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Effect of Process Parameters on Continuous Casting Products Solidification Using Surface Response Methodology: A Numerical Study

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ABSTRACT

The aim of this study is to numerically simulate the continuous casting products using commercial CFD software ANSYS FLUENT. CFD code only give numerical results on casting like fill time, conversion of liquid to solid phase and many more, but it is not show relation among factors and their responses, so in this study a DOE technique is used for making relationship among factors and responses. Surface response methodology is used for this study using MINITAB software. Four factors are selected for DOE analysis. Box-Behnken Design methodology is final approach which is used in this study.

Key words: Continuous casting, CFD, DOE, Box-Behnken Design, ANOVA,

INTRODUCTION

Casting is a manufacturing process in which liquid metal is usually poured into a mould cavity, the liquid takes desired shape of the cavity and then allowed to solidify. The solidify part is also known as a casting. There are several casting methods that are used to produce metal parts. The most widely used are Investment casting, permanent mould casting, centrifugal casting, continuous casting, sand casting. Continuous casting is a growing interest in the industry. Continuous casting of cast iron and covers many complex phenomena like turbulent multiphase fluid flow, heat transfer and solidification. Convection of liquid metal in a crystallizer, and thus shifting and changing shape of the crystallization front have a big impact on the quality of the ingot. Casting filling process plays important role in casting production. The defects are related to filling process like a blowhole, slag inclusion, shrinkage, cold shut etc [8]. The high quality casting products are obtained by controlling the filling order, process parameter (solidus temperature, liquid us temperature, pouring speed and pouring temperature.) and flow patterns is quite necessary. The study of process parameter and filling process is the first step of moulding process, as well as the most complicated process, because resolving this problem including computational fluid dynamics (CFD), heat transfer, numerical methods, computer graphics, partially differential equations, etc. therefore, CFD plays an important role in analysis of flow condition in case of continuous casting [1-3].

In this work FLUENT software is used for simulation. Main focus of this work is on solidification and melting analysis of a continuous casting process used in various areas. In CFD simulation selection of turbulence model is an important part of modelling. Finally simulate numerically the continuous casting products using commercial CFD software ANSYS FLUENT.

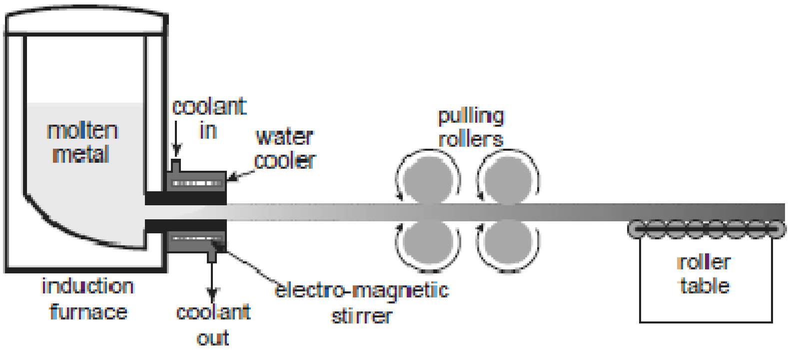

Fig. 1 Schematic continuous casting line

In this study a continuous casting product is used for analysis. Product is simple circular rod used in various areas. Fig. 2 show its cross sectional view. In Fig. 3 CFD domains is discussed in detail.

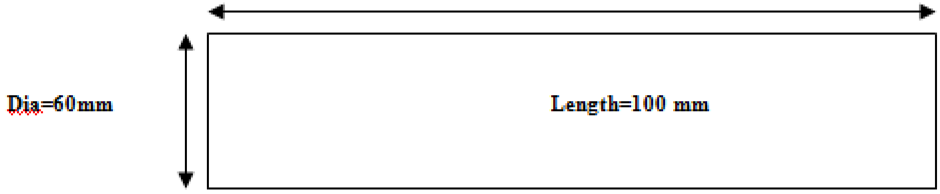

Fig. 2 Cross sectional area of casting product

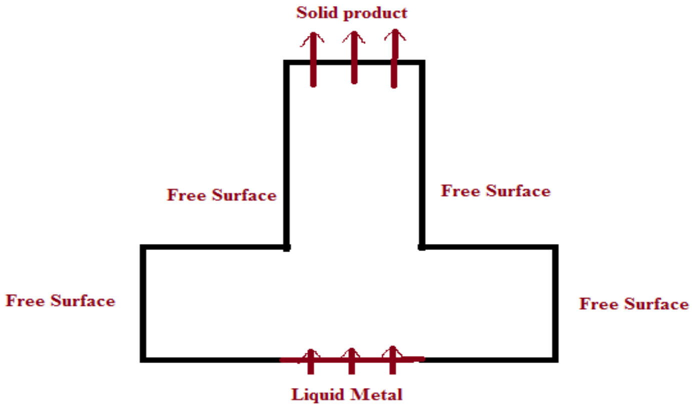

Fig. 3 CFD Domain

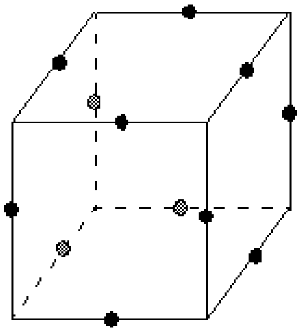

Fig. 4 Design methodology of Box Behnken

DESIGN OF EXPERIMENT

In this study design of experiment methodology is adopted for cases generation. Box-Behnken Design methodology is used for experiment generation using Minitab software.

Box-Behnken designs have treatment combinations that are at the midpoints of the edges of the experimental space and require at least three factors. In this study four factors are suitably used for numerical simulation. The illustration below shows a four-factor Box-Behnken design. Points on the diagram represent the experimental runs that are performed [7].

These designs allow efficient estimation of the first- and second-order coefficients. Because Box-Behnken designs often have fewer design points, they can be less expensive to run than central composite designs with the same number of factors. However, because they do not have an embedded factorial design, they are not suited for sequential experiments.

Box-Behnken designs can also prove useful if user know the safe operating zone for its process. Box-Behnken designs do not have axial points, thus, user can be sure that all design points fall within its safe operating zone. Box-Behnken designs also ensure that all factors are never set at their high levels simultaneously. Table -1 shows their factors and low /high limit for design of experiment.

Factor and levels

Table -1 Factor and Their Levels for Surface Response Design

level	A Pouring Speed	B Pouring Temperature	C Solidus Temperature	D Liquids Temperature
Low	0.0010	1250	1000	1150
High	0.0014	1400	1150	1300

This design process is done in Minitab software and summary of results are shown below. In table 2 all experiments are shown. [Factors: 4, Replicates: 1, Base runs: 27, Total runs: 27, Base blocks: 1, Total blocks: 1, Centre points: 3]

Table -2 Box-Behnken Design Table

Std. Order	Run Order	Pt Type	Blocks	Pouring Speed	Pouring Temp.	Solidus Temp.	Liquids Temp.
1	1	2	1	0.001	1250	1075	1225
2	2	2	1	0.0014	1250	1075	1225
3	3	2	1	0.001	1400	1075	1225
4	4	2	1	0.0014	1400	1075	1225
5	5	2	1	0.0012	1325	1000	1150
6	6	2	1	0.0012	1325	1150	1150

Std. Order	Run Order	Pt Type	Blocks	Pouring Speed	Pouring Temp.	Solidus Temp.	Liquids Temp.
7	7	2	1	0.0012	1325	1000	1300
8	8	2	1	0.0012	1325	1150	1300
9	9	2	1	0.001	1325	1075	1150
10	10	2	1	0.0014	1325	1075	1150
11	11	2	1	0.001	1325	1075	1300
12	12	2	1	0.0014	1325	1075	1300
13	13	2	1	0.0012	1250	1000	1225
14	14	2	1	0.0012	1400	1000	1225
15	15	2	1	0.0012	1250	1150	1225
16	16	2	1	0.0012	1400	1150	1225
17	17	2	1	0.001	1325	1000	1225
18	18	2	1	0.0014	1325	1000	1225
19	19	2	1	0.001	1325	1150	1225
20	20	2	1	0.0014	1325	1150	1225
21	21	2	1	0.0012	1250	1075	1150
22	22	2	1	0.0012	1400	1075	1150
23	23	2	1	0.0012	1250	1075	1300
24	24	2	1	0.0012	1400	1075	1300
25	25	0	1	0.0012	1325	1075	1225
26	26	0	1	0.0012	1325	1075	1225
27	27	0	1	0.0012	1325	1075	1225

CFD MODELLING

In past when numerical approach was not available to solve fluid flow problems, it was very difficult for engineers to analysis flow field conditions. Today with the help of CFD it is very easy to analysis complex fluid flow problems. In case of thermal flow analysis also, CFD plays a vital role because engineers can now see flow conditions visually. This is not possible in experimentation. However, CFD have also some limitations. Application of CFD needs good knowledge of CFD and CFD codes. CFD also has computational limitations. Lot of research is being carried out to overcome these limitations [4-5].

In this work FLUENT software is used for simulation. Main focus of this work is on solidification and melting analysis of continues casting process used in various areas. In CFD simulation selection of turbulence model is an important part of modelling. Although in most of the research papers STD k-ε turbulence model is used for building simulation but k-ω SST show better results [8].

The product selected for this study is assumed to be used in Indian continental specially in building construction. No heat source has been considered in the system. Boundary surfaces have been specified as coupled type surfaces with shell conduction boundary types. Quality of results from CFD simulation depends on quality of grid. Appropriate size of grid is necessary for proper resolution quality. Grid independency has also been checked to see that size of grid doesn't affect the results, but for present study two mesh sizes are used to check mesh quality.

All input parameters were decided according to literature data. These input parameters are given at primary stage of simulation. A residual criterion for simulation is also important because it controls the errors in simulation. In most of the research papers steady state simulation has been done, however in this case unsteady state simulation has been done.

In this section all experiments generated by DOE technique is numerically solved by Ansys fluent software and response liquid mass fraction at mid section of cavity is solved numerical for all design points and are shown in table -4.

Table -3 Response Results for All Design Points

Std Order	Run Order	Pt Type	Blocks	Pouring Speed	Pouring Temp.	Solidus Temp.	Liquids Temp.	Mass Fraction
1	1	2	1	0.001	1250	1075	1225	0.2258
2	2	2	1	0.0014	1250	1075	1225	0.2259
3	3	2	1	0.001	1400	1075	1225	0.4363
4	4	2	1	0.0014	1400	1075	1225	0.4384
5	5	2	1	0.0012	1325	1000	1150	**0.8213**
6	6	2	1	0.0012	1325	1150	1150	0.062
7	7	2	1	0.0012	1325	1000	1300	0.4154
8	8	2	1	0.0012	1325	1150	1300	0.0181

Std Order	Run Order	Pt Type	Blocks	Pouring Speed	Pouring Temp.	Solidus Temp.	Liquids Temp.	Mass Fraction
9	9	2	1	0.001	1325	1075	1150	0.6229
10	10	2	1	0.0014	1325	1075	1150	**0.6228**
11	11	2	1	0.001	1325	1075	1300	0.2394
12	12	2	1	0.0014	1325	1075	1300	0.2394
13	13	2	1	0.0012	1250	1000	1225	0.4832
14	14	2	1	0.0012	1400	1000	1225	0.6242
15	15	2	1	0.0012	1250	1150	1225	**0.0023**
16	16	2	1	0.0012	1400	1150	1225	0.067
17	17	2	1	0.001	1325	1000	1225	0.54
18	18	2	1	0.0014	1325	1000	1225	0.537
19	19	2	1	0.001	1325	1150	1225	0.0242
20	20	2	1	0.0014	1325	1150	1225	**0.0242**
21	21	2	1	0.0012	1250	1075	1150	0.4499
22	22	2	1	0.0012	1400	1075	1150	0.8057
23	23	2	1	0.0012	1250	1075	1300	0.1507
24	24	2	1	0.0012	1400	1075	1300	0.2908
25	25	0	1	0.0012	1325	1075	1225	**0.3383**
26	26	0	1	0.0012	1325	1075	1225	0.3384
27	27	0	1	0.0012	1325	1075	1225	0.3384

RESULT AND DISCUSSION

Continuous casting process is simulated in this study casting products using commercial CFD software ANSYS FLUENT. All experiments were designed according to DOE technique (Box-Behnken design), which were presented in table 2 and CFD modelling results in term of mass fraction is presented in table 3.Main outcomes focused in this study are following: [ANOVA Analysis, Signal to noise ratios analysis, Model equations generation].

In this study response is mass fraction developed during process parameter is selected, and all results according to CFD modelling is presented in table - 3. Minitab software is used for ANOVA analysis in this study. Summary table of four factors and their levels is presented in table 1.

Signal to Noise Ratio

Signal to noise ratio is simple technique to predict the effect of changing of factors according to their levels to find effect on product quality. In this study "larger is better" option is adopted as quality indicator for S/N ratio and means ratio. The response tables for S/N ratio and mean are presented in table 4 and table 5.

Tables 4 & 5 show factors importance ranking and it is clear that Solidus Temperature is most important factor, which can responsible for mass fraction on the moving wall. Best and worst cases from experiment factors and their levels are also presented in this study and were calculated from Fig. 5 and Fig. 6.

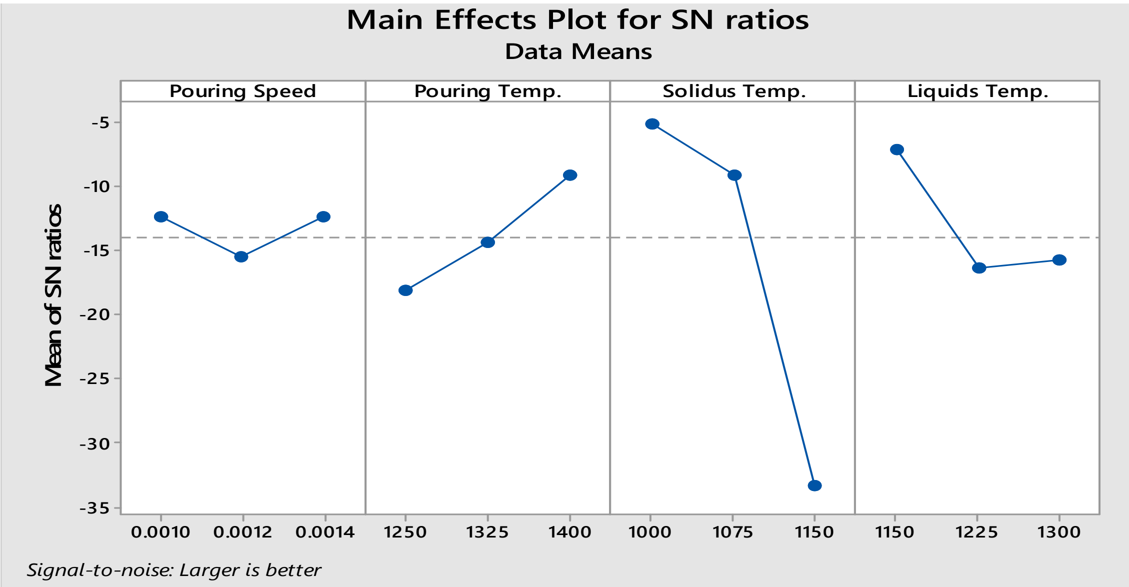

Fig. 5 Data Means for Larger is better for S/N Ratios [Best Case: 0.0014,1400,1000,1150, Worse Case: 0.0012, 1250, 1150, and 1225]

Table -4 Response Table for Signal to Noise Ratio

Level	Pouring Speed	Pouring Temp.	Solidus Temp.	Liquids Temp.
1	-12.389	-18.051	-5.084	-7.150
2	-15.414	-14.324	-9.128	-16.283
3	-12.390	-9.091	-33.315	-15.746
Delta	3.025	8.960	28.231	9.133
Rank	**4**	**3**	**1**	**2**

Table -5 Response Table for Mean Ratio

Level	Pouring Speed	Pouring Temp.	Solidus Temp.	Liquids Temp.
1	0.34810	0.25630	0.57018	0.56410
2	034838	0.34654	0.39126	0.30514
3	0.34795	0.44373	0.03297	0.22563
Delta	0.00043	0.18743	0.53722	0.33847
Rank	**4**	**3**	**1**	**2**

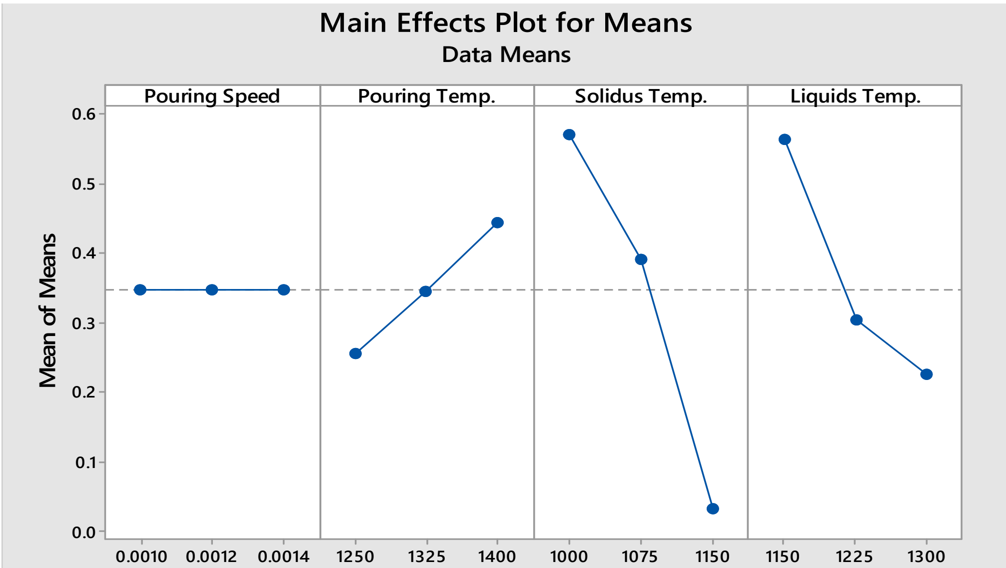

Fig. 6 Data Means for Mean Ratios [Best case: 0.0014,1400,1000,1150 Worse Case: 0.0010, 1250, 1150, and 1300]

ANOVA Analysis

The analysis of variance is calculated for this study and results are shown in table 6 respectively. In ANOVA analysis F-Test is conduct to compare a model variance with a residual variance. F value was calculated from a model mean square divided by residual mean square value. If f value was approaching to one means both variances were same, according F value highest was best to find critical input parameter.

Table -6 Analysis of Variance for Mass Fraction

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	1.31488	0.328720	44.52	0.000
Pouring Speed	1	0,00000	0.000000	0.00	0.998
Pouring Temp.	1	0.10539	0.105394	14.27	0.001
Solidus Temp	1	0.86581	0.865805	117.26	0.000
Liquids Temp.	1	0.34368	0.343679	46.54	0.000
Error	22	0.16245	0.007384		
Total	26	1.47732			

Table -6 list out one important result that F value for regression models are very high, than one and P value is very less (approx 0.0000) suggested that all cases were significant. From literature review various researchers found that if p value was very small (less than 0.05) then the terms in the regression model have a significant effect to the responses.

ANOVA analysis is also tell that Solidus and liquids temperature has very low p value than other factor like Pouring speed and temperature, All four factors in which only three factor have acceptable p value so it can concluded that mass fraction at moving wall are affected by mainly three factor, this ANOVA analysis is linear single factor analysis, multi product ANOVA analysis can show more accurate results, which are presented in table 7, but not show good agreement for this study. Model equations for mass fraction are presented in table 7 and ANOVA analysis with model equations.

Table-7 Model Summary for ANOVA Analysis

S	R-sq	R-sq(adj)	R-sq(pred)
0.0859299	89.00%	87.00%	82.67%

Table-8 Different Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	5.306	0.711	7.47	0.000	
Pouring Speed	-0	124	-0.00	0.998	1.00
Pouring Temp.	0.001250	0.000331	3.78	0.001	1.00
Solidus Temp	-0.003581	0.000331	-10.83	0.000	1.00
Liquids Temp.	-0.002256	0.000331	-6.82	0.000	1.00

Model Equation -Regression Equation

Mass fraction = 5.306 – 0 pouring speed + 0,001250 pouring temp.-0.003581 solidus temp. -0.002256 liquids temp.

The adequacy of regression models shall be inspected to confirm that the all models have extracted all relevant information from all simulated cases. If regression equations results were adequate, than the distribution of residuals should be normal distribution.

For normality test, the Hypotheses are listed below -

- Null Hypothesis: the residual data should follow normal distribution
- Alternative Hypothesis: the residual data does not follow a normal distribution Normal probability for all responses were shown in Fig.7.

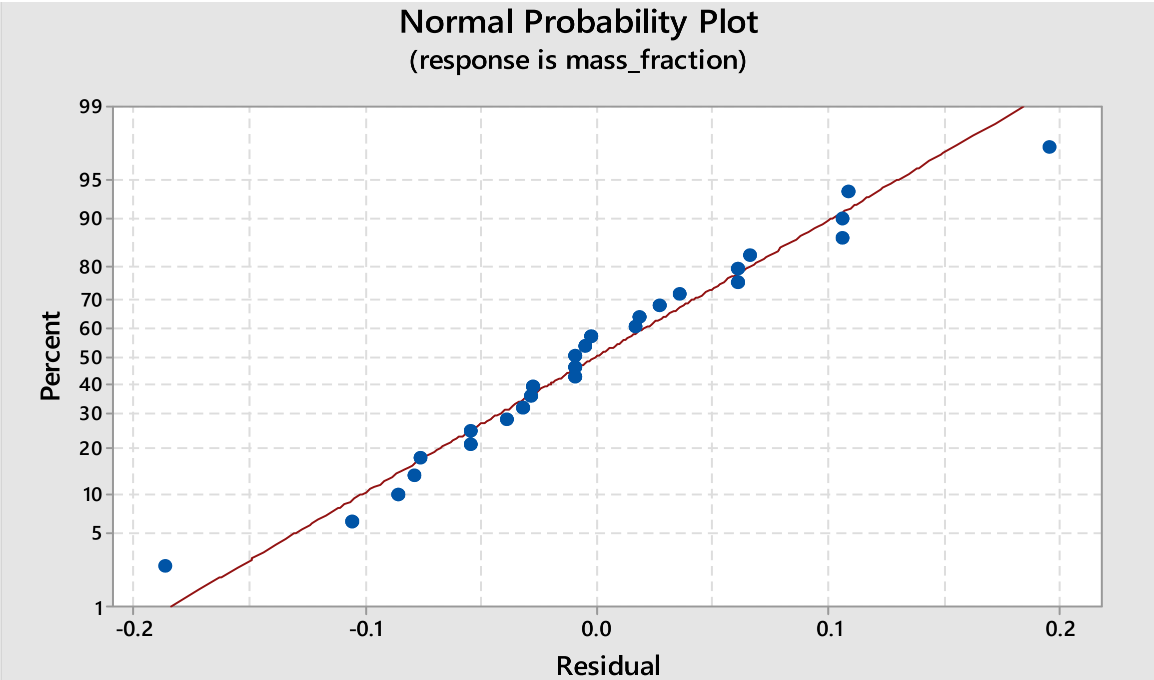

Fig.7 Normal probability for Von-Misses Stress

CONCLUSION

Continuous casting is numerically solved by CFD software. Design of experiment is used as tool in this study to find better results. Main outcome form this study is following

- Signal to noise ratio analysis is performed in this study and the final conclusion from this test is that solidus and liquids temperature play important role in solidification of casting product in proper time. Cooling rate is assumed constant in this study
- Best and worst cases are solved in this study and presented with values in this section (Only S/N ratio based cases are presented)
  Best case: 0.0014,1400,1000,1150 **Worse Case**: 0.0012,1250,1150,1225
- ANOVA analysis is performed in this study and with the help of regression modelling general modelling equation is generated for future application in casting industry
- Model equation generated in this study is following

Mass fraction = 5.306 – 0 pouring speed + 0,001250 pouring temp.-0.003581 solidus temp. -0.002256 liquids temp.

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