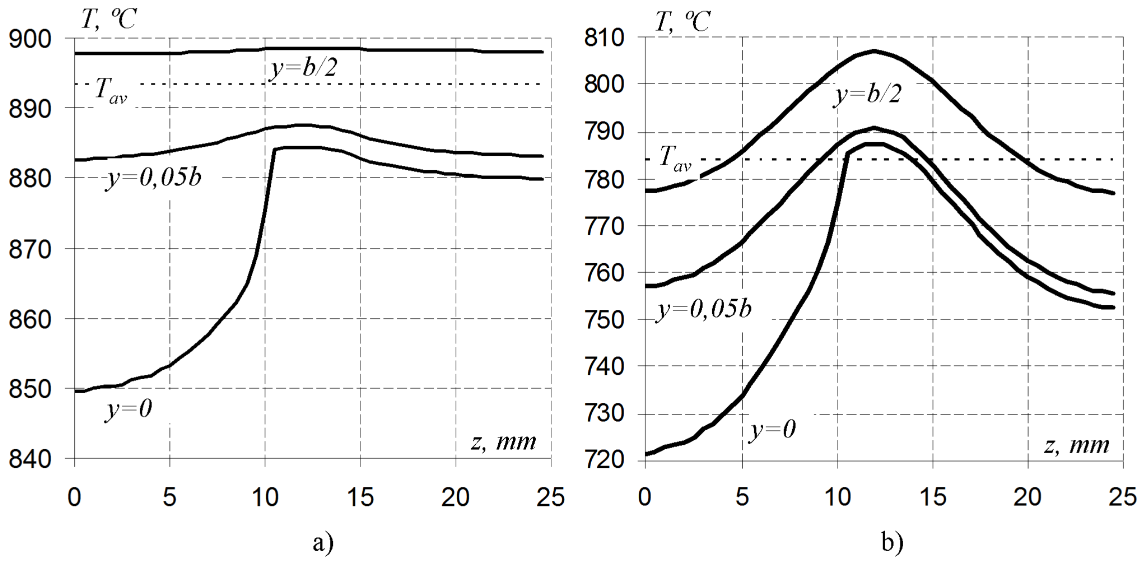

Fig. 4. Lateral temperature distributions in the upper part of the strip (a linear cooling scheme): (a) during the passage of the 3-rd row of the upper jets; (b) during the passage of the 39-th row of the upper jets (a strip thickness of 4 mm, a movement velocity of 10 m s^{-1}).

of the cooling modes of the strip is ensured not only by minimization of the distance between the impingement regions but also by the increase of the number of nozzles in the lower irrigation system.

Figs. 2 and 3 present examples of the temperature change calculation at points on the steel strip surface of the past impingement regions and in the middle part of the strip of a thickness greater that of these regions. The calculation results show significant differences in the temperature distribution in the direction of the steel strip movement in case a linear and a chess cooling scheme are used. However, the average mass temperature of the steel strip depends weakly on the layout of the jets. The cooling velocity of the steel strip is slightly higher in case of a linear scheme than that of chess scheme application. However, the uniform distribution of the temperature across the width of the steel strip is more important under real production conditions since the quality of the finished product depends directly on that.

Fig. 4 shows the lateral temperature distributions using a linear cooling scheme. Fig. 4 (a) shows that a temperature drop occurs in a very thin temperature layer near the surface of the steel strip in the impingement region. However, the non-uniformity of the boundary conditions has a big effect on the temperature distribution in the bulk of the steel strip (y = b/2) during the cooling process which can lead to a non-uniformity of the mechanical properties of the finished hot rolled steel strip (Fig. 4 (b)).

The temperature distribution looks more complicated with the staggered layout of the jets so it is decided to depict the distribution as a surface. Fig. 5 shows the temperature distribution calculated with similar initial parameters. The calculation results show that a more uniform temperature distribution over the width of the strip (z direction) is observed with such a scheme. A more uniform temperature distribution across the strip width (z direction) is also observed with such cooling scheme.

The chess layout of the jets provides a more stable temporal temperature distribution during the cooling process. The temperature difference between the middle part of the strip in respect to its width and the edge of the computational area (it coincides with the centers of the impingement regions of the jets) increases constantly in case of a linear scheme, while the temperature field obtains a certain shape quite quickly, which then changes slightly, in case of a chess pattern application.

A more detailed analysis of the jets layout effect on the temperature field of the moving steel strip as well as the effect of such geometric parameters like the distance between the rows of jets, the distance between the jets in a row and the thickness of the steel strip have been described in refs. [1 - 3].

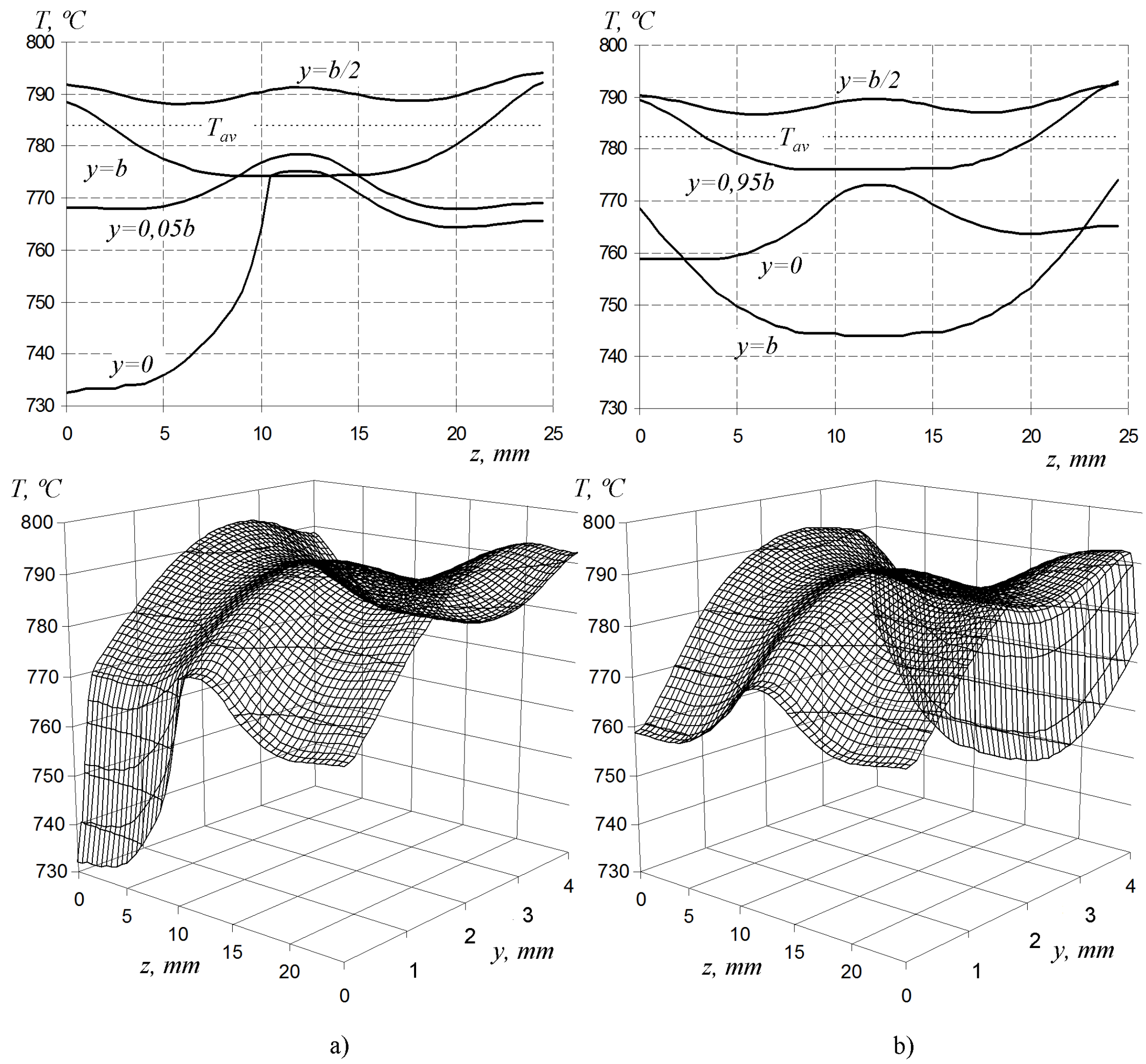

Fig. 5. A temperature field at the cut of the 39-th row: (a) upper jets; (b) lower jets (a strip thickness of 4 mm, a movement velocity of 10 m s^{-1}**).**

DESCRIPTION OF THE STUDY OBJECT

The previously proposed physical and mathematical heat transfer model during cooling of a moving steel strip with a jet system has been experimentally tested in a numerical modeling of the thermal processes during strip cooling in the laminar cooling section of Rolling Mill 2000 of the Public Joint-Stock Company «Magnitogorsk Iron and Steel Works». The general scheme of the studied cooling system is presented in Fig.6. The length of the entire system (from the last finishing stand to the steel strip cooling unit into a roll) is 75 m including an active water cooling zone of 39.5 m. The cooling zone can be divided into three sections in the direction of the steel strip movement:

- No 1 and No 3 consist of four sections, each one of them contains a single-row upper collector and four lower collectors. The length of these sections is about 7.2 m.

- No 2 consists of 14 sections including two two-row upper collectors and four lower collectors.

It is possible to regulate the water consumption or completely shut off its flow in all areas of each section (both in the upper and in the lower part). The diameters of the nozzles and the limits of the water consumption change are different for each of the sections both in the lower irrigation system and in the upper one. The maximum water consumption of the entire system is 12160 $m^3 h^{-1}$. These and other geometrical parameters such as

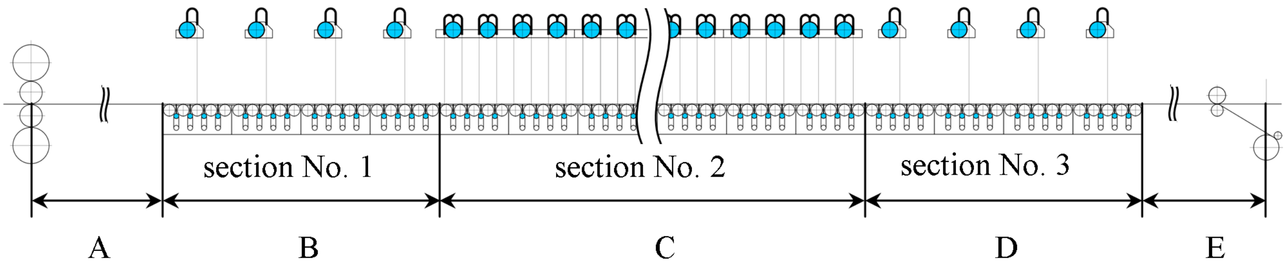

Fig. 6. A general scheme of the studied steel strip cooling system:

the distance between the nozzles in a row, the distance between the sections, the distance from the upper and the lower headers to the surface of the strip are taken into account in developing the model and the calculated heat exchange program.

A, E - air cooling zones; B, D - laminar (water) cooling sections with a single row of upper headers; C – a laminar (water) cooling section with a double row of upper headers.

MAIN RESULTS OF THE TEMPERATURE FIELD CALCULATION

The preliminary calculations show that the layout of the jets has a weak effect on the average cooling velocity (with a significant difference in the temperature distribution over the spatial coordinates). Therefore, the calculations are carried out in parallel for both the linear and the chess pattern. The change of the jets layout in this cooling system is considered during its reconstruction.

Fig. 7 shows an example of the temperature field calculated in the longitudinal direction of the strip as it moves in the cooling system studied (curve y = 0 refers to the temperature of the upper surface of the strip, while curve y = b/2 refers to the temperature in the middle of the strip in respect to its thickness). The figure shows the characteristic sharp temperature drops on the surface in the jet leakage areas as well as the significant difference between the surface temperature and that of the middle of the strip which increases as the strip moves in the jet cooling system.

The transverse temperature distributions (in case of identical initial parameters) at exiting section No. 2 of the studied jet system are shown in Fig. 8. The results of heat transfer numerical simulations show that the temperature distribution over the thickness of the strip (direction y) is slightly more uniform in case of using a linear scheme than that of chess scheme application. However, the use of a linear scheme leads to a significant increase of the non-uniformity of the temperature distribution in the transverse direction in all inner layers

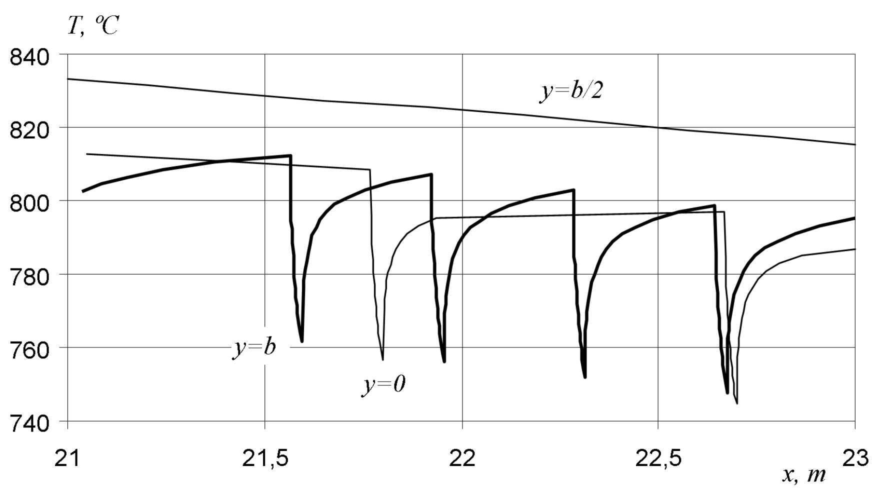

Fig. 7. A temperature distribution in the movement direction of a strip with a thickness of 4 mm, a speed of 10 $m\cdot s^{-1}$ and an initial temperature of 900°C in presence of a linear cooling scheme.

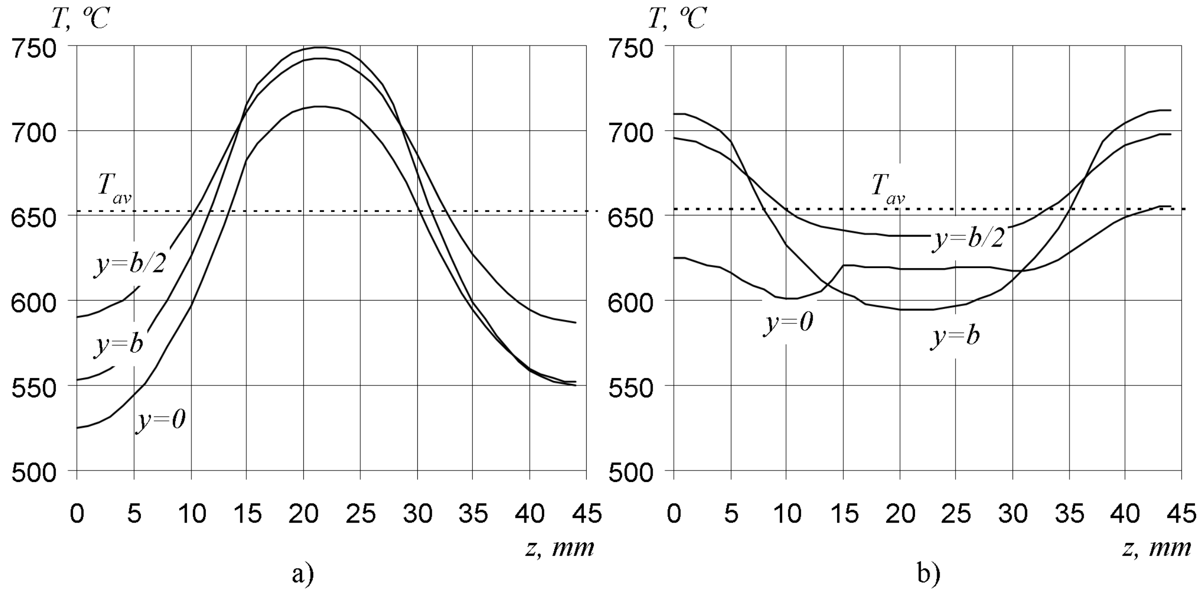

Fig. 8. A lateral temperature distribution of the strip at the exit from section 2 of the cooling system (a strip thickness of 4 mm, a movement velocity of 10 m s^{-1}, an initial temperature of 900ºC, all sections are included): (a) in a linear scheme presence; (b) in a chess scheme presence.

of the strip (Fig. 8 (a)). Such an uneven temperature can lead to substantial heterogeneity of the mechanical properties of the finished hot rolled strip.

Thus, the chess cooling scheme is more preferable despite of the large uneven cooling across the strip thickness (Fig. 8(b)). Another important factor affecting the temperature uneven distribution across the width refers to the presence of an air gap between the impingement regions on the lower surface of the strip. Since the heat transfer in air is significantly lower than that in other cooling zones, the presence of an air gap leads to a strong non-uniform strip temperature in the transverse direction, both for the linear and the chess cooling schemes (Fig. 9).

The numerical experiments carried out show also that it is possible to achieve a significant increase of the cooling velocity with an increase of the water consumption in the upper system through a decrease of the jet velocity in the lower one. This is due to the fact that the upper cooling system is more efficient in heat removal from the strip due to the presence of a wide film boiling zone on the upper surface. At the same time, the strip is cooled in air on the bottom surface outside the impingement regions.

AN ESTIMATION OF THE THERMAL MODEL RELIABILITY

The reliability of the proposed physical and mathematical model is verified by comparing the heat transfer calculation data and the results referring to the temperature cooling regimes of the steel strip in the existing Mill 2000 of PJSC “MMK” Magnitogorsk. A temperature regime including the largest number of main cooling sections is chosen aiming this. Such a choice implies the greatest discrepancy between the actual and the calculated final temperature due to a possible imperfection of the thermal water cooling model. The total water consumption in the cooling system is 8720 $m^3 h^{-1}$ (4400 $m^3 h^{-1}$ in the upper cooling system, while 4320 $m^3 h^{-1}$ in the lower one). The calculations refer to a strip with a thickness of 3 mm and 3.99 mm for steel 08 kp, whose thermo-physical properties can be readily found.

The cooling temperatures calculated according to the model developed for both bands (of a thickness of 3 mm and 3.99 mm) do not exceed the values prescribed by the temperature regimes spreadsheet of Rolling Mill 2000.

Moreover, the calculated rate of the strip cooling under these temperature regimes almost coincide (Fig. 10). This data provides to conclude that the physical and

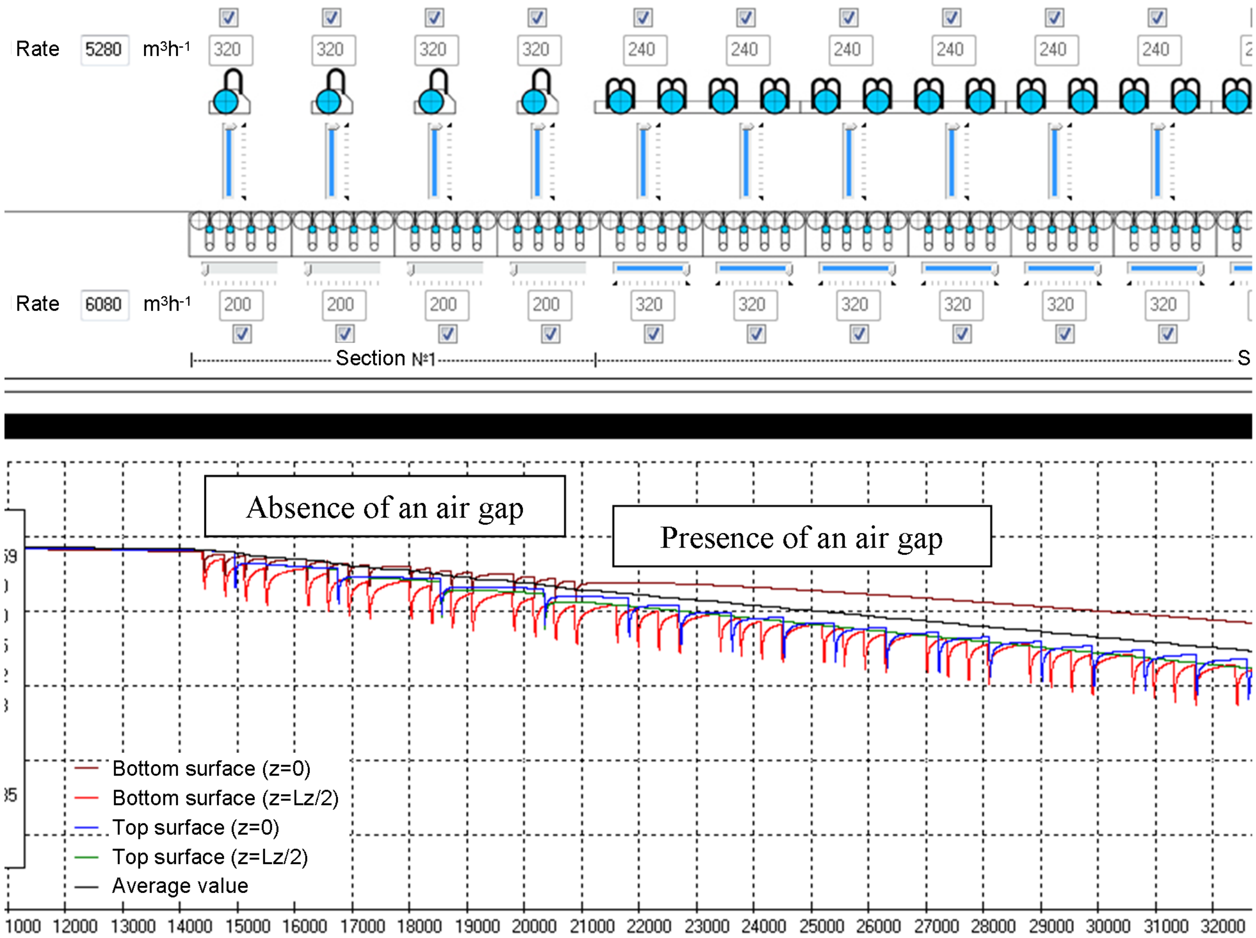

Fig. 9. Longitudinal temperature distribution of the strip (a thickness of 4 mm, a movement velocity of 10 m s^{-1}, an initial temperature of 900ºC) in absence and presence of an air gap between the impingement regions of the lower jets (a chess diagram is used).

mathematical heat transfer model advanced is reliable and the calculation program is correct.

AN EVALUATION OF THE EFFECT OF THE TEMPERATURE DEPENDENT THERMO-PHYSICAL STEEL PROPERTIES ON THE STRIP TEMPERATURE FIELD

The steel heat capacity and thermal conductivity are set constant in the course of the previous calculations. They refer to their average value in the temperature ranges of the cooling start and finish. However, the heat capacity of some grades of steel can change abruptly in this temperature range because of structural modifications taking place.

Typical dependences of the heat capacity and the thermal conductivity of low-carbon and stainless steels are shown in Fig. 11. It is evident that they are almost identical at temperatures above 900ºC for both types of steels. They can be taken as constant in the following calculations. However, the heat capacity of the low-carbon steel undergoes a sharp jump when the temperature of the strip falls in the range of 700ºC - 800ºC.

The number of the mathematical operations and the program time increase significantly because the task becomes nonlinear in view of this dependence. Furthermore, the thermo-physical properties of the metal have to be calculated at each time step not only at the point considered but also at points in its viscinity. The previous calculations have shown that a sharp temperature drop occurs in a thin surface layer when the strip passes through an impingement region under a stream of water. It is then quickly restored due to the heat input from the strip inner layers. Such a temperature drop can be tens of degrees Celsius and is observed in

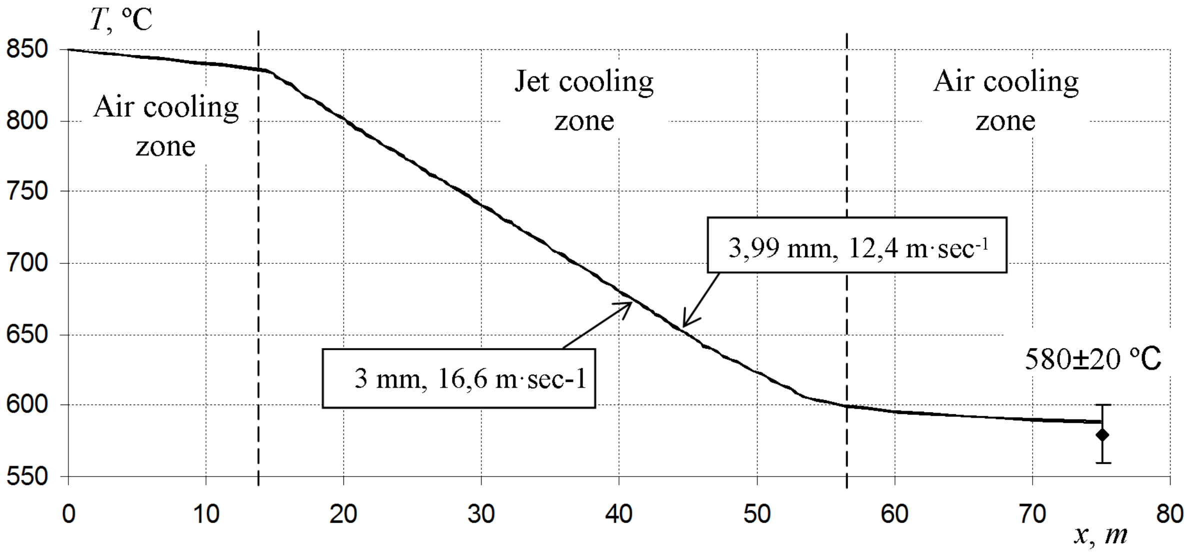

Fig. 10. An estimated drop of the mass-average temperature of the strip in the cooling system studied.

the region of a steel phase transformation. However, the passage time of this zone at a typical velocity of the strip movement of 10 m s^{-1} is $(2 - 5)\cdot 10^{-3}$ s. No significant structural changes are possible within such a short time and therefore the thermal properties of the metal are not expected to change. Thus, it is advisable to take into account the change of the thermo-physical properties of the strip at the average cross-sectional temperature. This will significantly reduce the time of the numerical calculation at each moment of time.

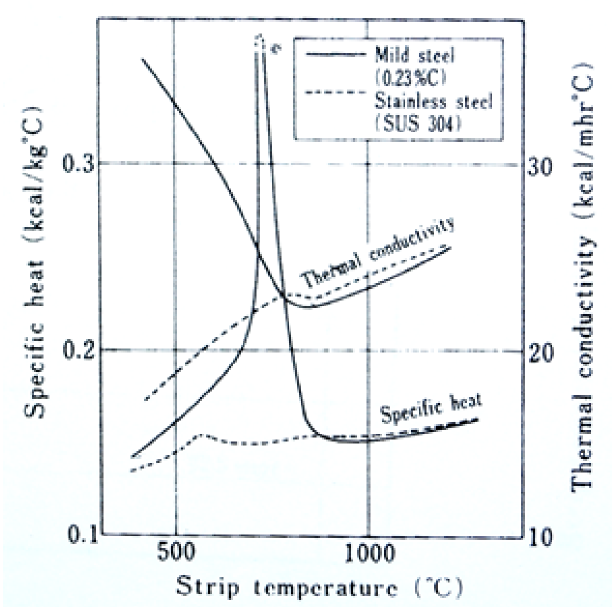

Fig. 11. A temperature dependence of steel thermo-physical properties [4].

Fig. 12 shows the calculation of the temperature drop of a low carbon steel strip (0.23 % C) of a thickness of 3 mm and 4 mm taking into account the change of its thermo-physical properties with the temperature increase (Fig. 11) at a strip movement velocity of 10 m s^{-1}. It can be seen that the strip cooling velocity varies significantly in the temperature range, while structural changes occur in the steel. This change of the cooling velocity becomes more noticeable with a strip thickness decrease.

The temperature dependence of the steel heat capacity also affects the calculation of the strip final temperature. The heat balance equation is not affected by the temperature dependence of the steel heat capacity or the assumption that the heat capacity is a constant, averaged over the entire temperature range of the cooled strip. However, the calculation of the average mass temperature of the strip taking or not taking into account the temperature dependence of the heat capacity gives different results in respect to the final strip temperature (Fig. 13). This is explained by the fact that the heat flux from the strip surface according to the proposed in Part 1 mathematical model is a function of its temperature. Therefore, the use of the heat balance equation for the simplified calculation of the strip temperature drop is incorrect. Thus, it is necessary to take into account the strip temperature effect on its thermo-physical properties when calculating the strip temperature of some steel grades (particularly in case of a low carbon steel) despite

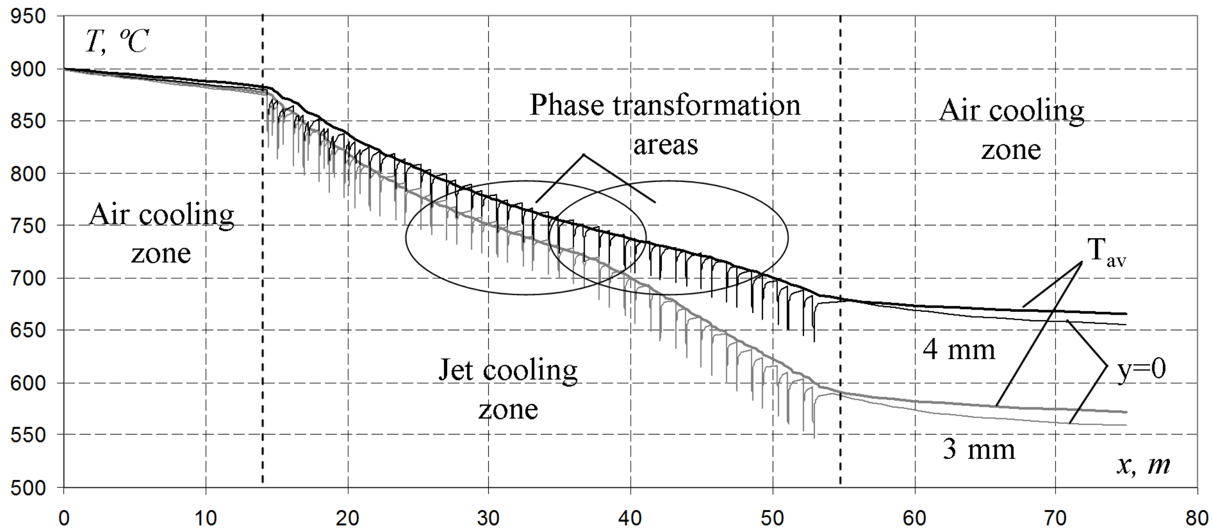

Fig. 12. A strip temperature distribution during cooling on a discharge roller table (y = 0 refers to the upper surface of the strip, T_{av} is the average temperature of the strip).

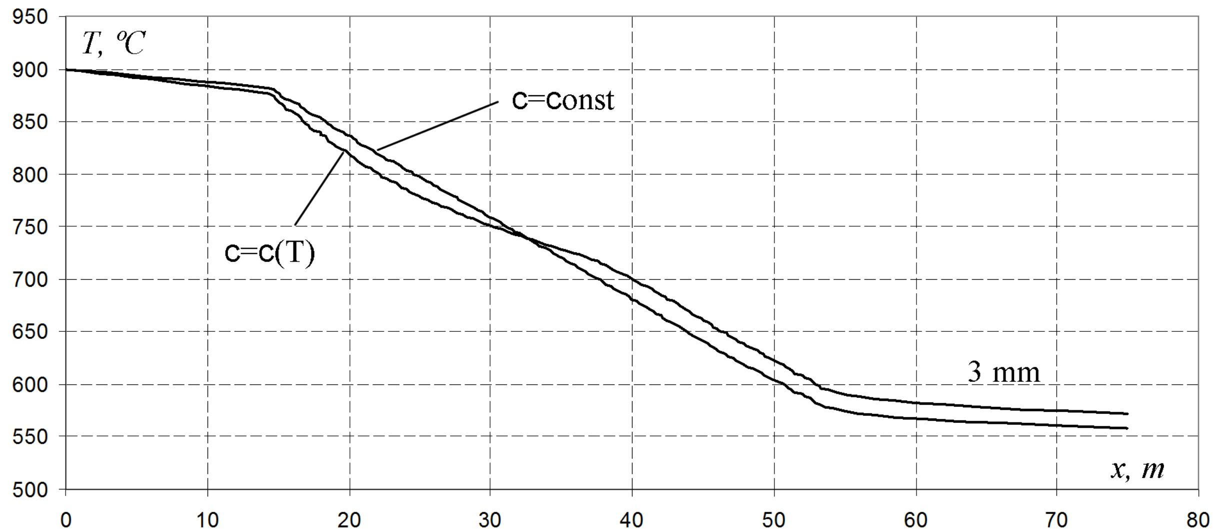

Fig. 13. A strip average temperature drop at a constant heat capacity (c = const) taking into account the latter temperature dependence (c = c (T)).

of the complexity of the mathematical model and the increase of calculation time.

CONCLUSIONS

The developed physical and mathematical model of cooling of a moving strip with the application of an inkjet system shows its adequacy when applied to accelerate the cooling of a hot rolled strip in Rolling Mill 2000.

The results of this investigation are used to introduce changes to the design of the developed cooling system of the hot-rolled strip of OJSC MMK 2000 aiming to improve the uniformity and the efficiency of strip cooling.

The developed physical and mathematical model and the results of the heat transfer calculations provide recommendations focused at the improvement of the efficiency of the cooling systems of a moving steel strip which are appropriate for the existing as well as for the newly designed jet cooling systems of various basic geometric features. This model can be used as a part of an integrated intellectual support system for managing multi-stage metallurgical processes [5].

REFERENCES

1. A. Koldin, N. Platonov, The study of heat transfer in the surface layer of the metal during the leakage of a liquid jet, / Thermal Engineering, 3, 2008, 37-40, (in Russian).
2. A. Koldin, Heat transfer of a moving steel strip during jet cooling, Dissertation, Yekaterinburg, 2012, 135, (in Russian).
3. A. Koldin, N. Platonov, V. Semenov, Investigation of heat transfer in a moving steel strip during jet cooling, Vestnik of Chelyabinsk State University, Series: Physics, 25, 3, 2008, 60-67, (in Russian).
4. G. Tacke, H. Litzke, E. Raquest, Investigation into the efficiency of cooling system for wide-strip hot rolling mills and computer-aided control of strip cooling, Accelerated cooling of steel, Proc. of a Symp., Pennsylvania, August 19-21, 1985, Ed. by Sothwick P. D.,1986, 36-54.
5. O. Logunova, I. Matsko, I. Posochov, Integrated system structure of intelligent management support of multistage metallurgical processes, Vestnik of Nosov Magnitogorsk State Technical University, 5, 45, 2013, 50-55.