УДК 621.771.23:621.77.016.2:621.78.08

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AN ANALYTIC MODELING THE AIR-MIST SECONDARY COOLING FOR CONTINUOUSLY CAST SLABS

An early developed approach toanalytic modeling the water-air cooling of flat steel products, based on meeting the "additivity" rule requirements, is applied to the secondary cooling of continuously cast slabs. The regimes, developed using the approach, provide optimal combinations of the heat transfer rate, residual stress levels and nonlinear phenomena absence during the cooling. Good accordance of the calculated and industrially measured cooling trajectories together with the corresponding regime parameters was reached. The use of analytic dependencies obtained provides the higher effectiveness to control the secondary cooling compared with currently applied techniques of numerical on-line solving the systems of differential equations. The cooling regimes developed provide "softer" cooling within the whole temperature range, compared with the early models. An additional improvement of the slabs' surface quality is expected to obtain because of the slow cooling according to the developed regimes.

Keywords: *water-air cooling, continuously cast slabs*, *air-mist secondary cooling,analytic modeling.*

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АНАЛІТИЧНЕ МОДЕЛЮВАННЯ ВТОРИННОГО ОХОЛОДЖЕННЯ БЕЗПЕРЕРВНО-ЛИТИХ СЛЯБІВ ВОДО-ПОВІТРЯНИМ ТУМАНОМ

Раніше розроблений підхід до аналітичного моделювання водоповітряного охолодження металопродукції було застосовано до вторинного охолодження безперервно-литих слябів. За розроблених режимів досягаються оптимальні комбінації швидкості тепловідведення, залишкових внутрішніх напружень та відсутність нелінійних явищ. Встановлено тісне співпадіння розрахованих та промислових траєкторій охолодження. Наголошено на вищій ефективності управління процесом порівняно з існуючими підходами. Нові режими забезпечують повільніше охолодження та підвищення якості слябів.

Ключові слова: *водоповітряне охолодження*, *безперервно-литі сляби, вторинне охолодження водоповітряним туманом, аналітичне моделювання.*

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АНАЛИТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ВТОРИЧНОГО ОХЛАДЖЕНИЯ НЕПРЕРЫВНО-ЛИТЫХ СЛЯБОВ ВОДО-ВОЗДУШНЫМ ТУМАНОМ

Ранее разработанный подход к аналитическому моделированию водовоздушного охлаждения металлопродукции был применен ко вторичному охлаждению непрерывно литых слябов. Установлено тесное совпадение расчетных и промышленных траекторий охлаждения. Разработанные режимы обеспечивают менее интенсивное охлаждение и повышение качества слябов.

Ключевые слова: *водовоздушное охлаждение, непрерывно-литые слябы, вторичное охлаждение водовоздушным туманом, аналитическое моделирование.*

Problem formulation. Secondary cooling of continuously cast slabs (SCCCS) in many respects is responsible for the production effectiveness and quality of the most types of modern steel product [1]. It's known [2,3] that in order to reach the high quality of CCS, a definite (nominal) time dependence of metal temperature $T_0 = T_0(\tau)$ has to be provided during the process. So, obtaining the quantitative relations between the temperature $T_0(\tau)$ and the technological parameters in analytic form for direct practical application is an important task. A known important feature of the secondary cooling is the obligatory process automated control, the accuracy and effectiveness of which is determined mainly by amount of online numeric calculations. The above problems become the most actual under the widely used water-air secondary cooling (WASC) conditions. Besides, the existing models [4,5]do not take into account necessity to fulfill the "additivity" rule, known also as "mixture" rule, concerning the main water-air cooling (WAC) characteristics: volumes and consumptions of the components. Evidently, that violation of the rule leads to nonlinear phenomena or processes appearing during the WAC and therefore to decrease the automated control accuracy and effectiveness.

Last publications brief overview. Basically, the conditions of SCCCS are defined proceeding from alternative requirements such as to avoid arising various types of cracks together with reaching the highest casting speed [1-5]. Since the dependence $T_0 = T_0(\tau)$ as a rule is defined by the mathematical modeling the various processes during the cooling, further verification and practical use of the results requires the quantitative relations between the temperature $T_0(\tau)$ and the technological parameters. So, the practical use of mathematical models [4,5] that require solving the systems of differential equations leads to substantial difficulties caused by a big amount of online numeric calculations needed, together

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with absence of direct relations between the metal temperature and industrial technology parameters. The corresponding novel model for WAC was developed earlier [6]. It was shown that the model eliminates such phenomena as exceeding or deficiency of a water-air mixture component contacting at a time with a cooled surface.

The aim of the investigations is to develop such regimes of WASC for CCS that correspond optimal combinations of the heat transfer rate, residual stress levels and nonlinear phenomena absence for increasing the accuracy and effectiveness of the process control together with the slabs' quality

Main results presentation. Calculations in the work were conducted according to the automated control realization algorithm. On the initial stage, the model parameters were defined to provide the maximum accordance of the calculated metal temperature time dependence with actual or nominal one. The last as a rule, is predetermined by using an optimization technique according to various criteria [4,5]. Further, the dependence of the heat transfer coefficient against secondary cooling zone length was calculated to specify the length distributions of cooling rate and the corresponding component fluxes. So, the data obtained using the proposed model can provide meeting the requirements to the SCCCS – process based on the one hand, on the optimization results, previously obtained using various criteria, and on the other hand- on the necessity to fulfill the "mixture" rule.

Following to the developed WAC model [6], meeting the "mixture" rule requirements is provided by the use of the following time dependence for the water fraction in a water-air mixture volume:

$$\beta(\tau) = \beta_0 \exp\left(\frac{\Delta Q_{В П}^{m}}{\Delta V_{В П}^{m}} \cdot \tau\right) + \frac{Q_{П}^{m}}{\Delta Q_{В П}^{m}}\left[\exp\left(\frac{\Delta Q_{В П}^{m}}{\Delta V_{В П}^{m}} \cdot \tau\right) - 1\right] \qquad (1)$$

where: β_0 -value of $\beta(\tau)$ at a time $\tau = 0$;

$\Delta Q_{\mathrm{ВП}}^{m} = Q_{\mathrm{В}}^{m} - Q_{\mathrm{В}}^{m}$;

$Q_{В(П)}^{m} = \frac{V_{В(П)}^{m}}{\tau_{В(П)}}$ - maximum flux of water(air) for exact cooling of a given metal volume using the single component;

$\Delta V_{ВП}^{m} = V_{В}^{m} - V_{П}^{m}$;

$V_{В(П)}^{m}$ - maximum volume of water(air) necessary to cool a given metal volume using the corresponding component alone;

$\tau_{В(П)}$ - full cooling duration in single water(air) for the metal volume.

According to the equation (1), water-air cooling should be conducted in such a way that every next portion of water has to contact with a given metal surface only if the previous portion has finished the heat transfer as a result of it's removing or evaporation. Otherwise, an exceeding or a deficit of a mixture component will arise with the corresponding discrepancies inthe cooling conditions.

Using the equation (1) the metal temperature time dependence during WAC $T(\tau)$, has been calculated using the next formula in accordance with the "mixture" rule as a base of the developed model:

$$T(\tau) = \beta(\tau) \cdot T_{В}(\tau) + [1 - \beta(\tau)] \cdot T_{П}(\tau) \qquad (2)$$

where $T_{В(П)}(\tau)$ – cooling trajectory for a metal volume exactly in water(air).

The dependences $T_{В(П)}(\tau)$ were calculated by numerical solving the heat transfer equation under the border conditions determined by an initial and finish metal temperature. The calculations were conducted using the corresponding thermo-physical characteristics for each moved cooling media.

The heat transfer coefficient was also calculated according to the formula:

$$\alpha = C_{Me} \cdot \rho_{Me} \cdot V_{Me} \frac{dT(\tau)}{d\tau} \cdot \frac{1}{[T(\tau) - T_{0c}]} \qquad (3)$$

where: C_{Me}–steel heat capacity;

ρ_{Me}– steel density;

V_{Me}– steel volume cooled;

T_{0c}– cooling media temperature

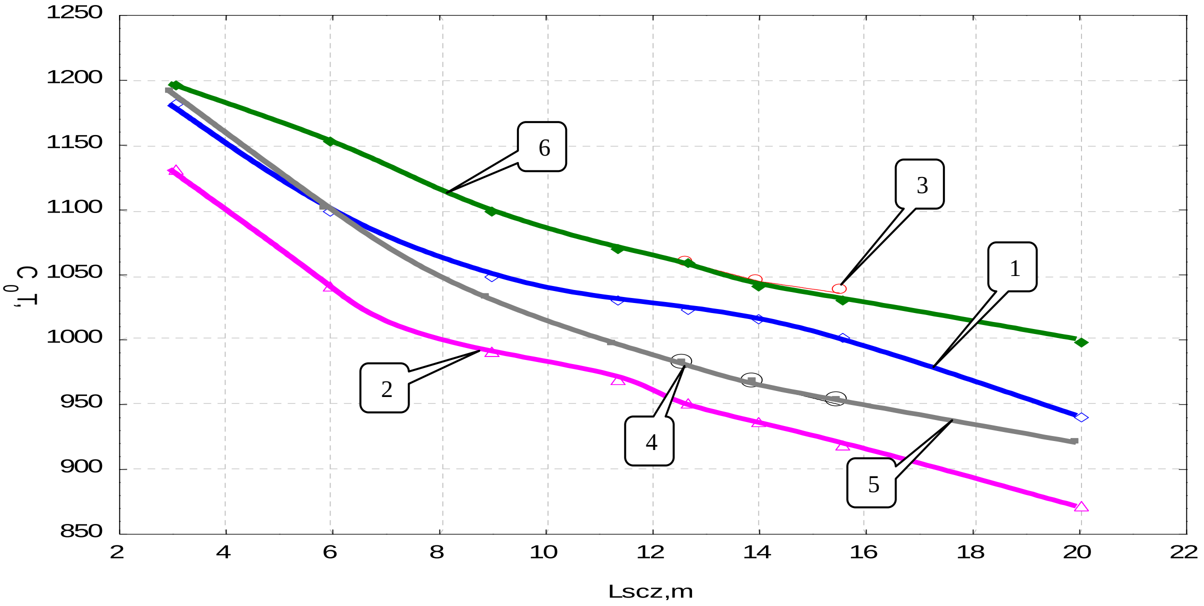

*Fig.1.***Secondary cooling zone length distributions of the continuous casting slab temperature according to existing model [4](curve 1,2), experimental measurements [4](curve 3,4), proposed model(curve 5,6)**

According to [4], there are two typical regimes of SCCCS: “soft” and “hard” depending on a steel chemical composition, the use of which is rather effective in industry. Modeling the regimes by the numerical solving the system of differential equations for heat transfer and residual stresses appearance[4] leads to some corrections of existing industrial regimes (see Fig.1, curves 1 and 2, respectively) and several improvements of the slabs’ quality concerned with surface cracks. Meantime, the most considerable additional decreasing the amount of cracked slabs was achieved by the authors [4]empirical increasing the theoretically calculated slabs’ temperatures at final secondary cooling stages (see Fig.1, curves 3 and 4, respectively). Taking into account the defect slabs appearance after such the model[4] corrections, reported results show insufficient adequacy of the model used [4], not only for low but for high temperature ranges calculations. Nevertheless, the experimentally confirmed slab temperature data [4], may be used to characterize the required CCS cooling trajectories for wide variety of steels (see Fig.1, curves 1…4).

The slab temperature vs. secondary cooling zone length dependencies, calculated using our model [6] under the same slab manufacturing conditions (1000×1200×250 mm slab size, 0,8 m/min casting speed) and steel grades are shown on Fig.1 as curves 5 and 6. It should be noted the following features of the calculated curves:

- General good agreement with the experimental data and calculated curves based on the existing model [4].
- Wide range of possible slab temperature changes by means of variations of only one well technologically defined, easy measured and controlled model parameter β: 0,17 and 0,23, respectively for “soft” and “hard” regimes.
- Cooling trajectory corresponding to the recommended by our model SCCCS regime (curve 5), in fact, unifies two early proposed separate “soft” (curve 1) and “hard” (curve 2) cooling regimeswhich cannot be realized under the same technological parameters together with the additional corrections (curve 4) providing reliable avoiding the cracks formation [4]

The obtained results particularly means that in the both cases of “soft” and “hard” SCCCS regime, the proposed model recommends “softer” cooling in the whole temperature interval, comparing with the calculated data [4] obtained based on the optimization of the heat transfer and residual stresses formation processes. So, an additional improvement of the slabs’ surface quality should be reasonably expected, due to decreasing appearance probability not only for the “cold” cracks but also for the “hot” ones during the SCCCS.

Based on the curves calculated using our model for the cases, corresponding to the “soft” (curve 6) and “hard” (curve 5) SCCCS regimes, an important cooling process characteristic – heat transfer coefficient, α, was defined for the above classification conditions. The results obtained for α are shown in

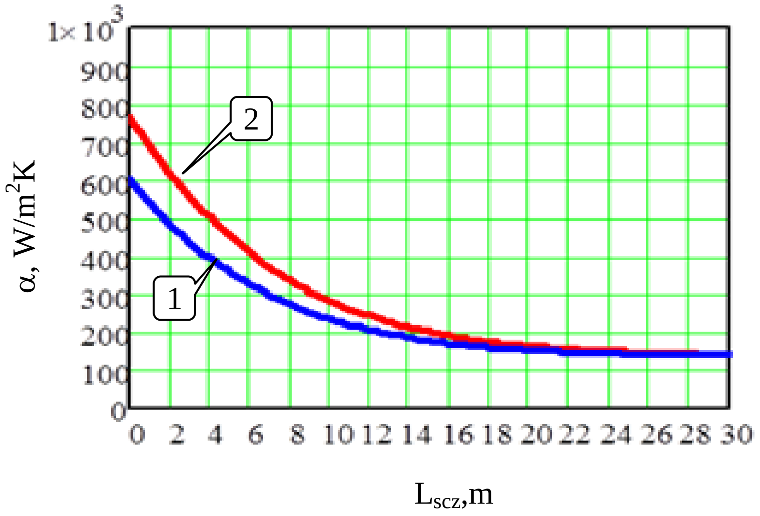

*Fig.2.***Secondary cooling zone length distributions of the heat transfer coefficient according to the proposed model for the “soft”(curve 1) and the “hard” (curve 2) cooling regimes.**

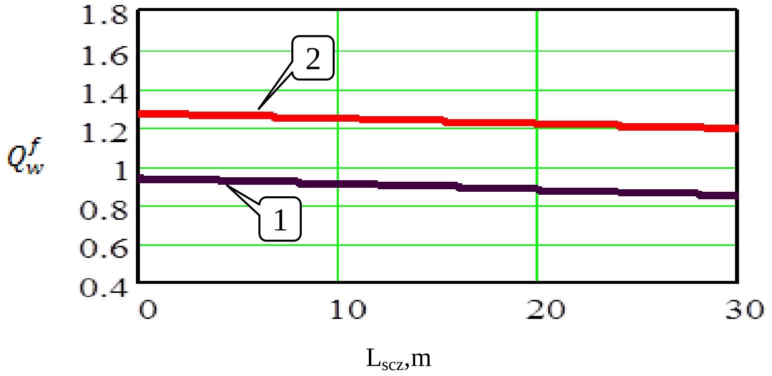

*Fig.3.***Secondary cooling zone length distributions of the actual cooling water consumption according to the proposed model for the “soft”(curve 1) and the “hard” (curve 2) cooling regimes.**

the form of its secondary cooling zone length dependence on Fig.2. Comparing them with the corresponding data given by other authors [5] shows also good adequacy of the proposed approach.

Based on the definition of β [6] in general case it may be written:

$$\beta = {}^{V_w^f}\!\big/_{V_w^m} \qquad (4)$$

where: V_w^f – actual (measured) volume of water used to cool a metal volume

V_w^m – maximum (nominal) water volume needed for exact cooling of the metal volume in necessary temperature interval.

As it was shown in [6] in dependence of WAC conditions, V_w^f may characterize on the one hand, a real time interval of the water usage during the consecutive water-air supply. On the other hand, under the air-mist cooling conditions, due to an equal time of the components supply, V_w^f should be considered as a part of total necessary amount of the cooling water. Proceeding from the above, for the air-mist cooling one may write:

$$\beta = {}^{Q_w^f}\!\big/_{Q_w^m}$$

So, using the formula (4), the length distribution of $Q_w^f = dV_w^f/d\tau$ – actual cooling water consumption may be defined for a necessary air-mist cooling conditions: β =β(τ). The corresponding calculated length dependencies of Q_w^f for the “soft” and “hard” secondary cooling regimes are shown of Fig.3. It is seen good agreement between calculated levels of Q_w^f and industrially applied ones:$Q_w^f \approx 0{,}4 \ldots 30\, m^3/h$, [7,8].

Conclusions

1. An early developed approach to modeling the water-air cooling processes, based on meeting the “additivity” rule requirements, is applied to quantitative description of the secondaryair-mist cooling of continuously cast slabs.
2. Obtained good accordance of the calculated and predefined cooling trajectories together with the regime parameters confirms high adequacy and flexibility of the approach to be used in various industry conditions including step-wise changes of the cooling regime parameters.
3. The use of analytic dependencies within the frame of the proposed approach to specify the necessary cooling regime parameters, provide the higher effectiveness to control the CCSSC process in comparing with currently applied numerical on-line solving the systems of differential equations

4. The WAC regimes, developed using the proposed approach, provide optimal combinations of the heat transfer rate, residual stress levels and nonlinear phenomena absence during the CCSSC process.
5. The CCSSC regimes, developed using the proposed approach provide “softer” cooling in the whole secondary cooling temperature range, compared with the calculated results [4] corresponding to optimization of only the heat transfer and residual stresses formation processes.
6. An additional improvement of the slabs’ surface quality due to decreasing appearance probability for not only “cold” but also for “hot” cracks during the CCSSC is expected to occur because of the “softer” cooling according to the developed WAC regimes.

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Стаття надійшла до редакції 05.05.2019

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