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FACTORIAL DESIGN AND SIMULATION FOR SOLIDIFICATION OF PURE COPPER

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ABSTRACT

The research work is concentrated with the numerical simulation of the solidification of thepure copper. This paper presents the influence of solidification process parameters like mouldtype, mould temperature, metal temperature, convection phenomenon on the solidificationprocess during the solidification of the pure copper. A plan of experiments based on fullfactorial design of experiment approach has been used to acquire the data. The normalprobability plot is employed to investigate significant influence of the solidification processparameters. By applying the above approach using the finite element method technique andthe ANSYS software program we find cooling graphs, thermal gradient, thermal flow and thetemperature distribution at various points in the solidifying specimen and cooling and heatingcurves in cast mould system. The analysis of the heat transfer result shows the nonlinearcharacteristics and temperature dependent thermo physical property of copper.

Keywords:ANSYS, ceremsite, copper casting,factorial design,finite element method, solidification simulation.

I.INTRODUCTION

The numerical simulation of process parameters during solidification is of considerable significance in understanding the development of temperature dependent thermo-physical property and optimization of the solidification for molten metal in moulds.

However the study of the temperature dependent thermo-physical property of the casting during solidification process is very complicated due to complex thermal and physical behaviour of the molten metal.

To solve engineering problem experimental design is a systematic, careful approach that applies optimization principles and techniques at the data collection stage so as to make sure the generation of valid, accurate, precise and engineering conclusions. In product design in manufacturing industry the casting process simulations are broadly accepted to improve quality and casting features [1]. For the solution of linear and non-linear problems finite element method (FEM) is preferred by several authors [2-6]. Design of experiment is a useful tool in order to characterize multivariable performance measures. It gives the possibility to identify any possible interactions among them, and to analyse the significant input factors of the process. The numerical simulation of process parameters during solidification is of considerable significance in understanding the development of temperature dependent thermo-physical property and optimization of the solidification for molten metal in moulds.However the study of the temperature dependent thermo-physical property of the casting during solidification process is very complicated due to complex thermal and physical behaviour of the molten metal. Once the casting begins to cool, it contracts, resulting in a reduction of heat transfer to the cast surface due to less contact pressure. There are several factors which affect the cooling process such as molten metal flow, metal properties and the mould filling velocity.The variations in the quality of the cast, the geometrical deviation in model profile and the shape of the surface finish will be produced by all these factors [7]. In this study solidification of pure copper is performed in sand mould AI 50/60 AFS and ceramsitemould and the properties of copper is considered as a function of the temperature and properties of the sand and ceramsitemould are measured constant because the temperature-dependency of these moulds are not found in literature. On outer surface of the mould convection phenomena is applied. Factorial design was performed for achieving the correlation with various process parameters and finding their influence on solidification and optimizing them. Finite element method was used to analyse this type of problem easily i.e. which shows nonlinear characteristic. In this paper a comparative study of two type of mould i.e. sand mould AI 50/60 AFS and ceramsitemould was performed with varying parameters for casting of copper metal. In this analysis it is shown that casting technique is not the only thing which influences the property of the cast part but it also depends on the properties and characteristics of the cast metal used, mould material used and moulding processes. From the economical point of viewit is very important for saving a considerable experimental time and the objects used for analysis and the personal expensesas well [8].

II.LEVEL FULL FACTORIAL DESIGN

2^k design is a factorial design, that is, a factorial arrangement with k factors each at two levels. Two levels of the factors are referred as low and high. Each treatment in the 2^k design are denoted by k digits, where the first digit indicates the level of factor A, the second digit indicates the level of factor B and the k^{th} digit indicates the level of factor k. Experiment is designed according to 2^4 full factorial design. The input parameter information is shown in the Table1.

Table 1: Input Parameter Information

Parameters	Low level	High level
Mould Type	Sand	Ceramsite
Mould Temperature	300K	400K
Metal Temperature	1373K	1473K
Convection phenomenon	5 W/m^{2}K	40W/m^{2}K

2^4 Full factorial design of the solidification process parameters are shown in Table 2.

Table 2: Factorial design of the solidification process parameters

S.No .	Process Parameters				Response Factor
	Mould TypeSand (-1)Ceramsite(+1)	Mould Temperature300K (-1)400K(+1)	Metal Temperature1373K (-1)1473K (+1)	Convection phenomenon5 W/m^2K(-1)40W/m^2K(+1)	Temperature after 4 hours of solidification
1	-1	-1	-1	-1	1022.08
2	+1	-1	-1	-1	1301.19
3	-1	+1	-1	-1	1074.98
4	+1	+1	-1	-1	1326.33
5	-1	-1	+1	-1	1071.83
6	+1	-1	+1	-1	1328.35
7	-1	+1	+1	-1	1126.86
8	+1	+1	+1	-1	1331.66
9	-1	-1	-1	+1	1004.73
10	+1	-1	-1	+1	1301.02
11	-1	+1	-1	+1	1046.81
12	+1	+1	-1	+1	1326.20
13	-1	-1	+1	+1	1054.20
14	+1	-1	+1	+1	1328.34
15	-1	+1	+1	+1	1098.34
16	+1	+1	+1	+1	1331.53

Based on calculations for different input parameters, the output parameters are calculated and the result is analysed according to two level full factorial design.

III. MAIN EFFECT & INTERACTION MATRIX PLOT

Based on above 2^4 full factorial design main effect plot and Interaction matrix are shown in Fig.1 and Fig.2. Main effect plot shows the significant factor of process parameters (mould type, metal temperature, mould temperature, and convection phenomenon) and interaction matrix represents the interactions between factors at low level and high level. From the Fig.1 it is clear that mould type is the most significant factor and metal temperaturehas a little bit smaller influence and mould temperature, has lower influence than metal temperatureand higher than convection phenomenon.

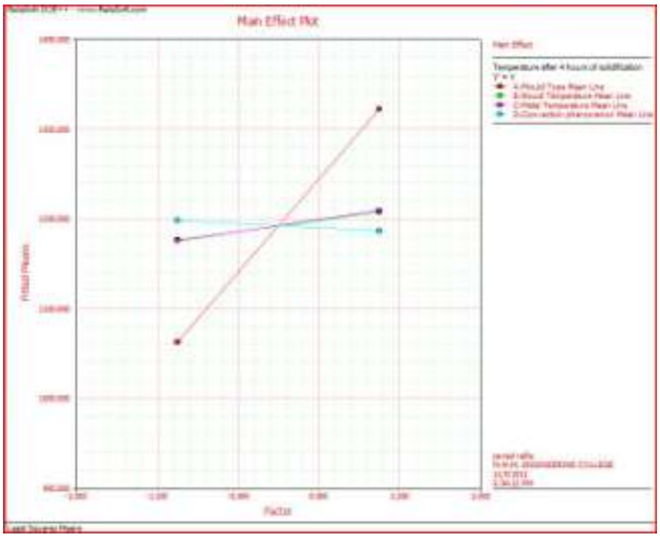


Fig.1: Main effect plot

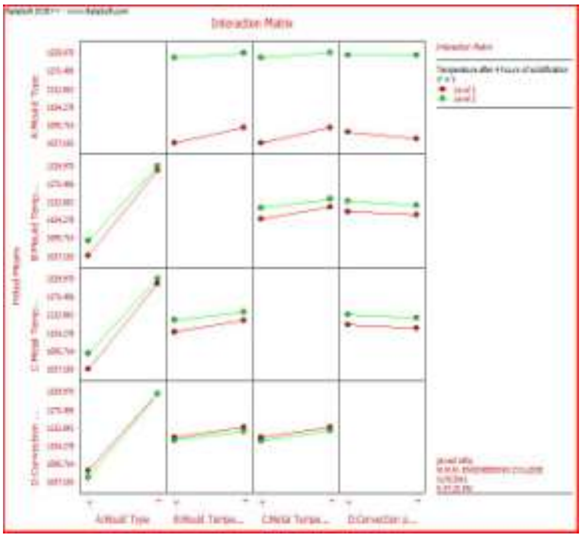
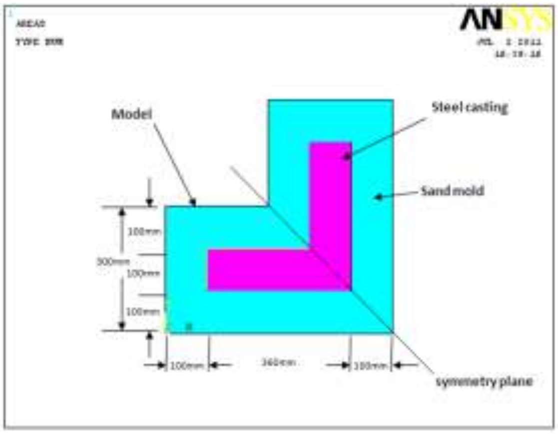
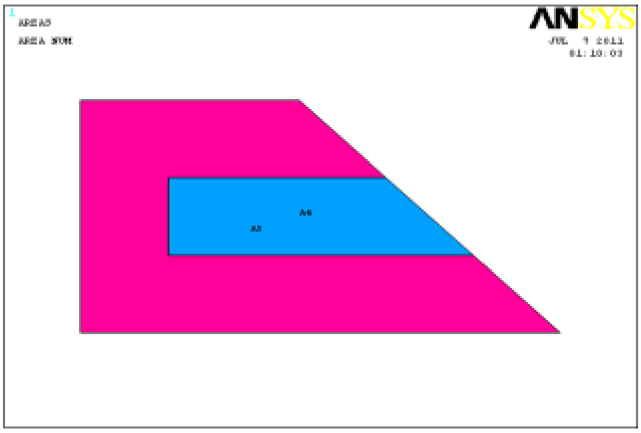


Fig.2: Interaction Matrix

IV.PART MODELLING AND SIMULATION

2D model of cast part with sand/ceramsite mould is shown in Fig 3.The casting is made in an L-shaped sand/ceramsite mould with 0.1 m thick walls.PLANE55 can be used as a plane element or as an axisymmetric

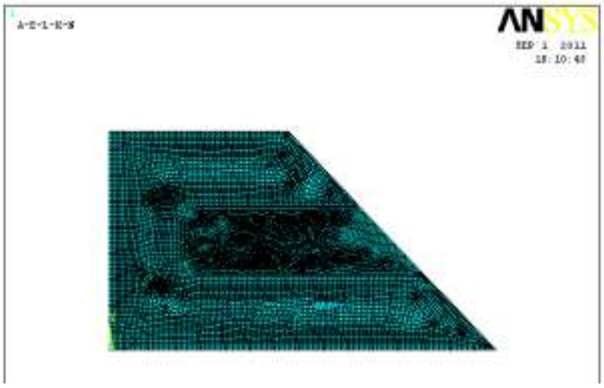




ringelement with a 2-D thermal conduction capability. The element has four nodes with a single degree of freedom, temperature, at each node. The 4 node tetragonal elements (PLANE 55) were used as shown in Fig.4.

Fig. 3: Symmetry of the cast part and mould in 2-D**Fig.4:** 2D model of cast part with sand mould

In order to obtain most precise solution ANSYS program allows control of size and geometry of the mesh. Meshing is done in order to generate system equation and find the result at each point in the cast part. Finite element mesh was generated using tetragonal elements with element length of 0.0045 m taken for mould material and 0.002 m for cast metal. The reason for choosing this element is that it has 2-D thermal conduction capability.



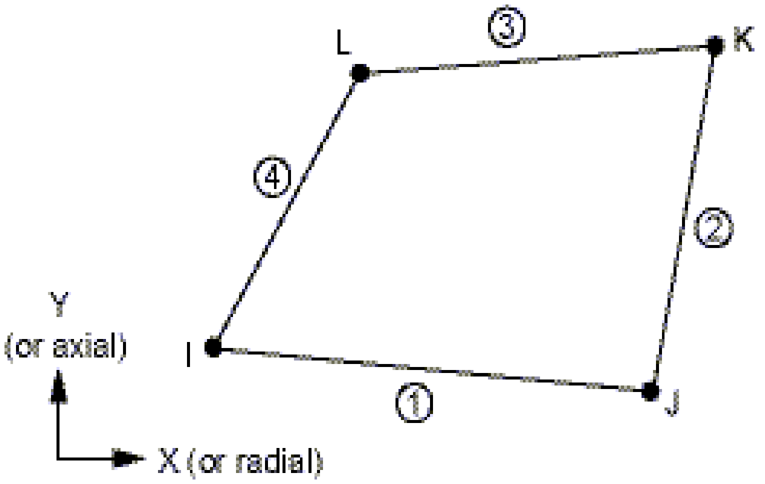


Fig 5: Meshing Model of cast part with mouldFig 6: The 4 node tetragonal elements (PLANE 55)

PLANE 55 elements are defined by four nodes and the orthotropic material properties. The element is defined by 4 nodes having single degrees of freedom, temperature at each node. Heat generation rates may be input as element body loads at the nodes. The element has output data as nodal temperatures included in the overall nodal solution.

V.RESULTS AND DISCUSSION

Simulation is performed for each and every line of factorial design array [10]. Heat transfer results for line 9 and 10 are shown in Fig.8 and for line 9 and 10 the results are more useful, because on these lines of factorial array the solidification temperature corresponds to the minimum value for sand and ceramsitemould correspondingly.Temperature distributions were observed in Fig.8 for metal to be cast i.e. copper and in mould i.e. sand and ceramsite and the values of temperature distribution were shown accordingly at various nodes in Kelvin at 4 hours of the solidification process. Variations for temperature allocation in both systems are shown by FEM results. By comparing Fig.8 (a) and Fig.8 (b), the range of temperature variation between 308.247K and 1012K is presented by sand mould and the ceramsite mould presented a range of temperature variation between 300.556K and 1302K,consequently, ceramsite mould presents significant temperature variation range, the explanation is that the greensand presents high thermal conductivity in relation to the mould of ceramsite.

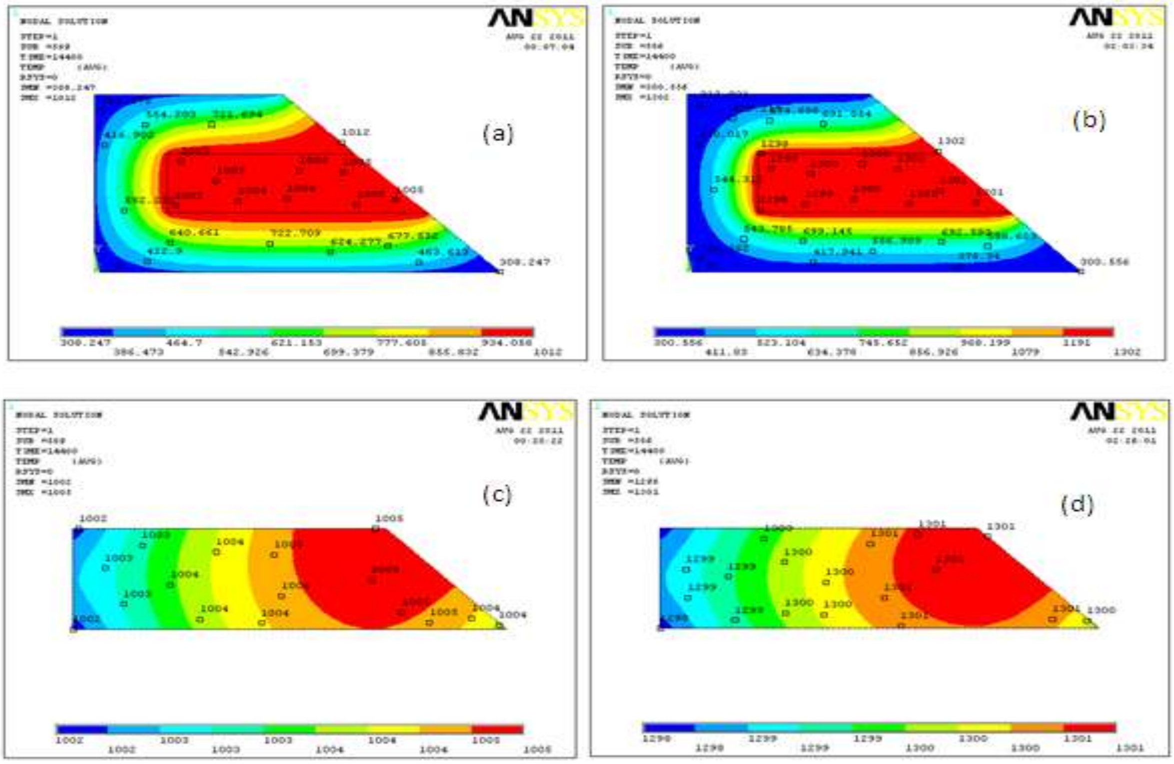


Fig.8: Temperature distribution in(a) Sand mould system(b) Ceramsitemould system(c) Cast metal in sand mould system (d) Cast metal in ceramsitemould system.

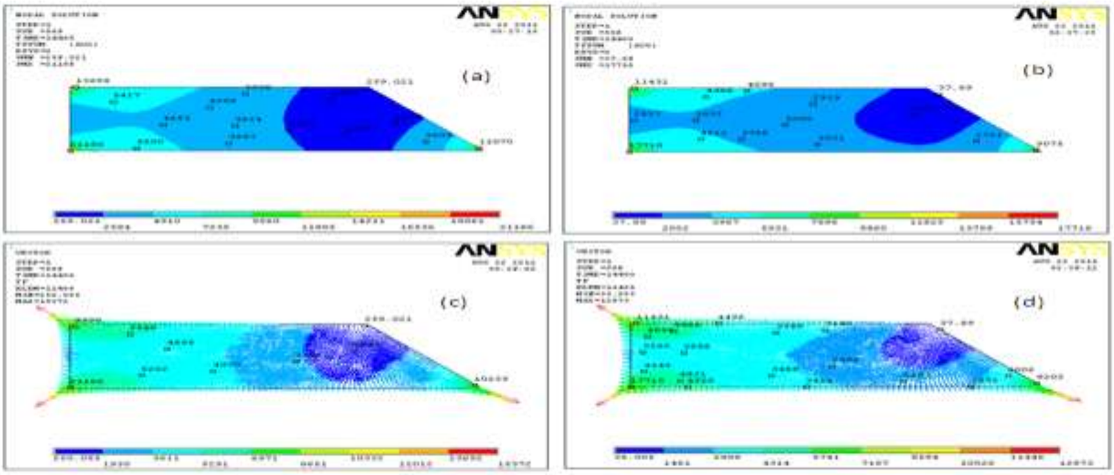


Fig.9 : Thermal flux in magnitude and vector form, as in cast metal in sand and ceramsitemoulds.

Besides, the thermal gradients were obtained for both ceramsite mould and sand mould systems. It is observed from the Fig.9 that the thermal gradient is larger in the ceramsite mould than in sand mould, this is why because the conductivity of the ceramsite is lesser than the sand mould. Moreover, the minimum and maximum thermal gradients are found just at the same positions that the thermal flux occurred. In this case, it is clear from Fig.9 (c) and 9 (d), that the thermal gradient direction is different from the direction of thermal flux. Also, moving from the cold zone to the hot zone the direction of the thermal gradient is corresponding to the direction of the solidification. The Lines 8 and 10 were relevant for the ceramsite mould; the smallest solidification temperature of 1301.02 K is corresponding to the line 10. The mould was without preheated before establishment and also the molten metal was without superheated. A significant loss of heat by convective heat transfer is occurred 40 W/m^2-K on the mould. The largest solidification temperature of 1331.66 K is corresponding to the line 8. As the mould preheating temperature was 400 K, the molten metal was superheated at the temperature of 116.85 K and the heat loss by convective heat transfer in the mould at the rate of 5 W/m^2.K was settled. From the result, this shows higher cooling in the sand mould than in the ceramsite mould due to the different physical properties of material, most importantly the influence of thermal conductivity of the sand. Clearly, the lower solidification temperature in the ceramsite mould and in the sand mould is shown in line 10 and 9 respectively. This is because the mould was without preheating and the molten metal was without superheating and a great heat loss due to the convective heat transfer in the mould.

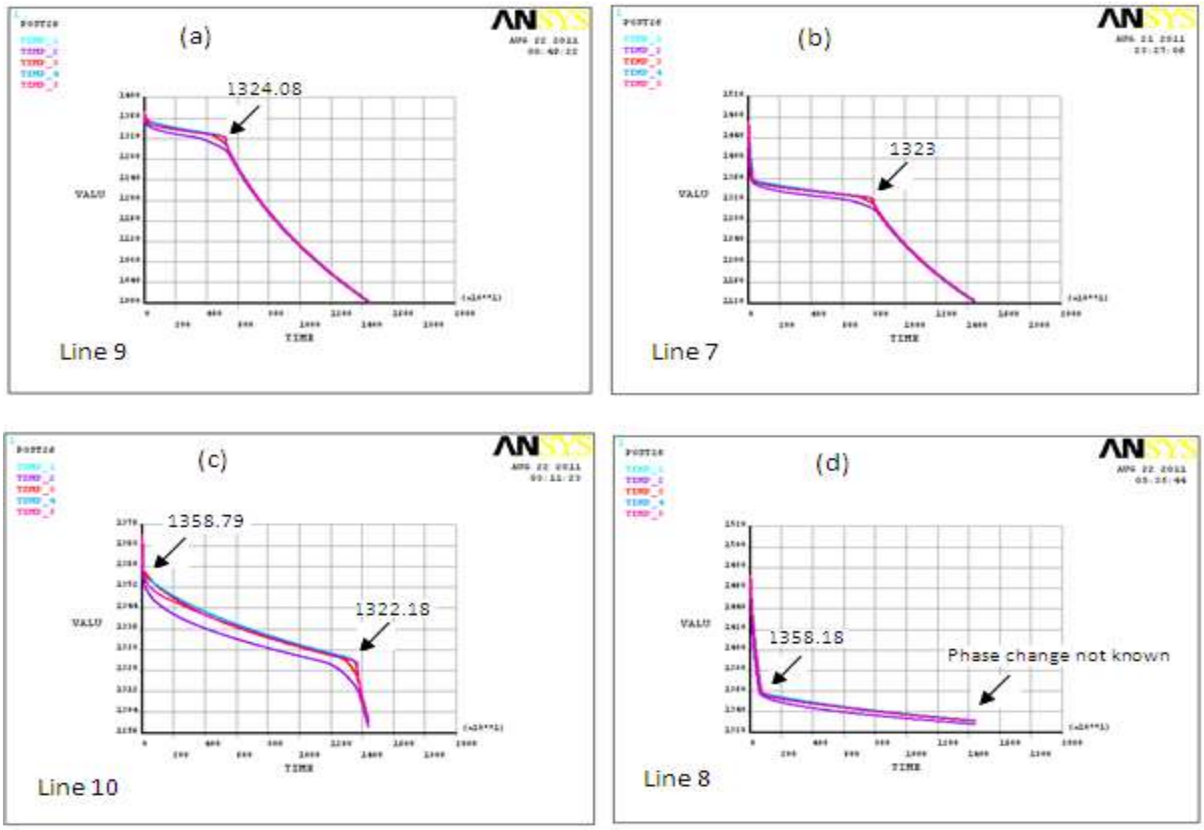


Fig. 10: Cooling curve of cast metal in (a, b) sand and in (c, d) ceramsite mould

The cooling curves were drawn at these numbered points which are shown in Fig.10. To better visualize the solidification process, we specify points for representation of phase change temperature in the sand mould and ceramsite mould. In Fig.10(a) and 10(b), line 9 and line 7 respectively show the combination of five different curves for the solidification of cast metal inside the sand mould and in Fig.10(c) and 10(d), line 10 and line 8 respectively show the combination of five different curves for the solidification of cast metal inside the ceramsite mould. In Fig. 10(a) line 9 shows that solidification of copper inside the sand mould i.e., the smallest solidification temperature (1004.73 K). For this case the mould temperature was 300 K i.e., environmental temperature, the molten metal was without superheating and a great heat loss due to the convective heat transfer in the mould and the phase change happened around 1324.08 K at the time 5126.8 second and Fig.10(b) shows that for line 7 i.e. for the largest solidification temperature (1126.86 K) in sand mould, for this, the mould temperature was preheated; liquid metal was superheated and low heat loss due to the convective heat transfer was established and the phase change happened around 1323 K at the time 7958.6 second. Experimental conditions for line 7 required more time than the line 9 for the reason that in line 9 phase transformation occurred at the temperature of 1324.08 K. Whereas for the solidification of copper inside the ceramsite mould Fig.10(c) shows that for line 10 i.e. the smallest solidification temperature (1301.02 K), for this case, the mould temperature was 300 K i.e., environmental temperature, the molten metal was without superheating and a great heat loss due to the convective heat transfer in the mould and the phase change has happened around 1322.18 K at the time 13671 second and Fig.10(d) shows that for line 8 i.e. for the largest solidification temperature (1331.66 K)in ceramsite mould, the preheating temperature of the mould, high superheating temperature of the liquid metal was fixed and low heat loss due to the convective heat transfer was established and the phase change occurred around 1358.18 K at the time 775 second. The result of phase change of ceramsite during the solidification is different in nature than sand mould for the reason that it has not proper indication for phase transformation at the lower temperature as indicated in the Fig.10(b), due to this reason we select the very first phase transformation condition (at 1358.79 K for line 10 and 1358.18 K for line 8). In this research, processes of heating and cooling in the sand and ceramsite systems were discussed and the study was also made for the solidification process in the copper metal. As represented the solidification process cooling curves in Fig.11 for the cast metal corresponding to the sand/ceramsite mould. We select various paths within the cast-mould system for checking the variation of temperature, thermal flux, and thermal gradient for PATH A, PATH B, PATH C, PATH D, PATH E, PATH F, PATH G, PATH H, and PATH I, the path and points are taken same for the cast mould system, for sand and ceramsite mould. And also there is shown the temperature variation, thermal flux variation and thermal gradient variation for line 9 and line 10 in Fig.12, Fig.13, and Fig.14 respectively.

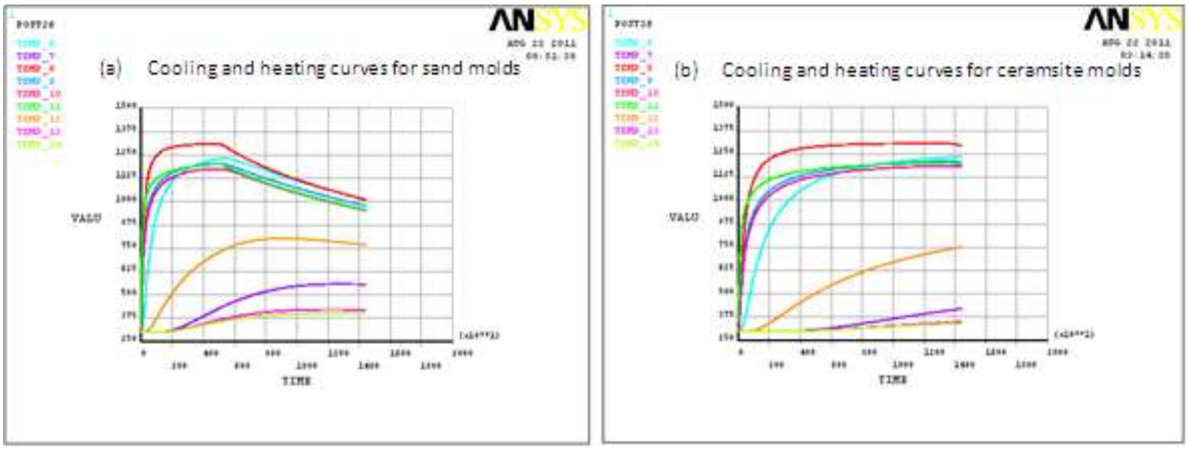


Fig. 11: Cooling and/or heating curves in sand and ceramsite moulds

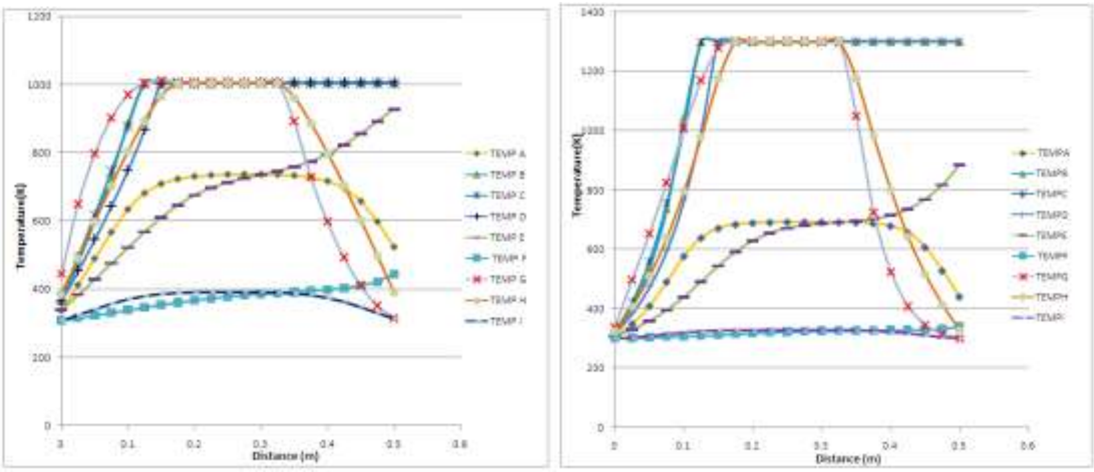


Fig.12: Temperature variations in different paths for line 9 and line 10

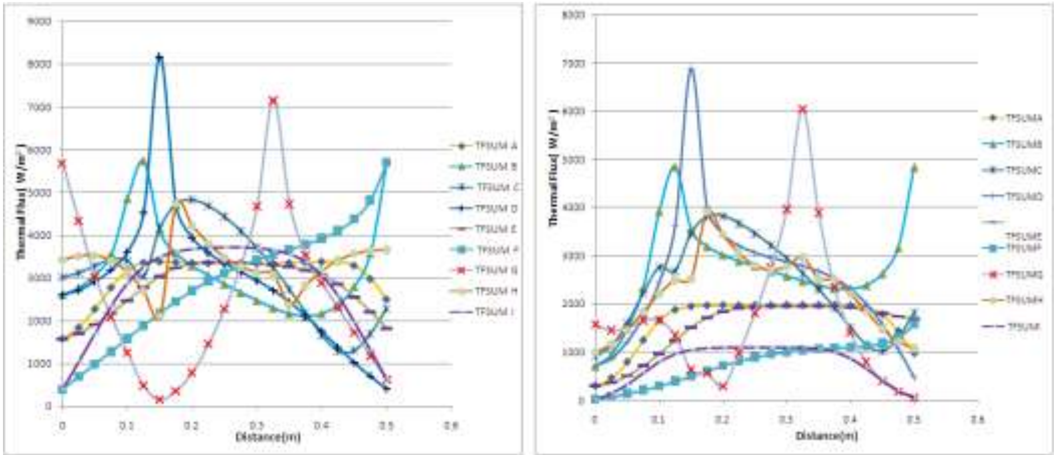


Fig.13: Thermal flux graph in different path for line 9 and line 10

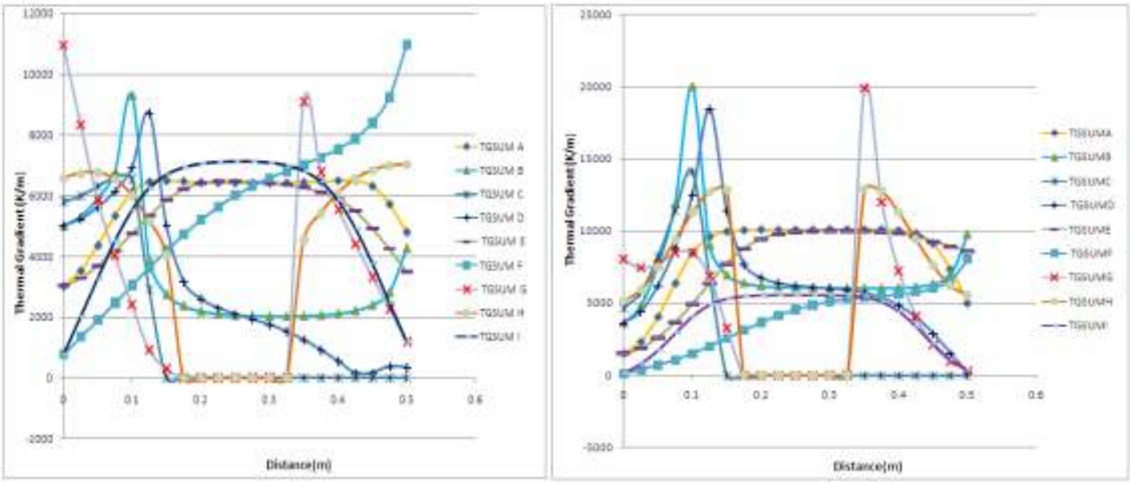


Fig.14: Thermal gradient at different path for line 9 and line 10.

Slower cooling observed where the phase changes. When the cooling velocity is rapid, it is not possible to detect the curvatures of phase change. Probably, the diffusion phenomenon controls the phase transformation. When the cooling velocity is lower, the curvature of phase change can be observed. The heating and corresponding cooling curves are shown by Fig.11(a) for the sand system, where the heating and cooling behaviour are presented by five points 6, 8, 9, 10 and 11 because, these points are close to the cast metal. However, heating behaviour are only comes at points 7, 12, 13, and 14, for the reason that with reference to cast metal these four points are not near. Heating and cooling curves are presented by Fig.11(b) in the ceramsite system, the heating and cooling behaviour corresponding to five points 6, 8, 9, 10 and 11, but after some interval of time the temperature of these points are almost constant and on the other hand, the heating curves are obtained on the points 7, 12, 13 and 14, for the reason that they are not near from the cast metal, this nature is observed in sand and ceramsite systems. The tendency of convergence is quicker for the sand mould. Finally the analysis of the design of experiment result of the input parameters was carried out, being this outcome correspondent to the least temperature after 4 hours of solidification. In order to study the significance of the process variable towards temperature after 4 hours of solidification Design of experiment was performed, the degree of Importance of each parameter considered, namely, mould type, metal temperature, mould temperature, and convection phenomena are given in Fig.15. It is clearly shown that mould type have the greatest influence on the temperature after 4 hours of solidification, metal temperature has a little bit smaller influence and mould temperature, has lower influence than metal temperature and higher than convection phenomenon.

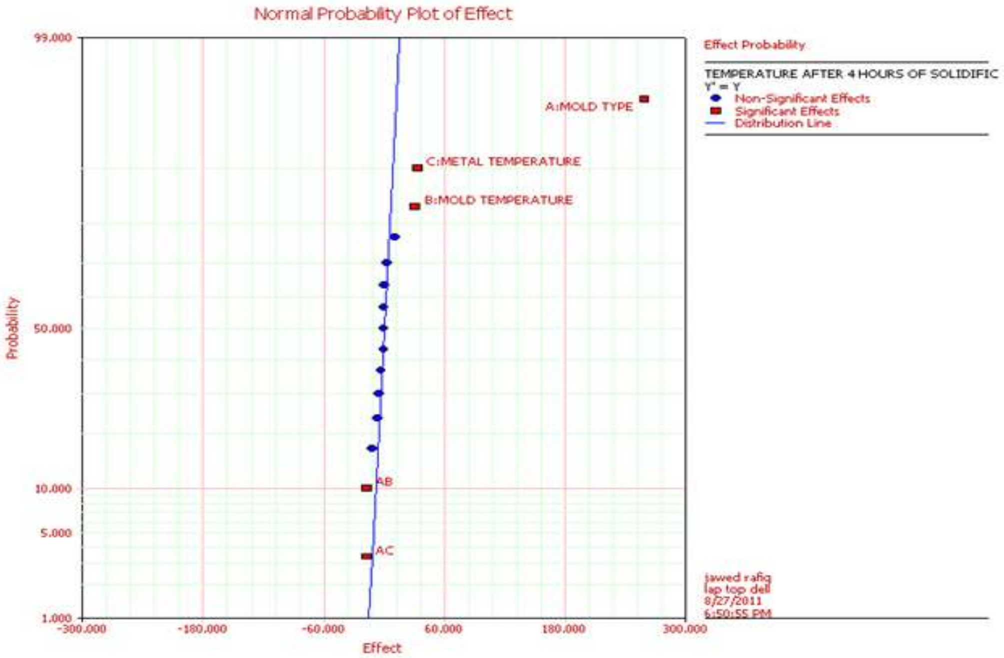


Fig.15: Normal probability plot effect.

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