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Optimal Design of Feeder for Sand Casted Steel Dumbbell: Simulation Studies for Techno-Economic Feasibility

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Abstract In the casting technology, defect free casting had been the primary goal since the inception of the technology. However in the present casting arena, emphasis on the precise and defect free casting has got greatly increased due to energy saving, environmental and economy considerations apart from the stringent product quality standard requirements. In order to achieve this level, computer simulation is inevitably necessary. FEM based simulation software is used to find solidification related defects specially shrinkage porosity very precisely. In the present work ANSYS, an FEM based versatile software has been used for hot spots identification in a two feeder system. The feeders have been designed and optimized. ANSYS has been used for transient thermal analysis and then optimization process has been performed. Path of two feeder optimization for steel sand casting on ANSYS have been searched. Conductive and convective heat transfer has been taken in to consideration. The whole process is performed using traditional modulus approach also. The results are compared. The comparison reveals that ANSYS optimizer provides better results for casting having two feeders. It saves material and energy thus resulting into economy and environmental benefits too. Hence it may be recommended as superior over modulus approach for two feeder system in sand casting.

Keywords: *feeder design optimization, FEM, modulus approach, sand casting, shrinkage porosity, steel*

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1. Introduction

Sand casting is the most widely used process for both ferrous and non – ferrous metals, and accounts for approximately 90% of all castings produced. Finite Element Method (FEM) is a powerful computational tool that is used to numerically solve many engineering problems. Most of the Research on the area of casting processes modeling uses FEM as a solver to the casting Process model. The numerical simulation of solidification process using either Finite Difference or Finite Element Methods (FDM/FEM) involves the following steps: [1]

1. Formulating an accurate mathematical model of the solidification process.
2. Specifying accurate values for thermal properties of material involved.
3. Performing the analysis to obtain the temperature history of casting and mould points.
4. Post – processing the results to visualize the solidification pattern and identify defects.

Feeders are designed to compensate the solidification shrinkage of a casting, and make it free of shrinkage porosity. Feeder design parameters include the number, location, shape and dimensions of feeder. Feed path and feeding distance influence the location and number of feeders. The volume of the feeders must be minimized to increase the yield. The criterion is given by for getting feeder yield C_{F3}:

$$C_{F3} = N_c v_c / \left(N_c v_c + \sum_i v_{fi} \right) \tag{1}$$

In sand casting, sand mixed with binders and water is compacted around wood or metal pattern halves to produce a mould. The mould is removed from the pattern, assembled with cores and metal is poured in to the resultant cavities. After cooling, moulds are broken to remove the casting. After casting is removed from the sand moulds, sand mould is destroyed [2]. In sand casting, molten liquid metal is poured into a cavity which takes the negative shape of the object and the mould is made from sands. Heat removal is by heat transfer in sand mould, the governing equations for heat transfer are [3]

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial^2 x} \tag{2}$$

$$T(x,0)=T_0 \tag{3}$$

$$T(0,t)=T_M\ (\text{Temperature at metal end}) \tag{4}$$

$$T(\infty,t)=T_0 \tag{5}$$

The method of steepest descent may appear to be the best unconstrained minimization technique since each one-dimensional search starts in the best direction. The use of negative of the gradient vector as a direction for minimization was first made by Cauchy in 1847. In this method we start from initial trial point X1 and iteratively move towards the optimum point [4].

Finite element analysis based software ANSYS 12.0 has been used. Modal of casting is done in Pro E wild fire and cylindrical feeders have been created in ANSYS modeling. Element selection and material property feeding is done latter. Convective load have been considered after proper meshing. Proper boundary values of temperature have been provided and then transient thermal analyses have been performed. DB log file has been assigned to ANSYS optimizer and then design variable, state variable and objective functions have been provided [5]. They are height of feeder, maximum temperature difference of feeder and respective casting zone, inverse of feeder yield respectively with suitable allowances and factor of safety. First order optimization has been performed through ANSYS 12.0.

Design optimization works entirely with the ANSYS Parametric Design Language (APDL) and is contained within its own module (/OPT). Design optimization is largely concerned with controlling user-defined, APDL functions/parameters that are to be constrained or minimized using standard optimization methods (e.g., function minimization, gradients, design of experiments). The independent variables in an optimization analysis are the design variables. The vector of design variables is indicated by: [6]

$$X=[X_1X_2X_3\ldots X_n] \tag{6}$$

Design variables are subject to n constraints with upper and lower limits, that is,

$$\underline{X}_i \le X_i \le \overline{X}_i\,(i=1,2,3,\ldots,n) \tag{7}$$

Where: n = number of design variables.

The design variable constraints are often referred to as side constraints and define what is commonly called feasible design space. Now, minimize

$$f=f(X) \tag{8}$$

Where: f = objective function

Subject to

$$g_i(X)\le \overline{g}_i\,(i=1,2,3,\ldots,m_1) \tag{9}$$

$$\underline{h}_i \le h_i(X)(i=1,2,3,\ldots,m_2) \tag{10}$$

$$\underline{W}_i \le W_i(X)\le \overline{W}_i\,(i=1,2,3,\ldots,m_3) \tag{11}$$

g_i, h_i, W_i = state variables containing the design, with underbar and overbears representing lower and upper bounds respectively. (input as min, max on OPVAR command) m_1+m_2+m_3=number of state variables constraints with various upper and lower limit values. The state variables can also be referred to as dependent variables in that they vary with the vector x of design variables [6].

In FEM, the field variables are the temperatures at all nodal points that vary with time. Thermal properties like thermal conductivity, density, specific heat also vary with temperature and hence the problem becomes non – linear transient in nature Galerkin's weighted residual approach has been reported [7]. The advantage of using FEM is the ability to handle complex boundaries, the ease in implementing boundary condition. But this method requires much effort for formulation of problem, data preparation and need long processing time [8].

In general, FEM is preferred as it allows a wider choice of element shapes and better accuracy, while FDM based simulation programs are faster and easier to execute. Recent advances have been in the areas of automatic preprocessing (mesh generation), adaptive re-meshing for better accuracy in critical regions, heat transfer models for considering the effect of variable air gap and mould coatings, convective and radiation heat transfer and improving the efficiency of computation[9]. Feeder optimization has been performed using topology optimization [10], poison equation approximation [11] and genetic algorithm [12].

P. Prabhakara Rao gives advantages of computer simulation based design enumerated. The procedures thus described have been demonstrated with the above case study of application of Pro CAST simulation at G.S alloy Foundry. It is demonstrated that the foundries can derive mileage by resorting to FEM simulations of the casting process for process development and optimization. [13] The application of casting simulation software's in the foundries not only minimizes the wastages of resources required for final castings, but also improves / enhances the quality and yield of castings, which implies higher value addition and lower production cost. The experimental study represents the effect of sizes of risers and necks on the solidification behavior of the aluminum alloy castings. The simulated results are more or less similar with experimental results [14].

The application of computer aided method, solid modeling, and casting simulation technologies in foundries can able to minimize the bottlenecks and non value added time in casting development, as it reduces the number of trial casting required on the shop floor. In addition, the optimization of riser neck reduces or completely removes the occurrence of shrinkage defect in the casting. The application of casting simulation software based on finite element method and vector element method shows good results and matched with the experimental results [15].

Over size feeder leads to not only the loss of material but also to the loss of energy required for molding and remolding the material again and again. In fact the repeated molding-remolding consumes huge amount of fuel ultimately contributing to the global warming which is the greatest havoc for modern civilization. Hence the optimal design of feeder system must be seen not only from the material saving point of view, it must simultaneously be pursued from the environmental considerations too [16]. The modern casting processes not only require high precision and accuracy, they require energy efficiency and environmental consistency too. The present work is a determined step in this direction.

2. Objective of the Study

The shrinkage porosity defect is one of the very common solidification defects of sand casting process. It occurs in the thickest sections of casting which is possessing lasting freezing point. The components gets fail due to inside porosity. As sand casting have the biggest part in manufacturing of world. The practical approach of design of feeder had normally high factor of safety and due to that over size feeders have normally been designed and tested on shop floor. This consumes lot of money and time. So there is required a facility of feeder design which is cheap in the affordable rang of small & medium scale casting industry. The ANSYS optimization tool can give the better design but one have to find out the way of formulate the casting problem in it. We do not found the work done by researcher with ANSYS optimization tool in multi feeder design of feeders for sand casting process. In this work we have fulfill the objective of to finding out the way of designing the two feeders for sand casting of steel and we found it better on conventional modulus approach.

3. Data Collection

Multi feeder optimization has been performed on a dumbbell casting of Steel. Two feeders have been designed.

Volume = 10.87×10^{-06} M^3, Surface Area = 12.98×10^{-03} M^2

Feeders can be optimized by modulus approach. The thickest section has highest value of modulus. The optimization can be performed on ANSYS12.

4. Optimization of Dumbbell Casting with Modulus Approach and Ansys

For removing shrinkage porosity defect, two feeders are designed here by modulus approach and ANSYS 12.0 design optimizer for dumbbell casting. Dumbbell has been considered in four sections A, B, C, D. First modulus approach has been used and then ANSYS Optimizer applied.

Modulus Approach-

Table 1. Dumbbell casting data (Section wise)

s	Volume M^3	Surface Area M^2	Modulus=V/A
A	2.16×10^{-4}	2.16×10^{-2}	0.01
B	1.5×10^{-5}	3.5×10^{-3}	4.3×10^{-3}
C	6.4×10^{-5}	9.6×10^{-3}	6.67×10^{-3}
D	1.5×10^{-5}	3.5×10^{-3}	4.3×10^{-3}

Modulus Approach For medium size Dumbbell Casting with two feeders-

Diameter of Feeder = 56.074 MM

Height of Feeder = 84.11 MM

Diameter of Second Feeder = 42.213 MM

Height of Second Feeder = 63.3 MM, feeder yield by Modulus method is =51.12%

The process of analysis of this case with Design optimizer of ANSYS 12.0 (An FEM Based general purpose software) has been search out for two feeders. Here we have taken height of feeders as a design variables, State variable S1 = FT1-CT1 (always positive), State variable S2 = FT2-CT2 (always positive) with suitable allowances and factor of safety so that hot spot must not remain in casted part. It should be in respective feeder. FT= maximum feeder temperature for respective zone, CT= maximum casting temperature of catchment. Following are the graphs as a result of optimization. Figure 1 is showing the temperature according to cooling. It can be seen that higher temperature are with feeders as compare to casing. This assures that the shrinkage porosity will be in feeders only.

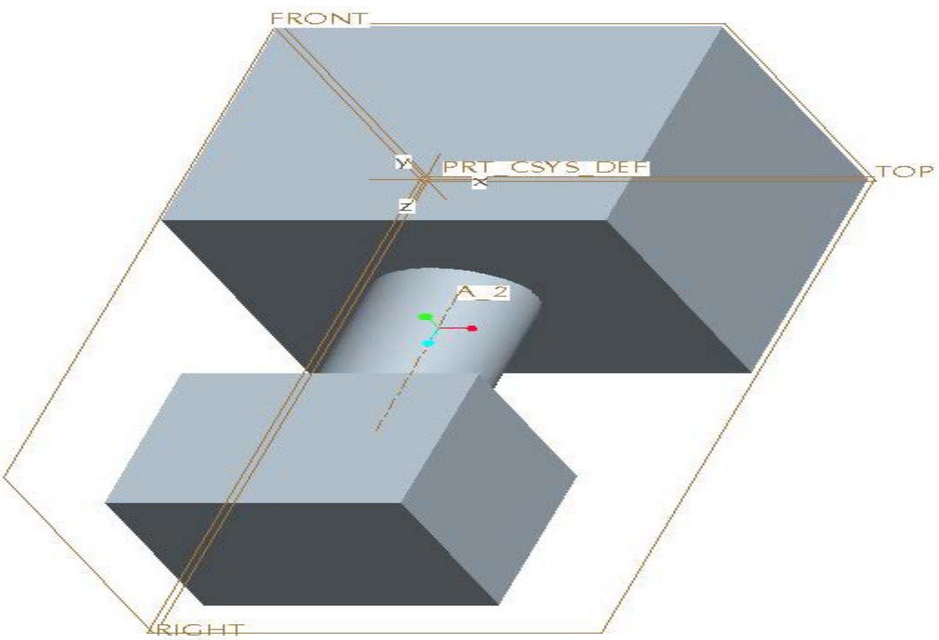

Figure 1. Dumbbell shape casting of Steel

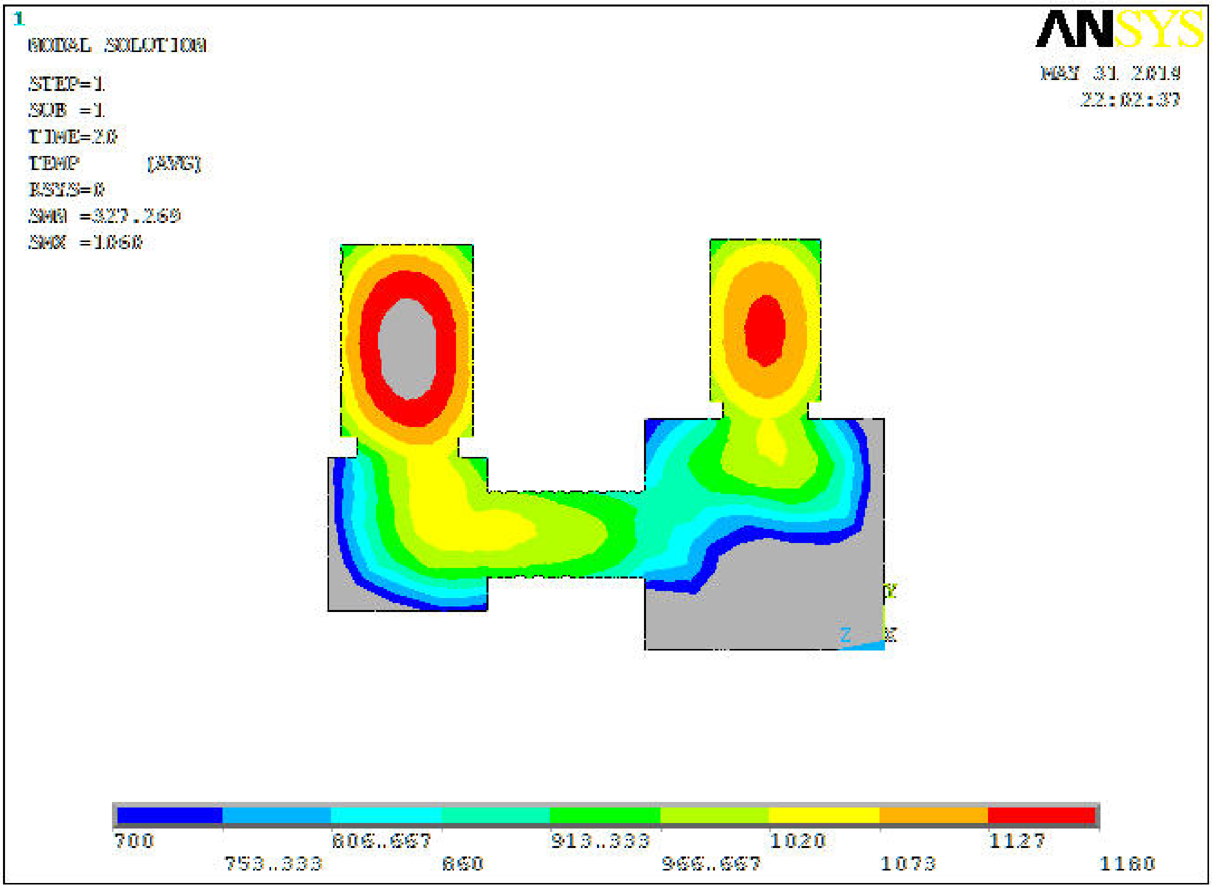

Figure 2. Dumbbell shape casting with optimized feeders

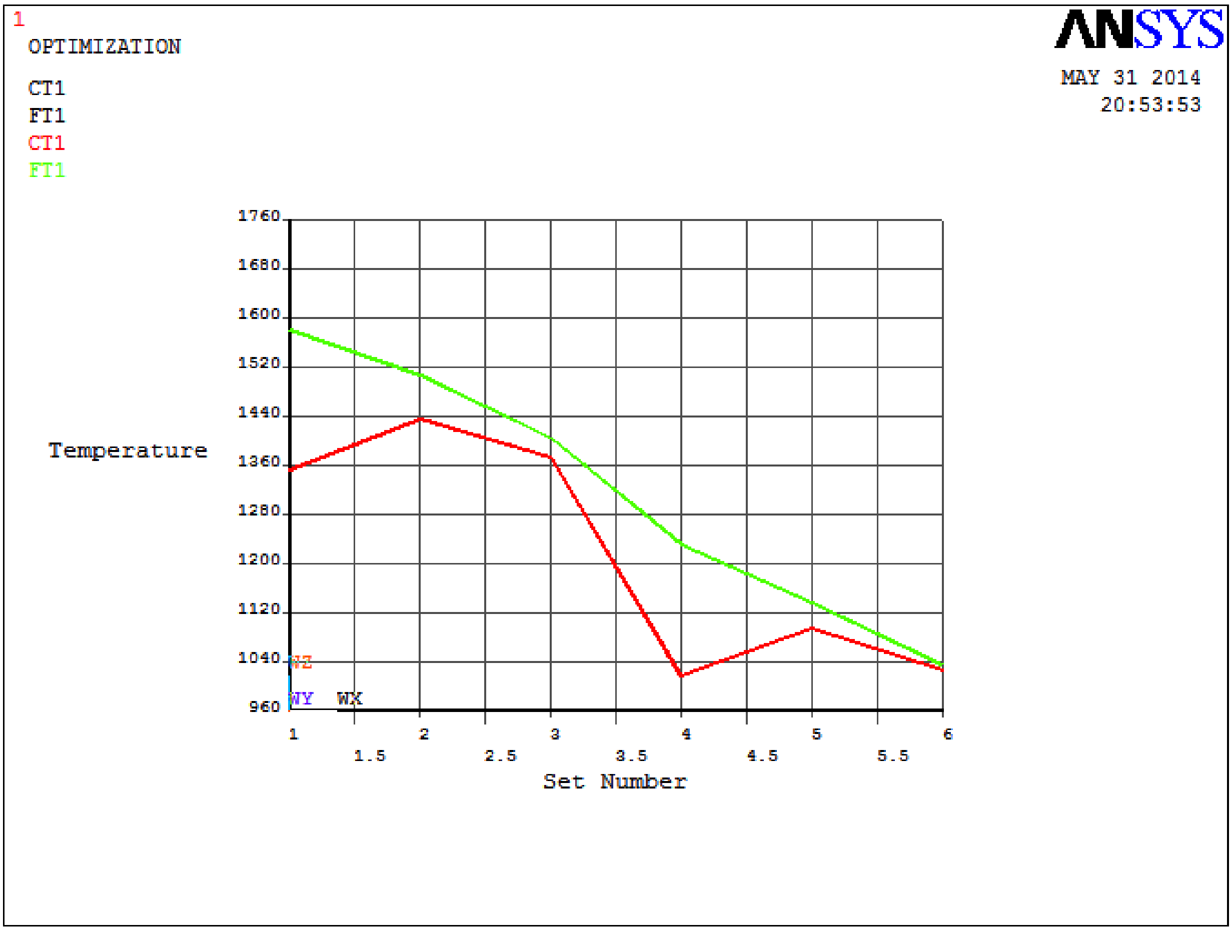

Figure 3. Feeder 01 Temperature remained higher than corresponding casting zone 01 temperature during entire optimization process.

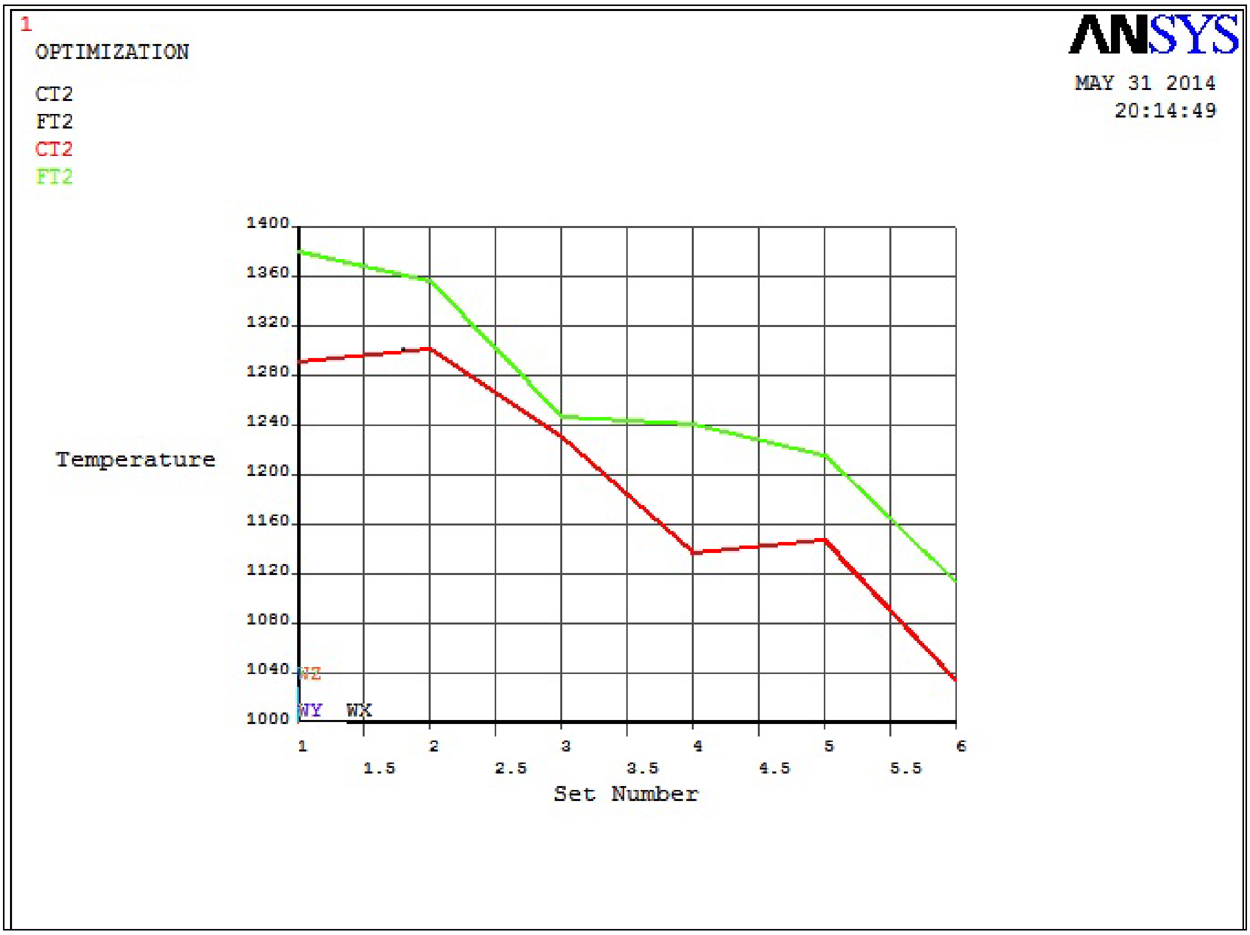

Figure 4. Feeder 02 temperatures remained higher than corresponding casting zone 02 temperature during entire optimization process.

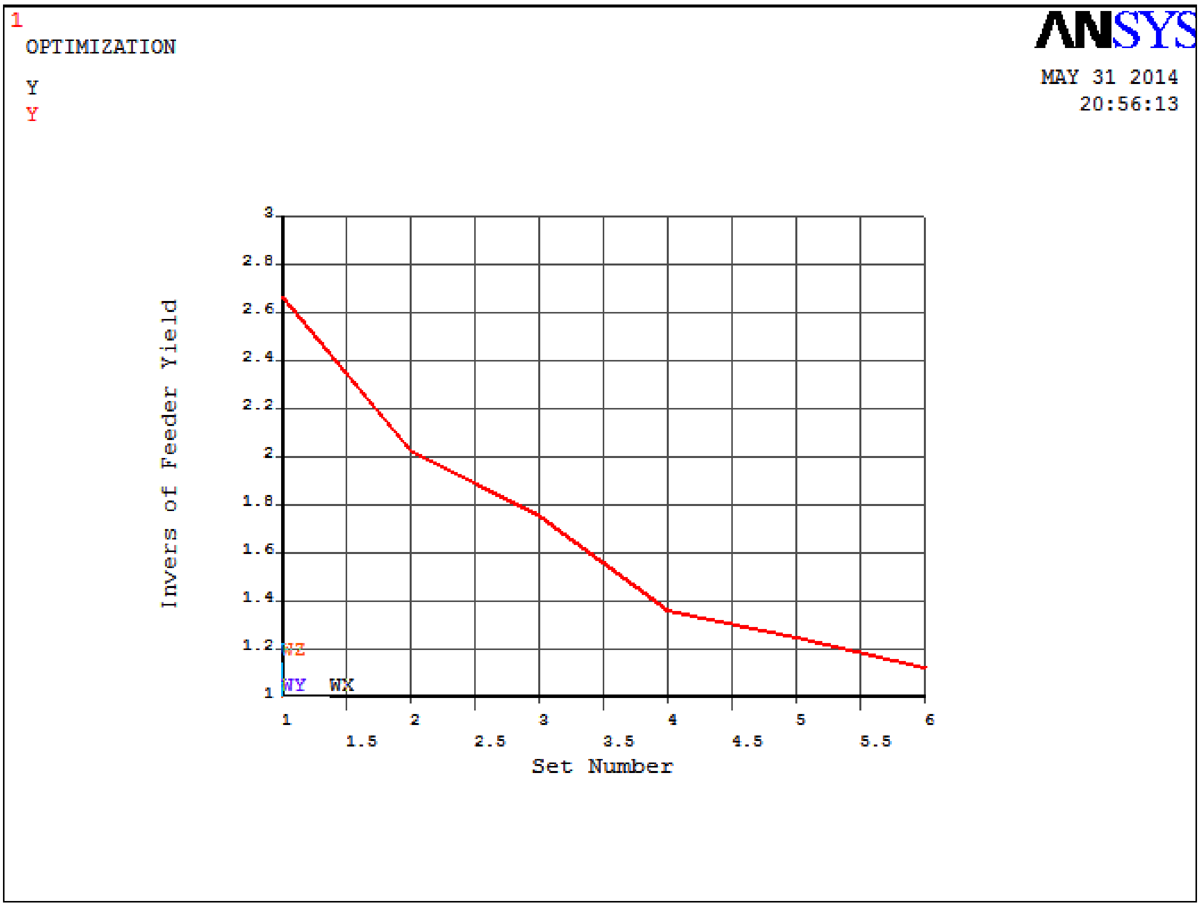

Figure 5. Inverse of feeder yield which is continuously dropped during optimization

Figure 2 is showing the temperature variation on the central plane of Casting and Feeders.

Figure 3 and Figure 4 are showing that maximum temperature of Feeder remained higher than respective casting zone temperature.

Figure 5 is showing the inverse of feeder yield (objective function) which is continuously drop during optimization. Here objective is to achieve higher feeder yield.

5. Result and Analysis

In the view of outcome of modulus approach and finite element method based ANSYS 12 design optimization tool, we can say that the two feeders are designed efficiently for dumbbell shape steel casting. Feeder yield comes out from modulus method for Steel is equal to = 51.77%. Feeder yield obtained from ANSYS 12 design optimizer is equal to = 88.92%. So net advantage gained by ANSYS 12.0 design optimizer is 37.15%. Optimization on ANSYS works better for small castings. Importing IGES file, Modeling, Meshing, in ANSYS may put produce problems for complicated complex shapes in transient thermal analysis and required deep knowledge of design optimization tool and casting process. After optimization of feeder design, the suggested value can be checked by animation on the center plane and temperature contour can be plotted at every time step. Two feeder design optimization can be performed on ANSYS 12 which is low priced general purpose FEM based software. ANSYS optimizer is producing precise feeder design as compare to modulus approach for design of feeder but optimization process on ANSYS requires more time, advance and powerful computer system and skills relatively. The ANSYS would be a efficient tool for design and simulate feeders in virtual environment for sand casting industry globally.

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