A heat balance model of zinc pot and its application

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Abstract. In this paper, the problem of stripe temperature at the entrance of the zinc pot is addressed in a novel way. Based on in-depth analysis of thermal features of hot-dip galvanization, a generalized heat-balance mode has been established that has wider adaptivity within the production lines. The relationship between the pot load, the galvanization load and the productivity has been re-characterized by introducing a new concept of line-area ratio. Subsequently, the stripe temperature can be estimated based on the model. The effectiveness of the proposed model has been verified by real-time application to the production lines with temperature estimation error within ±3 ℃. As such, effective temperature compensation can be implemented that significantly improves the galvanization quality.

Keywords: Energy balance model, Galvanization,, Heat loss quantification, Stripe temperature.

1 Introduction

Hot-dip method is one of the most popular galvanization techniques which has been widely used in the production lines around the world. Accurate status monitoring and the effective control of the zinc liquid temperature are two key factors that determine the quality of the products. Due to limited measurement techniques, the temperature of the zinc liquid cannot be obtained accurately. Moreover, the type, the size and the productivity of the process tend to cause unpredictable temperature variation of the steel at the entrance, so that the temperature control strategy cannot be implemented effectively. Such temperature issue has been a main obstacle for increasing the quality of the products that exists widely in the production lines. Therefore, researchers from both academic institutes and industries have been keen in looking forward to the possible solutions to the temperature issue from various aspects. Dong et. Al [1-4] proposed a method based on heat balance tests to calculate the temperature of the steel stripe. Dubois Michel[5] established the heat-balance model deploying historical production data that selected with strict constraint, so that the temperature of the steel stripe at the entrance can be obtained. Heat balance-based methods are known as the most effective way for steel stripe temperature estimation. Under the

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circumstance of material balance, the balance between the incoming and output energy can be quantifies by the heat balance equation. Therefore, the energy that brought by the steel stripe can be retrieved accurately, so that the stripe temperature can be calculated. Commonly, the estimation is conducted during a short period of time, usually 4-6 hours when the speed of the production line remains at a low level. The heat dissipation is obtained by stopping the production line for 24 hours. However, such heat-balance estimation results are not practically useful in real production process due to three facts: ① Maintaining the production at a low level for 4-6 hours cannot be guaranteed;②it is hard to keep the liquid temperature steady for a long period of time; ③The heat dissipation, which contain the dissipation caused by the air knife and the heat loss at the liquid surface, is much more than the heat load of the zinc pot during temperature keeping process. Moreover, such heat loss cannot be quantified by existing techniques. Therefore, the aforementioned heat balance methods under strict constraints are not implementable for large practical production lines.

2 Thermal features of the zinc pot

The operation of zinc pot obeys an energy balance principle, i.e. the heat income equals to the heat output, if the material balance is attained. Bounded by the material flow, the zinc pot of the production line can be regarded as a comparatively isolated energy system, thanks to the fact that independence thermal features of the hot-dip equipment. The so-called thermal feature characterize the relationship between the productivity, energy loads and the parameters of the pot structure and the operation, which become a heat load function of merely productivity if the structure parameters are fixed.

There are three main approaches for characterize the thermal features of the zinc pot: analytical method, area method, and flow method. If adopted, an in-depth insight of the zinc pot operation can be characterized in a general way. However, due to practical limitation, it can only be analyzed by theoretical analysis and not suitable for calculation in practice.

Empirical method are usually deployed in industrial scenario for characterize the thermal features of the zinc pot which, instead of using thermal process parameters, makes use of the real time measurement or statistic data. The empirical relationship between the pot structural, operational parameters and productivity can be obtained based on regression analysis. Given the structure parameters, the thermal features are simplified as the relation between the operational parametrization and productivity which benefits for practical application.

In this paper, based a deep insight of the historical production data, the thermal relationship is characterized as

$$\boldsymbol{Q} = \boldsymbol{f}(\boldsymbol{P}) \tag{1}$$

where $\boldsymbol{Q}$ denotes the total galvanization load of the zinc pot in KW and $\boldsymbol{P}$ is the productivity of the pot in Kg/h.

Based on such thermal relationship, in a certain period of time, a balanced energy relationship can be concluded as

$$Q_1 + Q_{stripe} + Q_4 = Q_3 + Q_2 \tag{2}$$

where Q_1 is the electrical energy provided by the inductor in the calculation period, Q_2 the galvanization load including the energy of the zinc dross within such period Q_{stripe} represents the heat that bring in or out by the stripe when its temperature differs from that of the zinc liquid. Q_3 is the total dissipation heat of the zinc pot and Q_4 is the heat storage caused by the temperature variation of the zinc liquid.

As a result, the stripe temperature at the entrance of the pot , t_{stripe} can be retrieved as

$$t_{stripe} - t_{bath} = (Q_1 + Q_4 - Q_3 - Q_2)/c \tag{3}$$

in which, t_{bath} the reference temperature of the liquid temperature controller, c is the equivalent specific heat capacity of the stripe. It is worth noting the productivity is the average value within certain producing condition, whose unit is Kg/h. However, in practical producing process, the product feature may vary. In that case, specific processing is necessary which will be discussed in the following section.

3 Theoretical heat balance and calculation analysis of zinc pot

Theoretically, when material balance is attained, the heat balance of the zinc pot can be described as the energy income equals to the sum of all heat outputs. The heat outputs of the zinc pot consists of the heat loss, through both convection and radiation, at the surface of the zinc liquid (Q1, Q2), from the periphery of the pot (Q3, Q4), and from the bottom of the pot (Q5, Q6) and the heat caused by melting Q7.

The heat income includes the heat brought by the stripe Q8 and the electrical energy provided by the inductor Q9. As such, for steady pot temperature and liquid level, it holds that

$$Q1 + Q2 + Q3 + Q4 + Q5 + Q6 + Q7 = Q8 + Q9 \tag{4}$$

which is the theoretical heat balance equation of the zinc pot. In independent zinc pot system, (4) can be used to judge the correctness of the heat outputs and moreover, used to calculate unmeasurable value of heat if other values are known.

It is worth noting that the blow of air knife may cause heat loss but it is not included in (4). Although JOHN A. THORNTON et al. conducted extensive experiments to characterize the heat dissipation of air knife in [6~11], the results are suitable only for specific circumstance. On the other hand, the stripe temperature at the entrance of the pot is also known, so that (4) cannot be solved directly due to multiple unknowns. Moreover, the liquid temperature in the pot tends to varies periodically and the heat storage is highly sensitive to the temperature change. Therefore, the choice of the calculation period is a key factor that have significant influence on the temperature estimation accuracy. In the following analysis, the heat in/out involved in the heat balance calculation is quantified as listed in Tab. 1-3, which are the size of the zinc pot, the feature of the zinc liquid and the theoretical heat calculation corresponding to temperature variation respectively.

Table 1. Structural parameters of the zinc pot.

Size	Length,(m)	Width,(m)	Height of liquid,(m)	Area of the entrance,(m2)
	5.3	3.6	2.7	19.08
Environment parameters	Environment temperature,(℃)		Pot temperature,(℃)	Weight of zinc liquid (Kg)
	25		460	343191.865
Process parameters	Speed of the stripe,(m/min)		Rate of zinc slag production,(Kg/h)	Thickness of plating,(mm)
	118		18.203	77

Table 2. Physical parameter of zinc.

State	Temperature, ℃	Density,Kg/m³	Specific heat, J/Kg.K	viscosity, Pa.s	Thermal conductivity,w/m.K
Solid	20	7099.3			
	25	7102.55	388.462		
	419		458.492		
Liquid	419.5	6791.85	482.769		
	427		482.769		
	450			4.92E-06	
	455	6830.85			
	463	6661.85	482.769		60.25

Table 3. Heat variation caused by heat dissipation and parameter changes.

Surface of the pot entrance	Theoretical heat flow, (KW)	Heat flow change, (KW)
Convection heat loss	70.82473367	
Radiation heat loss	91.64401862	
Surface of the pot entrance	1℃change in molten pool or environment	0.16281548
Convection heat loss	1℃change in molten pool or environment	0.03418258
Radiation heat loss	1℃change in molten pool or environment	0.5123223
Zinc addition, (Kg/h)	Zinc melting heat, (KW)	
1195.3125	99.26934117	
Zinc weight per hour	Error 1Kg	0.083048861
Heat storage change with molten pool temperature (KW/(℃*h))		46.0229
Heat storage change with the liquid height (KW/(mm*h))		0.0170
Heat change with stripe temperature at the entrance (KW/℃)		8.63

Based upon the heat loss listed above, comparing to the heat caused by stripe temperature change, the heat storage change caused by temperature change of molten pool is significantly larger than caused by a tiny change of the liquid height. As such, heat storage caused by the temperature variation within the molten pool is nonnegligible in heat balance calculation notably, the aforementioned theoretical values of the convection and radiation heat loss are under the assumption that the liquid surface is steady. However, in the practical production process, zinc liquid in molten pool tends to keep rolling due to the movement of the strip and the rotation of the support roller and steering roller. Additionally, the jet stream flushes the liquid surface in the pool, so that actual convection loss is much higher than that in the steady liquid condition.

4 Heat balance model of the zinc pot

Aiming at a highly generalized heat-balance model, to avoid the error caused by unknown parameters, the thermal features of the zinc pot has been investigated in depth, the heat income and output has been characterized in a novel way, based upon regression and empirical methods, driven by large amount of historical data.

Considering the thermal feature of the zinc pot, the pot temperature is maintained by the continuous heating from the inductor. If the type, the size and galvanization thickness of the product are confirmed, apart from the heat dissipation, the heat from the inductor are all used for melting zinc, under the assumption that the stripe temperature at the furnace entrance are identical to that of the zinc liquid. In the mean time, the heat output is consists of heat dissipation to the environment and the dissipation of air knife flushing. In this regard, denoting the gross load of the zinc pot by $\boldsymbol{Q_1}$, galvanization load by $\boldsymbol{Q_2}$ and the total heat dissipation load by $\boldsymbol{Q_3}$, one can conclude that $\boldsymbol{Q_2}$ is linear in the productivity $\boldsymbol{P}$, i.e.

$$Q_2 = K_2 \cdot P + C_2 \tag{5}$$

where $\boldsymbol{K_2}$ is ratio parameter related to the thickness of the zinc layer, $\boldsymbol{C_2}$ is the heat provision when the productivity is zero, KW.

As for the gross heat loss $\boldsymbol{Q_3}$, it includes the heat loss from the peripheral of the the pot and the liquid surface, and also the flush heat loss from the air knife $\boldsymbol{C_f}$, the values of which depend only on the temperature of the environment and the incoming compressed air flow, $\boldsymbol{C_f}$ For fixed production condition, environment temperature and the temperature of the incoming flow. The rest of the gross heat loss, denoted by $\boldsymbol{Q_{sp}}$ can be regarded as a function of the productivity. So that the gross heat loss of the zinc pot can be expressed as the following equation:

$$\boldsymbol{Q_3 = C_f + Q_{sp}} \tag{6}$$

The productivity of the zinc pot can be expressed as the weight of steel stripe in a unit of time while the type of the product is confirmed. In practical process, for required thickness of the zinc layer, the galvanization load Q2 is proportional to the surface area of the stripe. Catering various width and thickness of the steel stripe, it would be useful to defines a line-area ratio to indicate the linearity between the galvanization load and the productivity. Based on the data acquired from two production lines C608 and C708 in a steel production industry, the line-area ratio is related to $\boldsymbol{Q_1}$ and $\boldsymbol{Q_2}$ as:

$$Q_{1-608} = C_{1-608} + K_{1-608} \times P_{608} \tag{7}$$

in which Q_{1-608} denotes the gross galvanization load in KW, $C_{1-608} = 451.29$ is the heat loss portion in the heat load of the zinc pot which is irrelated to the productivity, KW,

$K_{1-608} = 0.0265$ the proportional rate of the production-related part of the pot heat load, P_{608} denotes the productivity of C608 production line, m^2/min.

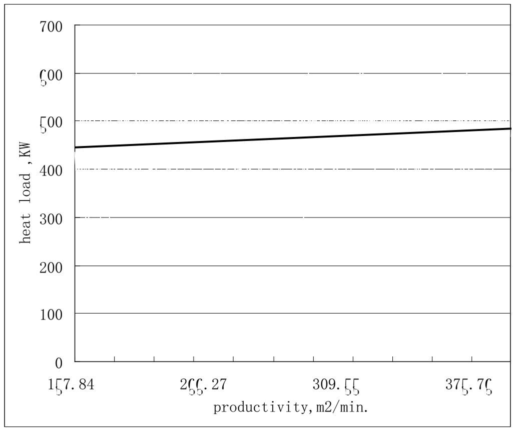

Fig. 1. Relationship between pot heat load and the productivity (line-area ratio) of production line C608.

$$Q_{2-608} = C_{2-608} + K_{2-608} \times P_{608} \tag{8}$$

where: Q_{2-608}——Galvanization load of production lineC608, KW,

$C_{2-608} = 70.776$——Heat loss irrelated to the production, KW,

$K_{2-608} = 0.00342$——Proportional rate of the production-related part of the pot heat load,

$\boldsymbol{P_{608}}$——Productivity of the zinc pot, m^2/min.

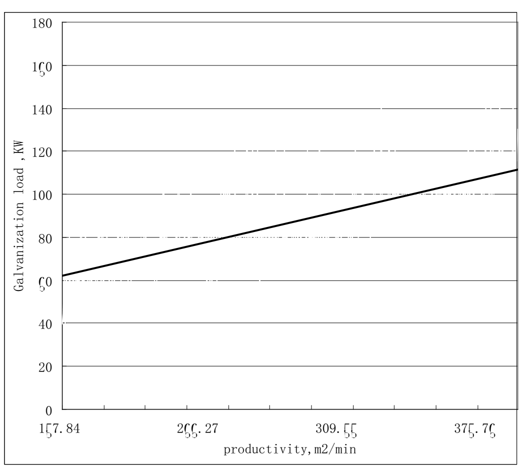

Fig. 2. Relationship between galvanization load and productivity (line-area ratio) of production line C608.

Similarly, based on the historical data of production line C708, the relationship between the pot heat load and the productivity $\boldsymbol{P_{708}}$ can be concluded as

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$$Q_{1-708} = C_{1-708} + K_{1-708} \times P_{708} \tag{9}$$

$$Q_{2-708} = C_{2-708} + K_{2-708} \times P_{708} \tag{10}$$

parameterized with $C_{1-708} = 415.02$ KW, $K_{1-708} = 0.0214$, $C_{2-708} = 70.776$ KW/h, $K_{2-708} = 0.00342$.

The production data of both production line indicate that the gross load of the pot and the galvanization are all linear with productivity. As such, for arbitrary production line, one can define the relationship of the gross load of the pot $\boldsymbol{Q_1}$ and the productivity P as

$$Q_1 = C_1 + K_1 \times P \tag{11}$$

and the galvanization load $\boldsymbol{Q_2}$ can be expressed as a function of the productivity $\boldsymbol{P}$ such that

$$Q_2 = C_2 + K_2 \times P \tag{12}$$

$\boldsymbol{Q_2}$ with the proportional constant $\boldsymbol{K_2}$.

As a result, the heat balance of the zinc pot writes $\boldsymbol{Q_1 = Q_2 + Q_3}$ which, recalling (6), can be rewrite as

$$Q_3 = Q_1 - Q_2 = (K_1 - K_2) \times P + (C_1 - C_2) = C_f + Q_{sp}$$

So that, one can conclude

$$C_f = (C_1 - C_2) \tag{13}$$

$$Q_{sP} = (K_1 - K_2) \times P = K_p \times P \tag{14}$$

$$K_p = (K_1 - K_2) \tag{15}$$

All in all, the gross heat loss of the zinc pot can be expressed in the following form

$$Q_3 = K_p \times P + C_f \tag{16}$$

When the productivity is 0, $\boldsymbol{C_f}$ is equal to the heat load for temperature maintenance. $\boldsymbol{K_p}$ is the gradient that the total heat loss varies with the productivity.

As such, the heat balance equation can be expressed in a productivity-related way

$$Q_1 = Q_2 + K_p \times P + C_f \tag{17}$$

which can be quantified using historical data. Nevertheless, (17) is under the assumption that the temperature of the stripe is identical with that of the zinc liquid temperature. Once they are not equal, extra heat is needed to maintain the temperature of the zinc liquid, increasing the gross heat load, denoted as $\boldsymbol{Q_{stripe}}$ .In this case, the heat balance equation is

$$Q_1 + Q_{strip} = Q_2 + K_p \times P + C_f \tag{18}$$

which is equivalent to

$$Q_{strip} = Q_2 + K_p \times P + C_f - Q_1 \tag{19}$$

Regardless of the heat storage variation in the zinc pot, the stripe temperature at the entrance of the pot can be estimated based on historical data, using the model which is suitable for online calculation for arbitrary production line under any production condition.

5 Heat balance calculation period

The energy of the zinc pot is provided by the inductor. Heated by the inductor with a periodic heating mechanism, the zinc liquid temperature are depicted in Fig. 1. Based on the former analysis, the energy storage changes 46.02KW, while the liquid temperature varies with the rate 1℃/h. Therefore, the selection of the calculation period may corresponds to large amount of the heat storage and tends to have significant effects on the calculation results.

To avoid the estimation error caused by heat storage of the zinc pot, in this paper, the calculation period is selected as shown in Fig. 3, which starts from a temperature peak at τ_1 until the next peak at τ_2. Considering the temperature values at two peaks are not identical, their difference Δt is introduced for compensation of the heat storage.

Within a calculation period, the temperature of the zinc liquid decrease to a minima and then increase to the next peak. If Δt=0, the pot does not store heat. Despite the heat loss, the heat provided by the inductor is all used for galvanization.In the case that at the end of the period, the temperature does not reach the starting point, a part of the heat storage in the zinc liquid is consumed so that the liquid temperature is lower than it was. Denoting the heat storage change per degree centigrade is Q_4,it holds that

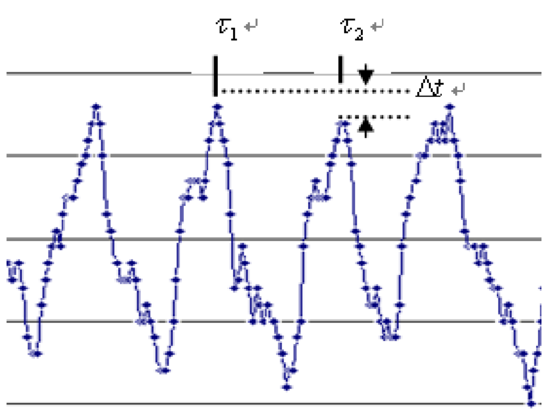

Fig. 3. Temperature variation of the zinc liquid.

$$Q_4 = \frac{l_1 \times l_2 \times h \times \rho \times c_y}{\tau} \times \Delta t \tag{20}$$

where l_1, l_2 and h are the length , width and the depth of the molten pool.

ρ_z is the density of the zinc liquid, c_z is the specific capacity of the zinc liquid.;

τ denotes the period length.

In this case, considering heat storage, (19) is corrected as

$$Q_1 + Q_{stripe} + Q_4 = Q_2 + K_p \times P + C_f \tag{21}$$

After some algebra, the stripe temperature can be estimated as

$$t_{stripe} - t_{bath} = \frac{Q_2 + K_p \times P + C_f - Q_1 - Q_4}{c_s} \tag{23}$$

where t_{stripe} is the stripe temperature before galvanization, t_{bath} is the temperature of the molten pool and c_s is the specific heat capacity of the steel stripe.

Therefore, for an arbitrary production line, the featured parameters K_1, K_2 and C_1, C_2 by fitting with the historical data. The parameters acquired by historical data indicates the production and statistic features of certain production line,

6 Practical Application of the heat balance model

In practical production, the actual stripe temperature is different with the preset goal, so that slagging phenomena sometimes exists on the sink and poses negative effects on the surface quality of galvanization. Based on the proposed heat balance mode and the production data of Production line C608, within February to June 2018, the stripe temperature at the furnace entrance is estimated. The temperature deviation, as depicted in Fig. 4 coincides with the actual slagging occurrence in terms of the time and frequency.

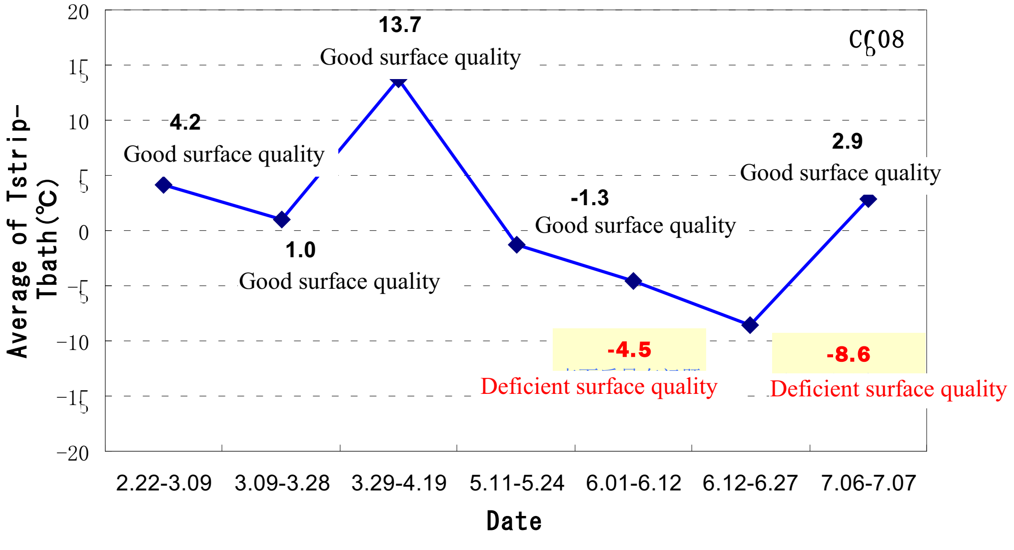

Fig. 4. Correspondence between temperature deviation surface quality.

It is readily seen that the time instants of large temperature deviation corresponds to the occurrence of slagging. In the meantime, the quality of the production surface becomes poor. Therefore, the available data of both production lines are used to estimate the stripe temperature respectively, and it comes to the result that the maximum temperature deviation is 8.6℃ for C608, and 6.3℃ for C708. Thanks to the estimation results, since July 2018, the preset temperature of the stripe temperature at the entrance had been corrected as +8℃ for C608 and +5℃ for C708.

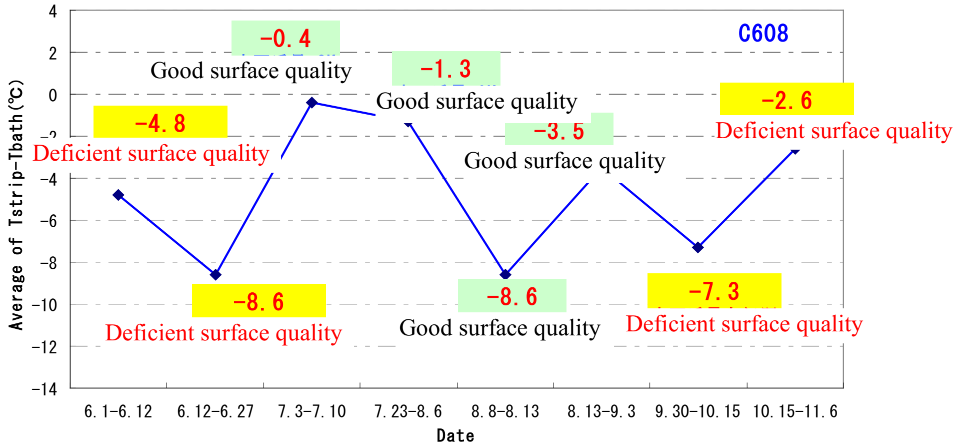

Fig. 5. Correspondence between temperature deviation surface quality.

After preset temperature correction since July 3, 2017, 2 out of 7 sink roll on C608 have slagging phenomena until September 25, 2018. The ratio for C708 are the same from July 6, 2018 until November 6, 2018. Such ratio is dramatically reduced which could reach 4-5 of 7 without correction. The occurrence of slagging has been effectively suppressed by the introduction of temperature correction. Moreover, the large temperature deviation corresponds well with deficient surface quality. To conclude, the stripe temperature is effectively estimated by the proposed heat balance model. With verified effectiveness, the estimation method has been implemented online for real-time calculation for both production lines since January 2019. The occurrence of severe surface problem are avoided and the quality of the galvanization has been significantly improved.

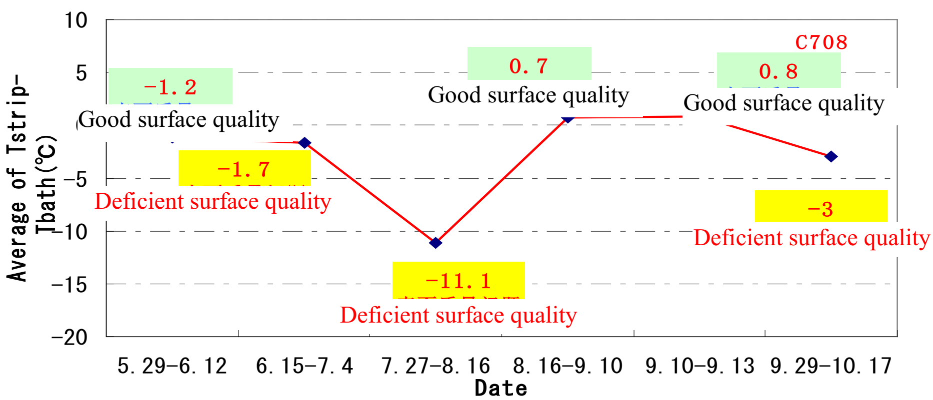

Fig. 6. Correspondence between temperature deviation surface quality.

In order to justify the estimation occurrence, due to the fact that Q_4 tends to zero for a computing interval, the heat imbalance can be quantified from (4) as

$$Q_{\Delta} = Q_1 - Q_2 - Q_3 - Q_4 - (t_{stripe} - t_{bath}) \cdot c \tag{24}$$

which is caused by the estimation error of the heat loss and temperature estimation. In this case, such heat imbalance are used to retrieve the temperature estimation error Δt_{se} as

$$\Delta t_{se} = Q_{\Delta} / c \tag{25}$$

To indicate the stripe temperature estimation accuracy as listed in Tab. 4-5.

Table 4. Estimation error analysis of C708.

Production date	**Average galvanization load, KW**	**Heat loss of Cooling, KW**	**Estimation of temperature deviation, ℃**	**Heat injected by stripe, KW**	**Heat imbalance, KW**	**Estimation error of stripe temperature, ℃**
20180319-0408	76.19	358.97	-6.38	-45.79	-11.89	-1.66
20180408-0502	87.33	359.11	-2.76	-20.37	-14.23	-1.93
20180502-0523	91.56	359.11	-1.69	-12.36	-13.9	-1.9
20180529-0612	86.58	358.88	-1.18	-8.89	-15.93	-2.12
20180615-0704	85.22	359.2	-1.45	-13.18	-12.39	-1.37
20180706-0726	90.6	359.3	1.55	11.91	-9.57	-1.25
20180727-0806	83.75	359.25	-0.02	-0.16	-6.92	-0.89
20180913-0929	83.39	359.2	-0.52	-3.6	-7.14	-1.04
20180929-1017	90.46	359.22	-2.97	-21.47	-10.24	-1.42
20181018-1106	82.77	359.12	-11.12	-73.41	-16.86	-2.55
20181106-1117	**80.06**	**358.97**	**-17.28**	**-124.56**	**-44.74**	**-6.21** *note
20181117-1123	**81.24**	**359.07**	**-8.65**	**-60.98**	**15.17**	**2.15**
20181124-1217	**82.03**	**359.17**	**-18.43**	**-141.22**	**-24.36**	**-3.18**
Mean					**-13.30**	**-1.79**

Note:Due to the occurrence of a fault in production in the last 3 months, the values increase.

Table 5. Estimation error Analysis of C608.

Production date	Average galvanization load, KW	Heat loss of Cooling, KW	Estimation of temperature deviation, ℃	Heat injected by stripe, KW	Heat imbalance, KW	Estimation error of stripe temperature, ℃
20180222-0309	86.55	378.32	1.84	13.06	-8.46	-1.19
20180309-0328	83.64	378.38	1.05	7.05	-2.73	-0.41
20180329-0419	86.27	378.3	13.58	86.16	-6.54	-1.03
20180420-0508	98.62	378.26	17.05	113.74	-0.7	-0.11
20180511-0524	91.13	378.15	-1.31	-9.52	-13.53	-1.86
20180601-0612	89.58	378.07	-4.84	-38.65	-6.11	-0.76
20180612-0627	86.91	378.27	-8.63	-56.98	-9.63	-1.46
20180627-0702	71.8	378.72	-6.86	-40.84	-14.16	-2.38
20180703-0723	86.56	378.33	-2.87	-19.19	-12.6	-1.89
20180723-0806	86.05	378.31	-1.29	-8.22	-6.32	-0.99
20180904-0925	85.14	378.23	-3.49	-24.93	-11.61	-1.62
20180930-1015	81.72	378.36	-7.32	-46.36	-15.8	-2.5
20181015-1106	90.87	378.17	-2.17	-16.39	-6.75	-0.89
20181110-1203	83.34	378.45	-1.8	-12.07	-14.61	-2.18
20181203-1224	89.32	378.19	-1.63	-11.97	-9.56	-1.3
Mean					**-9.274**	**-1.371**

According to the data of C708 listed in Tab.4, the heat imbalance is around -13.30KW. Correspondingly, the temperature estimation error is about -1.79 ℃. As for C608, Tab.5 indicate the heat imbalance is -9.274 KW corresponding to temperature error around -1.371℃. In general, the imbalance heat can be Q_{Δ} has been proven to remain at a low level that keeps the temperature estimation error $\Delta t_{se} < \pm 3$ ℃ within a calculation period, which meets well with the accuracy requirement.

7 Conclusion

In this paper, a novel heat-balance-based model is established to estimate the stripe temperature at the entrance of the zinc pot with wider adaptability. By redefining the thermal features of the zinc pot and the productivity, the heat loss of zinc pot is been quantified based on characterizing the galvanization load as a function of productivity. Moreover, proper calculation period has been chosen that significantly avoids the estimation error caused by the change of heat storage. By real-time application on actual production line, the effectiveness of the proposed estimation error is confirmed. The occurrence of slagging has been suppressed so that an improvement of the galvanization quality is attained.

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