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Establishment and Application of A Mathematical Model for Rectangular Billet Continuos Casting

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Abstract: A two dimension unsteady heat transfer model is established for rectangular billet casting. Solidification process of liquid steel in secondary cooling zone was analyzed using direct difference method. The influence of operation parameters including casting speed and temperature of liquid steel was investigated. Experimental results have been used for increasing the casting speed.

Key words: continuous casting, rectangular billet, direct difference method, mathematical model

1 Mathematical Model of Solidification and Heat Transfer of Rectangular Billet

The sampled hypothesis and assumptions on which the model is based are as follows:

(1) Since the withdrawal speed is far more than the velocity of heat transfer along the strand, heat transfer along the strand can be neglected.

(2) In a fixed coordinate system, the temperature of any point in the cross section does not change with time under a steady casting speed.

(3) The heat transfer of solidified shell is predominated by thermal conduction.

(4) Convection movement within the liquid pool enables the heat transfer coefficient changing with the state of liquid steel.

(5) The density (ρ) of different phases are considered as constant.

(6) Specific heat capacity c_p also changes with steel state during solidification.

(7) Among the different secondary cooling zones of continuous caster, the cooling in every part is well-distributed.

Direct difference method[1] is to divide system calculated into lots of tiny units whose physical phenomena are described as difference equation directly instead of differential equation. Digital solution can be achieved by computer. According to the method of defining point and its domain[2], direct difference method can be grouped into two types with the same principle.

In the light of energy conservation principle (Fig. 1), general difference equation can be established by tiny element analysis method on a domain i with complex boundary condition. It is:

$$(\rho c_p V T^{t+\Delta t})_i - (\rho c_p V T^t)_i = \sum_a \bar{\lambda} \frac{S\alpha}{l_{i\alpha}} (T_\alpha - T_i)\Delta t + \sum_b S_b \frac{(T_b - T_i)\Delta t}{ra + l_{ib}/\lambda_i + l_{bi}/\lambda_b} + \sum_e \varepsilon_e \sigma [(T_e + 273)^4 - (T_{se} + 273)^4] S_e \Delta t + \sum_d S_d q_d \Delta t \quad (1)$$

And then mathematical model can be developed[3]. If the number of a and b, etc. is too many in formula (1), the total number is taken into account.

Numerical analytical method is the main method to calculate mathematical model of solidification and heat transfer, which has four types in common use. They are finite difference method, finite element method, boundary element method and integral profile method. The former two ones are often used, especially the finite difference method. The direct difference method used in this paper has the following advantages compared with other ones above:

(1) It can use various units such as triangle and rectangle, etc. (in three-dimensional space, they are tetrahedron, pentahedron, hexahedron, etc.) to solve complicated problems.

(2) It can define physical property of each unit and thus problem of complex system containing lots of materials can be solved easily.

(3) Difference equations can be deduced with clear theory and simple process. When a system is divided regularly, the procedure of direct difference method is

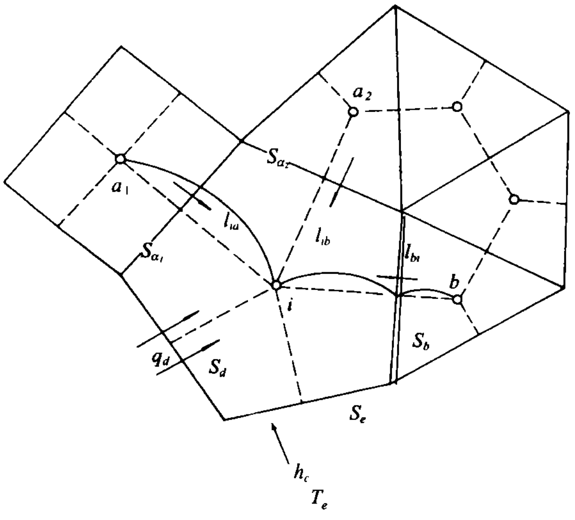

Fig.1 Heat balance of inner node unit *i*

similar to that of finite difference method. Its merit can be showed obviously and practically when used to solidification and heat transfer problem of strand, especially to that of irregular section strand.

The section of rectangular billet is 150 mm × 280 mm in this study. Considering its complexity of molten steel heat transfer in the mould across the wide surface, narrow surface and corner point is different. Combined with the solidification theory in continuous casting, the average heat flux density is defined as:

wide surface: $\overline{\Phi}_X = 268.0 - 17.35\sqrt{t}$ (2)

narrow surface: $\overline{\Phi}_Y = 223.0 - 14.46\sqrt{t}$ (3)

corner point: $\overline{\Phi}_{XY} = 201.0 - 13.01\sqrt{t}$ (4)

With metallurgical criteria as restrained conditions and target surface temperature control method as guide, relevant calculation software for the mathematical model is developed by using Borland C++ computer language[4~6]. Process parameters for various sections, steel grades, casting speeds, pouring temperatures, etc. are obtained. Fig. 2 shows relationship between input and output parameters of the mathematical model. Fig. 3 shows function diagram of calculating software.

2 Application of the Model

The various process parameters obtained from calculation of the model influence the solidification and heat transfer process of strand, and affect the practical production of continuous casting machine directly.

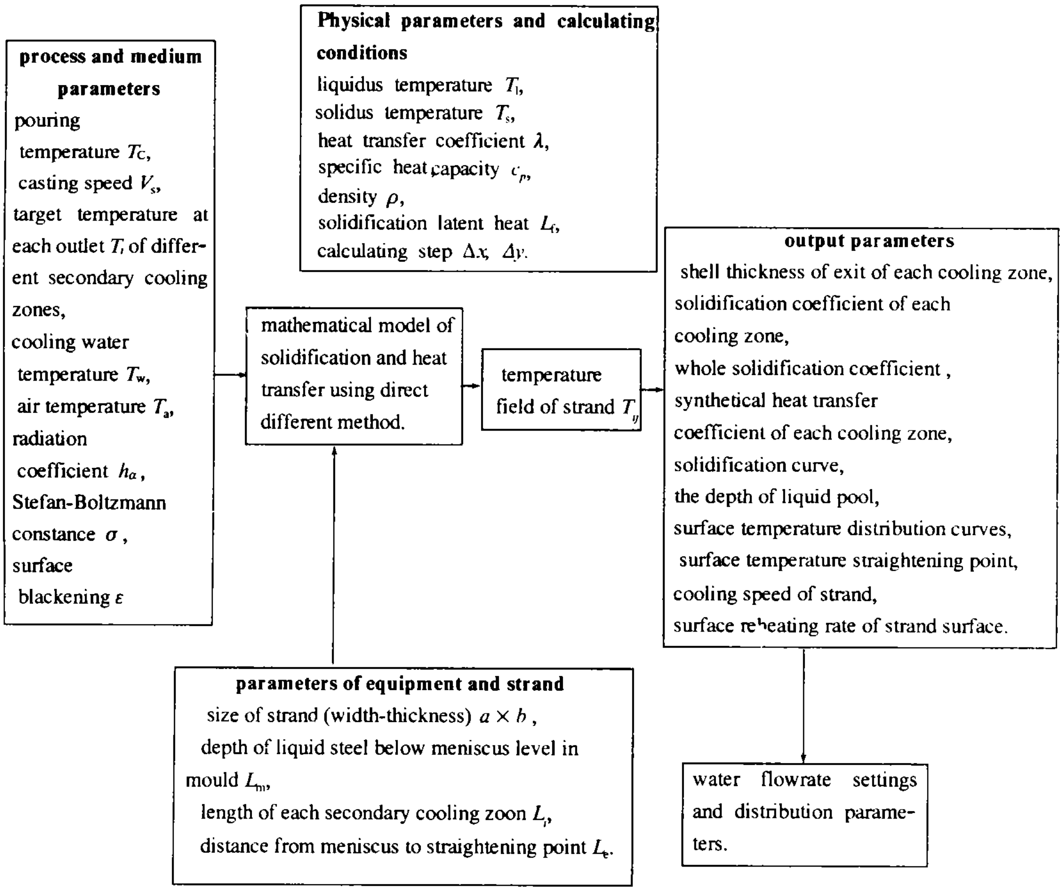

Fig.2 Relationship between input and output parameters of the mathematical model

2.1 Influence of withdraw speed v and heat transfer coefficient β on shell thickness e at the mould exit

It can be deduced from formula (2) to (4) that β (coefficient of $\sqrt{t}$) is the main element that reflects the amount of heat flux in the mould. Calculation indicates that e keeps almost unchanged with β in a certain scale when withdraw speed is defined. When β is defined, e changes slightly with withdraw speed. For example, with low alloy steel, the following relative formula can be obtained by linear regression for the three variables:

$$e = 43.57 - 12.16v - 0.65\beta \qquad (5)$$

Through obviousness test, it can be seen that the regression equation (5) is reliable. The influence of v on e is larger than that of β, so it can not be neglected.

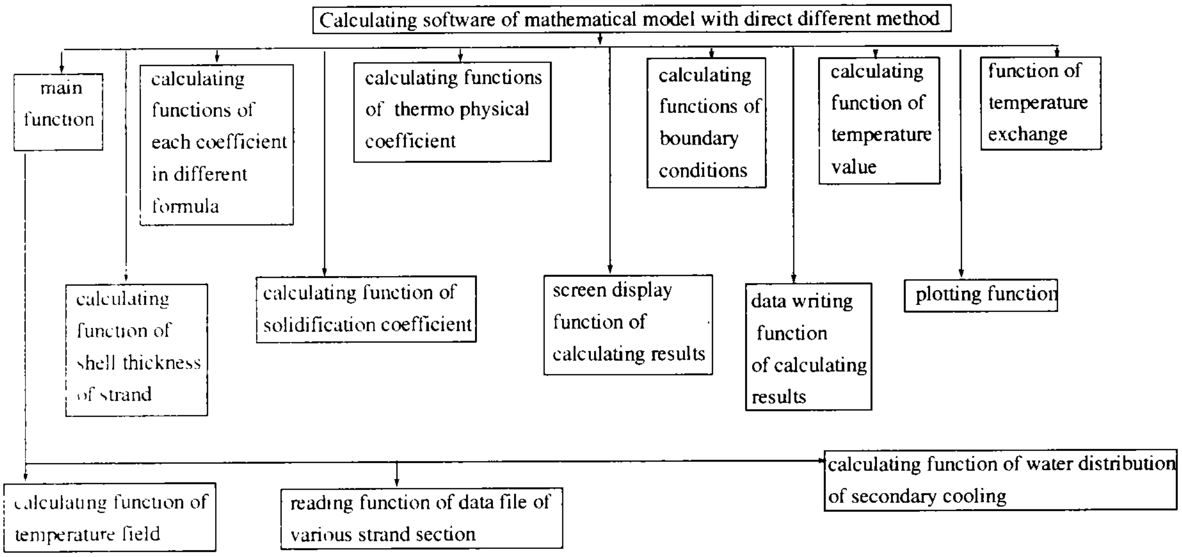

Fig.3 Function diagram of calculating software

2.2 Influence of convection interaction coefficient on e

The kinetic energy of casting flow in the mould can cause liquid steel convection movement at the front of solidification, whose intensity is expressed by convection interaction coefficient m. Under the assumption that heat transfer coefficient in liquid phase is 2 ~ 7 times of that in solid phase, the influence of convection movement on e is studied. When other process parameters are the same and when $m \geq 3.5$, e is not influenced by m, and if $2.5<m<3.5$, e increases with m, but not much. For low-alloy steel, e will decrease 22% due to convection movement.

2.3 Influence of casting temperature T_c on shell thickness e at exit of the mould

The pouring temperature of low-alloy steel in Shanghai Pudong Iron & Steel Co. Ltd. ranges from 1 525 to 1 540℃, and e almost unchanged. It can be concluded that pouring temperature primarily influences the solidification structure and slightly does the thickness of shell at the mould exit.

2.4 Influence of casting temperature T_c on the depth of the liquid pool L

The casting temperature of low carbon steel in Shanghai Pudong Iron & Steel Co. Ltd. ranges from 1 525 to 1 550℃. L will increase 0.3 m when T_c increases 2℃ within the above temperature range.

2.5 Influence of withdrawal speed v on the depth of the liquid pool L

The depth of the liquid pool increases 0.8~ 0.9 m with withdraw speed v increasing 0.1m/min.

2.6 Surface temperature of strand

Fig. 4 shows the change of surface temperature on strand when v is 1.0 m/min.

2.7 Shell thickness change during solidification

The influence of withdrawal speed on the depth of the liquid pool during solidification is shown as Fig. 5.

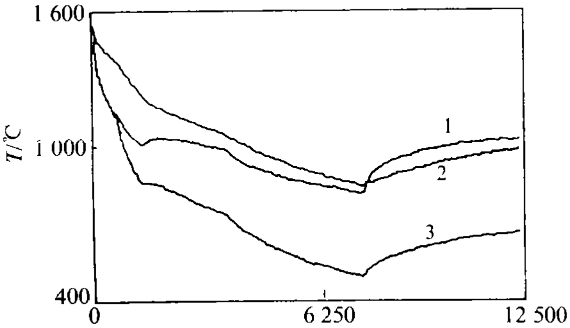

Fig.4 Change of strand surface temperature (low-carbon steel 150mm × 280mm)
1—center point of wide surface of strand;
2—center point of narrow surface of strand;
3—corner point of strand

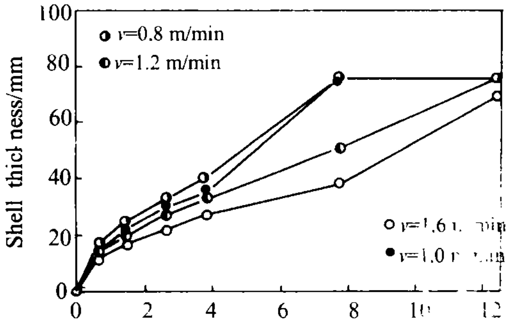

Fig.5 Effects of casting speed upon liquid steel solidification process (low alloy steel 150 mm × 280 mm)

2.8 Theoretic foundation to increase withdrawal speed

Withdrawal speed of No. 1 caster at Shanghai Pudong Iron & Steel Co. Ltd. is a little lower now, which influences economic benefits directly. It is a critical problem needed being solved that whether it is possible to reach 3H(high yield, high quality, high efficiency) gradually without changing the fundamental equipments of casting machine. Theoretic foundation to increase withdrawal speed is listed in table 1.

By calculation, rational pouring temperature and better control of the depth of the liquid pool can be obtained. When withdrawal speed increases to 1.5 m/min, straightening operation can be proceeded without liquid core. The current machine has the possibility to increase withdrawal speed.

According to the target temperature at each exit of secondary cooling zone, secondary cooling water distribution scheme is made. It meets metallurgical criteria after increasing withdrawal speed. This provides a reliable foundation to improve process control at Shanghai Pudong Iron & Steel Co. Ltd. Practice of No. 1 caster modified at Shanghai Pudong Iron & Steel Co. Ltd also shows that the maximum water flow rate has not been applied at present withdrawal speed of 1m/min. The new setting system of secondary cooling will meet the requirement when withdrawal speed increases to 2 m/min.

On the basis of calculation, secondary cooling inten-

Table 1 Some calculating results and state of meeting metallurgical criteria

Withdrawal speed /(m · min^{-1})	1.1	1.2	1.3	1.4	1.5
Surface cooling speed of strand$^{1)}$/(℃ · m^{-1})	<156.3	<166.4	<95.3	<42.3	<111.8
Surface reheating at strand$^{2)}$/(℃ · m^{-1})	32.0	31.1	46.9	41.1	41.9
The length of the liquid pool/mm	8 439.7	9 272.8	10 017.6	10 695.4	11 706.3
Surface temperature at solidification point/℃	963.0	999.9	1 024.0	1 034.0	1 053.7
Surface temprature at strighening point/℃	1 010.9	1 013.1	1 018.1	1 015.3	1 020.9
Temperature fluctuating range of secondary cooling zone/℃	860～1092	859～1102	868～1041	862～1001	864～1129
Shell thickness at exit of each zone/mm					
Mould	14.22	14.22	14.22	14.22	11.64
Footroller	19.40	19.40	19.40	19.40	16.81
Zone Ⅰ	27.16	27.16	24.57	24.57	21.98
Zone Ⅰ	32.33	32.33	29.74	29.74	27.16
Zone Ⅲ	58.19	50.43	47.84	45.26	40.09
Air cooling zone	75.00	75.00	75.00	75.00	75.00
Total solidification coefficient/(mm · min$^{-1/2}$)	27.08	26.98	27.02	27.13	26.85
Specific water flowrate/(l · kg^{-1})	1.532	1.534	1.533	1.531	1.530

Note: 1) assigned <200℃/m; 2) assigned <100℃/m;
Calculating condition: grade, low-alloy steel; section, 150mm × 280mm; target pouring temperature, 1530℃; liquidus temperature, 1506℃; solidus temperature, 1428℃.

sity and enough shell thickness of strand at mould exit can be controlled efficiently and no breakout occurs after withdrawal speed increases.

3 Verification of Model

(1) The target withdrawal speed of process control before modifying secondary cooling system at Shanghai Pudong Iron & Steel Co. Ltd. was 1 m/min. At this speed the depth of the liquid pool calculated from the model is 8.54 m, which is very close to practical measurement result.

(2) The secondary cooling water flow rate settings obtained from the calculated temperature field make the cooling of strand homogeneous. The damage rate of the bearings of straightening machine and that of the 500 t hydraulic shear decreased by 50% and 70% .

4 Conclusions

(1) The depth of the liquid pool obtained from simulation calculation for low-carbon steel and low-alloy steel with section 150 mm × 280 mm is very close to the practical results. This proves that the developed model is reliable and has a wide usage domain and a great expectation.

(2) The simulating calculation of solidification process of mold shows that influence of withdrawal speed V_c on e_m is larger than heat transfer coefficient β, so it can not be ignored.

(3) Convection movement at solidification front and pouring temperature do not influence e very much; Withdrawal speed and pouring temperature greatly influence the depth of the liquid pool. Strand shell grows slower with the withdrawal speed increasing.

(4) By dealing of average heat flux in mould and determining of target temperature of each exit of secondary cooling zones, rational temperature field and water distribution can be obtained. This provides reliable theory foundation to increase withdrawal speed up to 1.5 m/min at No. 1 caster in Shanghai Pudong Iron & Steel Co. Ltd.

(5) Calculating software of mathematical model developed by Borland C++ language has a strong function in common use, which can be used in solidification and heat transfer calculation and water settings for secondary cooling of various types of casting machines, different steel grades and strand sections.

List of symbols

ρ—density, kg/m^3;
c_p—specific heat capacity, kJ / (kg · ℃);
V—volume of tiny unit, m^3;
T—temperature, ℃;
t—time, s;
$\lambda_a, \lambda_b, \lambda_i$—thermal conductivity, kJ / (m · s · ℃);
l_{ia}—distance from point i to a, m;
l_{ib}, l_{bi}—distance from point i, b to interface S_b respectively, m;
S_a, S_b, S_d, S_e—contacting area from domain i to other domains a, b, d, e, mm^2;
r_b—heat resistance between domain i and b, m^2 · ℃ · s / kJ;
q_d—heat flux, kJ / (s · m^2);
ε_e—radiation coefficient;
σ—Stefan—Boltzmann constant, kJ / (s · m · ℃);
$\overline{\Phi}_X, \overline{\Phi}_Y, \overline{\Phi}_{XY}$—average heat flux, kJ / (s · m^2);
e—shell thickness, m;
v—withdraw speed, m/min.

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