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Experimental Study of Fluid Flow in Thin Slab Continuous Caster Mould with Water-Model

Yanping Bao, Jianqiang Zhu, Naiyuan Tian, Baomei Xu

Metallurgy School, University of Science and Technology Beijing, Beijing 100083, China

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Abstract: Model study is an efficient method for optimizing the structure of the mould and the submerged entry nozzle (SEN). Based on the similarity criteria, a full-scale water model has been established in accordance with the mould of thin-slab caster of the CSP (Compact Strip Production) operation. The effects of SEN structure including outlet area, outflow angle, nozzle width, nozzle thickness and immersion depth have been studied under high speed casting by measuring the amplitude and the impetus of top waves. By the orthogonal experiment design, not only the influence of the factors was estimated, but also the optimum work condition was judged. The rules of the fluid flow phenomena were summarized. The principle for choosing a reasonable structure of SEN was discussed.

Key words: thin-slab casting mould; submerged entry nozzle (SEN); water-model

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The submerged entry nozzle (SEN) is one of the essential parts of a continuous casting. Fluid flow conditions in the continuous casting mould have a large influence on quality and productivity. The flows at the top surface are particularly important, as it is in this region that initial solidification occurs. Top surface fluctuations prevent the formation of a uniform layer of mould flux, adversely affecting the uniformity of lubrication and heat spread. In case of the thin slab casting, this is particularly challenging, due to the high casting speed and strong cooling intensity.

Several authors have reported that the flow of the liquid steel in the mould is not steady [1~4]. In thin slab casting, the bigger the casting speeds the larger the flow velocities in the mould. Problems associated with meniscus stability, top surface fluctuations and mould flux entrapment may therefore be more severe [5~ 7], so it is necessary to study the fluid flow in thin slab continuous casting mould. In this paper, The effects of SEN structure including outlet area, pouring angle, nozzle width, nozzle thickness and immersion depth have been studied under high speed casting by measuring the amplitude and the impetus of top waves. Because many factors affect the fluid flow, the orthogonal experiment design is also needed.

1 Experimental

A full-scale physical model of the thin slab caster mould was constructed using transparent plexiglass. Water was used as modeling fluid, thereby satisfying both the Froude and Reynolds number similarity criteria at any given volumetric throughout. The water model system is shown in **figure 1**.

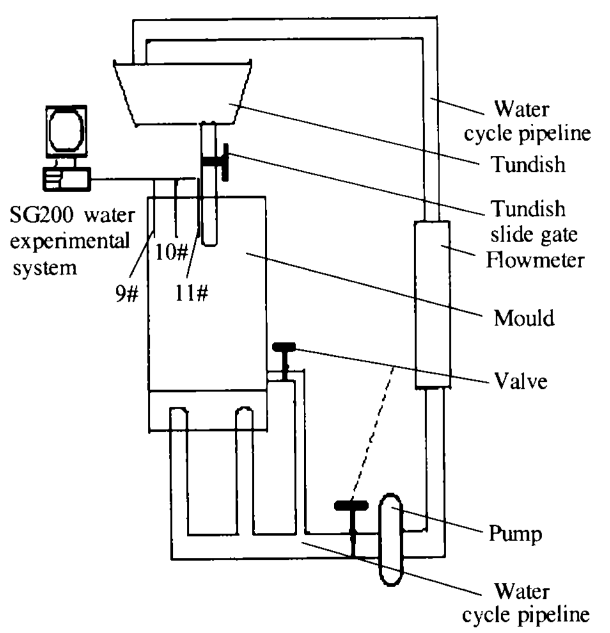
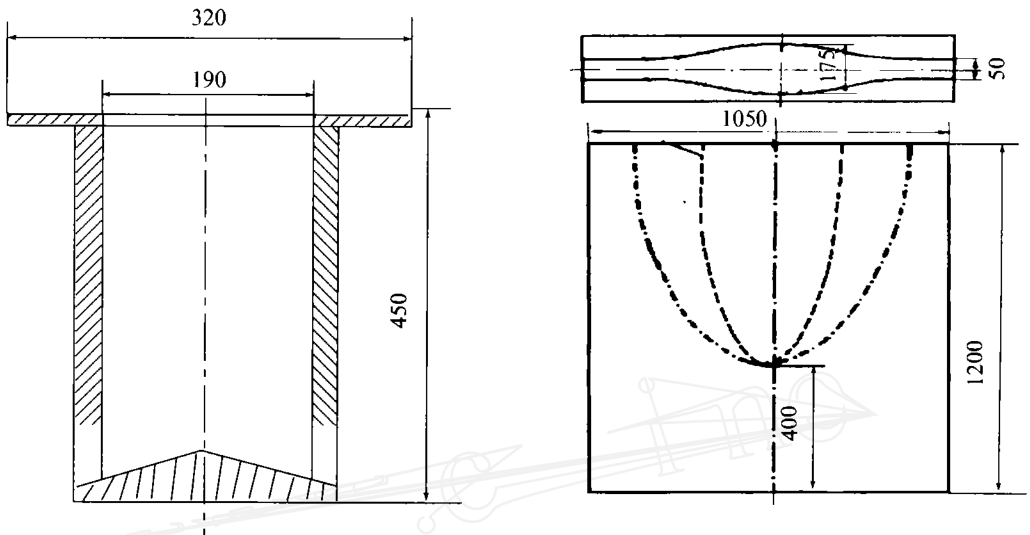


Figure 3 Experiment equipment

The mould that was funnel-shaped in cross-section is shown in **figure 2**. The model of SEN design is also shown in figure 2, the structure of SEN varies in outlet angle, outlet area, nozzle immersion depth and width of mould.



(a) (b)

Figure 2 Equipment structure, (a) SEN structure; (b) mould structure; unit: mm.

The surface fluctuations and wave impetus depth were measured by using SG200 water experimental system. This system can measure the wave number, wave height, maximum wave height and flow penetration depth.

To study the fluid flow in a thin slab caster mould, all the factors which may affect the fluid flow such as immerge depth, outlet area, outlet shape, outflow angle and casting speed must be measured. It is very important to research how those factors affect the fluid flow phenomena, such as wave height and penetration depth. So an orthogonal experiment design is needed.

Orthogonal design is a scientific tool to deal with multi-factors research. The experiment scheme was arranged based on a criterion table-orthogonal list. To estimate the influence of the factors and their levels, fewer experiments are needed by this way, but a more complete result may be obtained.

According to the requirement of steel solidification in the mould, two indexes of the fluid flow must be considered, one is the surface turbulence, the other is the penetration strength to the solidified shell. The surface turbulence determines the degree of powder entrapment and the interior quality of the slab. At the same time, the penetration strength determines the creation of a uniform shell and the surface quality of the strip. Both of them are important to produce high quality slab. Therefore, we take the average height of the surface wave and the penetration depth as two fluid flow index. The higher the surface wave height is, the easier the mould powder entraps into the fluid. The deeper the fluid jet penetrates, the worse the uniformity shell creates. An ideal SEN configuration is the one, which not only brings lower surface wave but also shallower penetration depth. The experiment scheme $\{L_{25}(5^6)\}$ is shown in **table 1**.

Table 1 The experiment scheme

No.	Outlet area ratio	Outflow angle/(°)	Immersion depth/mm	Nozzle width/mm	Nozzle thickness/mm
1	1.8	15	315	200	32
2	0.8	−5	280	200	16
3	1.0	−25	245	200	20
4	1.3	5	210	200	24
5	1.5	−25	315	190	24
6	0.8	−15	245	190	32
7	1.0	15	210	190	16
8	1.3	−15	315	180	16
9	1.8	−5	245	180	24
10	1.3	−25	280	170	32
11	1.5	5	245	170	16
12	1.5	−5	210	160	32
13	1.5	−15	175	200	28
14	1.8	5	280	190	28
15	1.3	−5	175	190	20
16	1.5	15	280	180	20
17	0.8	−25	210	180	28
18	1.0	5	175	180	32
19	1.8	15	210	170	20
20	0.8	15	175	170	24
21	1.0	−15	280	160	24
22	1.8	−25	175	160	16
23	1.0	−5	315	170	28
24	0.8	5	315	160	20
25	1.3	15	245	160	28

Nore: (1) All the casting speed is 6.0 m/min;

(2) The sign "−" in the outflow angle means downward, and the others means upward

The outlet area ratio= the value of outlet area / nozzle area

2 Results and Discussions

2.1 Results

According to the orthogonal list $L_{25}(5^6)$, the fluid flow of 25 kinds of conditions has been tested. The results are shown in **table 2**.

2.2 Discussions

Among all the factors listed in the experiment scheme above, the most important factors which remarkably affects the fluid flow is shown in **figures 3** and **4**.

Table 2 The last results of the experiment

No.	Average wave height				Average penetration depth		
	9#	10#	11#	Average	Left	Right	Average
1	0.245	0.320	0.415	0.330	47.5	35.3	41.38
2	0.560	0.470	0.440	0.490	51.0	48.0	49.50
3	0.240	0.200	0.240	0.230	58.0	51.0	54.50
4	0.970	0.770	0.500	0.750	39.0	35.5	37.25
5	0.380	0.605	0.375	0.450	62.5	54.5	58.50
6	0.445	0.525	0.460	0.480	34.5	34.0	34.25
7	0.485	0.480	0.405	0.460	31.0	30.5	30.75
8	1.120	0.540	0.470	0.710	48.5	53.0	50.75
9	0.365	0.420	0.405	0.400	34.5	35.0	34.75
10	0.240	0.240	0.280	0.250	51.0	47.0	49.00
11	0.450	0.585	0.490	0.510	34.5	34.5	34.50
12	0.490	0.490	0.530	0.500	33.0	28.0	30.50
13	0.845	1.020	0.635	0.830	32.5	28.0	30.25
14	0.260	0.280	0.355	0.300	41.0	39.8	40.38
15	0.480	0.515	0.620	0.540	31.5	31.5	31.50
16	0.365	0.380	0.450	0.400	37.0	36.0	36.50
17	0.530	0.595	0.580	0.570	34.5	36.5	35.50
18	1.190	0.875	0.785	0.950	28.0	32.0	30.00
19	0.495	0.590	0.480	0.520	33.5	36.5	35.00
20	0.670	0.815	0.705	0.730	19.0	21.5	20.25
21	0.215	0.495	0.480	0.400	42.0	39.0	40.50
22	0.445	0.405	0.500	0.450	40.5	38.0	39.25
23	0.435	0.485	0.530	0.480	43.0	43.5	43.25
24	0.460	0.655	0.505	0.540	41.0	40.0	40.50
25	0.665	0.815	0.650	0.710	28.0	26.0	27.00

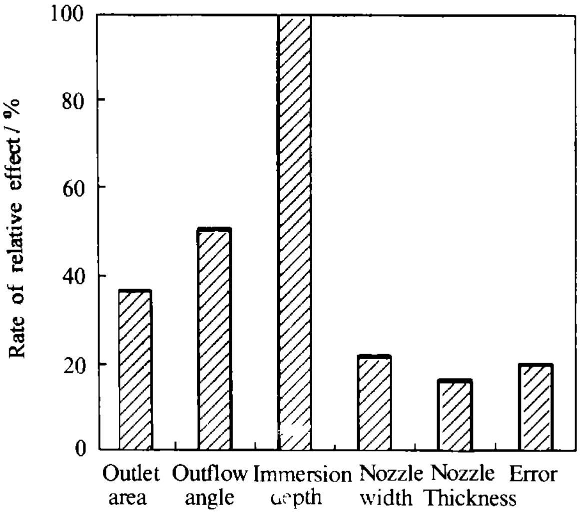


Figure 3 The relative significance of SEN variables on surface turbulence

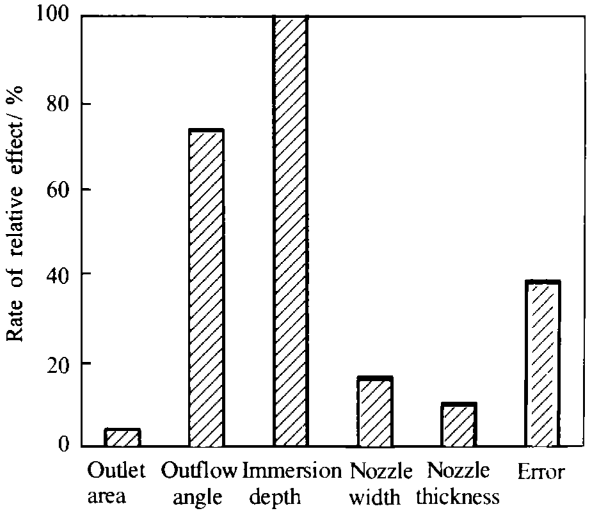


Figure 4 The relative significance of SEN variables on penetration depth

Comparison of the factors in figure 3 and figure 4 shows that the nozzle immersion depth has the strongest effect. The outlet shape (include outlet area and outflow angle) and the nozzle width have some effects on the fluid flow too. The effect of the nozzle thickness is smaller even than that of error, so it can be neglected

Figure 5 shows that the average wave height decreases significantly with the nozzle immersion depth increasing. It can be explained that the jets out from the SEN are more close to the surface with the immersion depth decreasing, and then the surface velocity increased significantly.

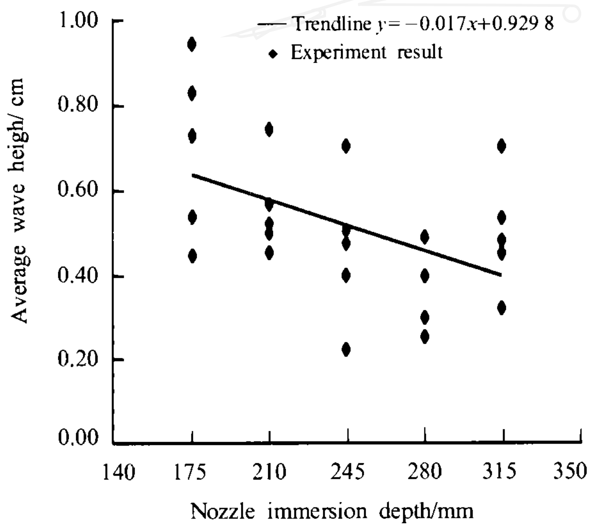


Figure 5 Effect of immersion depth on surface turbulence

Figure 6 shows that the penetration depth increased with the SEN immersion depth increasing. This effect is in conflict with the surface turbulence. Therefore, in order to get an optimum condition, it is necessary to balance the effects of the surface turbulence and the

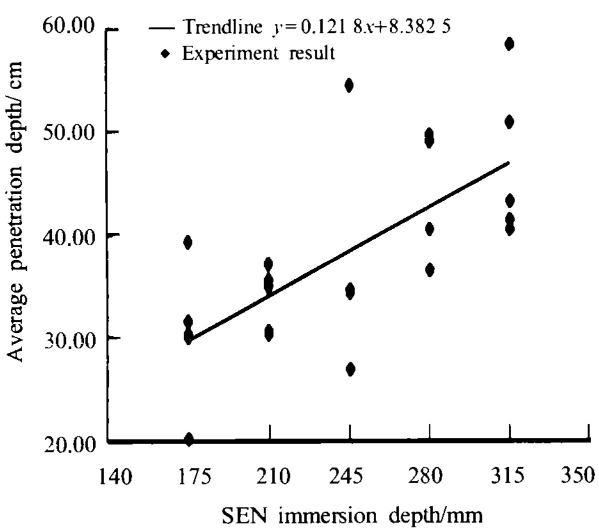


Figure 6 Effect of immersion depth on penetration depth

penetration. In our experiment the best nozzle immersion depth is 245 mm.

Figure 7 and **figure 8** show the effect of outflow angle. It can be explained that the angle varies from upward to downward, the liquid jet tends towards the same direction. Comparing figure 7 with figure 8, it can be known that the outflow angle has more significant influence to penetration depth than to surface turbulence.

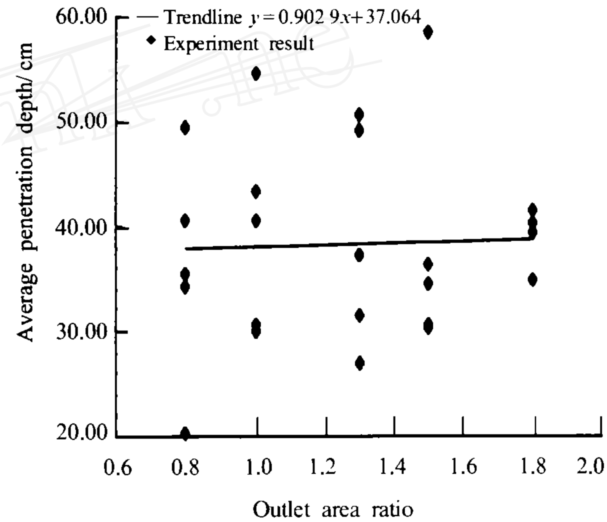


Figure 7 Effect of outflow angle on penetration depth

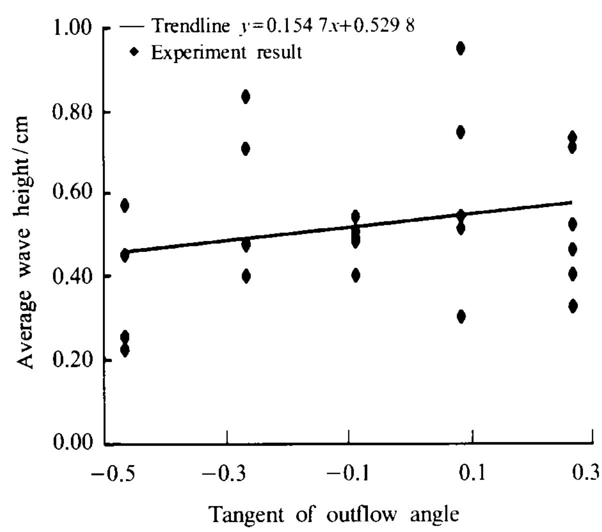


Figure 8 Effect of outflow angle on surface turbulence

Figure 9 and **figure 10** show the effects of outlet area and nozzle width. The smaller the outlet area, the bigger the jet velocity from the hole, and then the surface turbulence increases. From the orthogonal list analysis, it can be shown that they have less influence than immersion depth and outflow angle. Nevertheless, to satisfy the casting demand, an adequate outlet area and nozzle width is also needed.

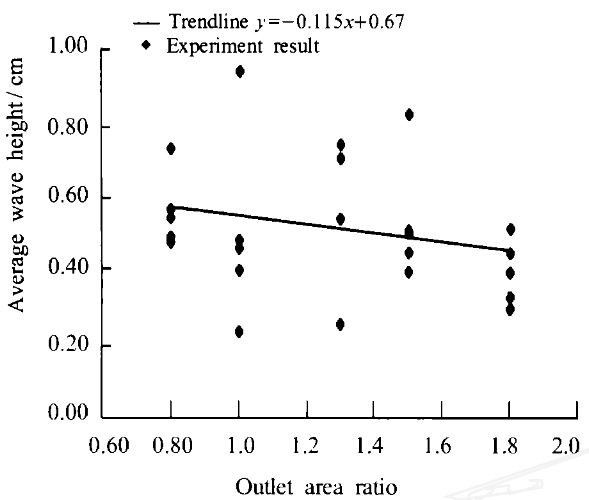


Figure 9 The effect of outlet area on surface turbulence

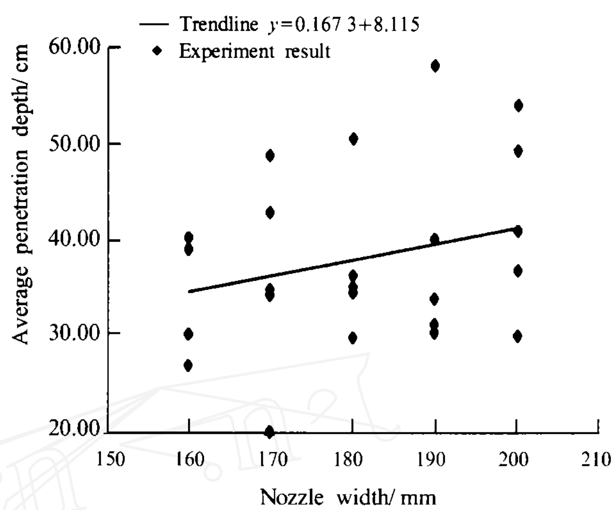


Figure 10 The effect of nozzle width on penetration depth

3 Conclusions

The effect of each SEN design variables on fluid flow in the mould was studied. Our experiment of CSP mould fluid flow showed that the surface turbulence and penetration strength to the solidified shell are all important index of casting technology. An ideal SEN configuration is not only bring lower surface waves but also shallower penetration.

The most important factor of SEN structure is immersion depth. The surface turbulence strengthens with the immersion depth decreasing, at the same time the penetration depth lowers.

SEN outlet shape (include outlet area and outflow angle) and width have effects on the fluid flow. The fluid flow does not change significantly during the nozzle thickness changing. The surface turbulence strengthens with the outlet area decreasing and the outflow angle tends upwards. The penetration depth will lower while the outflow angle upwards.

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