ABSTRACT

Iron foundries have been playing a vital role in the industrial development of India. They are part of a core industry producing castings, which are basic raw materials in almost all industrial sectors. The major problems being faced by iron foundries are restrictions on emission levels as laid down by Central Pollution Control Board (CPCB) and limits of energy consumption as laid down by The Energy and Resources Institute (TERI). Thus, a majority of ferrous foundries in India using coke fired cupola furnaces are facing lot of problems. Agra, one of the important clusters of cast iron foundries in India exists on the world map because of its high quality casting and is home to the glorious epitome of architectural splendor; the Taj Mahal. The Taj a world heritage site, has been a jewel in Agra’s fabled history and is today the harbinger of numerous employment opportunities for the local population. However, there is a dark side to this story; That which is hailed as the symbol of love, has become the nemesis of all industries set up in and around Agra. Agra was known for its large number of cast iron foundries in India numbering more than 300 along with and other related industries. The quality of castings produced was excellent, which resulted in a huge turnover. The foundries manufactured general castings along with the graded and quality castings as required by renowned private and public sector undertakings like ESCORTS, KIRLOSKAR, MARUTI, ABB, Punjab Tractors, CIMMCO etc. Beside this, several units were export oriented, exporting C.I. pipes and fittings to Middle East and African countries. A few units were also exporting C.I. castings to Great Britain. The Foundry industry was not the only industry flourishing in Agra, but large number of small machining workshops, sprung up in Agra whose primary business was to procure castings from the foundries and finish it for further processing.

The effluents from the foundries became one of the significant reasons for the intolerable levels of pollution in Agra. Investigations carried out by TERI and National Environmental Engineering Research Institute (NEERI) in foundries showed that the emission levels are exceedingly high. In most of the foundries the average Suspended Particulate Matter (SPM) level in the
exhaust gases was about 1500 mg/Nm$^3$ which is ten times the permissible limits. These pollutants not only adversely affected the texture of the pristine white marble of the Taj Mahal and put the existence of this world heritage site in jeopardy but also left drastic effects on the human health.

The emission of the gases, suspended particles, dust and grit was not within the pollution control limits. The gases emitted by these foundries were pollutants that violate the Clean Air Legislation Act. In accordance with the order of the Honorable Supreme Court (1996), the government in 1997 was forced to ban the use of coke fired furnaces in the foundries. Therefore, all the 310 foundries lying in Taj Trapezium Zone (TTZ) were closed down. This affected approximately 3 lakh people directly or indirectly dependent on these industries in Agra. Because of the closure of the foundries, the diesel engine and generator industries also suffered.

Pollutants emerging from various districts like Agra, Mathura, Firozabad and Bharatpur were the main source of pollution causing damage to the Taj. The NEERI redefined the TTZ which is spread over 10,000 Sq. kilometers and suggested various measures for controlling pollution in this area.

The problem of excessive pollution has assumed a national character and foundries in West Bengal, Gujarat and Maharashtra are also facing closure. It is expected that if suitable steps are not taken, all foundries in India will have to be shut down in near future.

In view of the Supreme Court's verdict on MC Mehta's case, various alternatives were suggested by Varadarajan Committee and Mahajan Committee, for the survival of small-scale foundries of Agra. One of the suggestions made was shifting the polluting industries to an area outside the TTZ and government had allotted plots to several industrial units. But not many industries shifted out of Agra because of the heavy involvement of finances and non-availability of land as per the choice of the foundry owners. The second suggestion made was the use of natural gas operated gas fired cupolas. The other notable recommendation was setting up of green belt
development plan around the Taj Mahal to save it from the effect of pollution.

A number of foundries did nothing about relocating or switching to natural gas. According to the representatives of Agra Foundries Association, the basic equipment for the gas fired cupola costs between 45 to 55 lacs which is beyond the scope of large number of the small scale units. Also there was a serious problem of gas supply by Gas Authority of India Limited (GAIL). It has been reported that a number of foundries have deposited the requisite money to GAIL for the supply of gas connection but have not been able to get the gas connection till date. Also fixing up suitable scrubber, cyclone or bag filter along with the dry or wet arrester to reduce the particulate emission level was costing a lot.

This ban created a need for the use of advanced scientific design of the furnace and a suitable fuel having low pollution contents very well within the limits laid by CPCB. This solution should not only satisfy the environmentalist by protecting the grand Taj Mahal, but also regain the lost pride of Agra for its foundry works without affecting human health. Noticing the problems faced by foundries in general and Agra in particular the study was mainly concentrated on cast iron foundries of Agra. This requires a vast survey which is mainly done in Agra in various foundries and the industries dependent on it, to look for the quality of the final product required. The design of the furnace should be in line with the requirements and should be such that it produces as low end-product waste as possible including gases as pollutant. The design can further be modified to capture the produced pollutants so that the final waste is non-polluting. The fuel should be chosen and modified not only looking at scientific aspects, but also looking to the availability of resources and cost effectiveness. After deciding the resources and design there is always a need for looking at the practical viability of the design, which requires vast experimentation, the result of which can then be optimized to built a technically feasible, economically viable and environment friendly furnace for the foundries.
So, it has become imperative to find a feasible, affordable, energy efficient and eco-friendly melting technology by which not only the Taj Mahal but human life is also protected.

In this thesis an attempt has been made to find such an alternative melting technique using alternative fuel which will try to rehabilitate the foundries without affecting the grandeur of historical monuments particularly, the Taj Mahal and protecting human life.

A vast survey of cast iron foundries was conducted mainly in Agra and the industries dependent on it, to look for the quality of the final product required. As per the problems of foundries of India and Agra in particular, detailed study of the various furnaces available for melting was done along with the effluents emitted by them. A rigorous discussion of melting techniques adopted in foundries of Agra i.e. coke-fired cupola furnace and crucible furnace has been done. The five melting techniques using Electric Arc furnace, Plasma Arc Furnace, Laser Furnace, Coke-less Cupola and Induction Furnace, due to their high cost of installation and operation have been negated for their adoption in small scale foundries, particularly in Agra. On the basis of views of foundry experts identifying the parameters influencing the melting process Multi Criteria Decision Making (MCDM) tools were applied to select the optimal melting technique and the Rotary Furnace was found to be the best alternative. Experiments were conducted to optimize the different parameters of the furnace such as speed of rotation, percentage of excess air, shape of nozzle, preheat temperature, flame temperature and melting rate etc. using Light Diesel Oil (LDO) as fuel. This furnace turns out to be very suitable melting technique prima-facie as it has low initial cost and is economically viable too. Pollution studies were also conducted and found that pollution levels were very close to CPCB control limits but considerable amount of sulphur present in the melt affected the texture of pristine white marble of the Taj Mahal.

Rotary Furnace was found to be the best alternative considering the initial installation cost involved and the present day economic demand, so that production capacities be optimized with least possible down time, low
maintenance cost etc. Studies were conducted on this furnace with LDO (a by product of Mathura refinery which is cheap and easily available in Agra) as fuel but all the pollutants specially SO$_2$ are not within the CPCB norms. So, to make the castings from the selected eco-friendly furnace three alternative fuels are selected. On the basis of views of foundry experts identifying the parameters affecting the melting process, state-of-the-art Fuzzy Analytical Hierarchy Process (AHP) has been applied to identify the best alternative fuel. It has been interpreted from the result of FAHP that for producing castings in an eco-friendly environment Jatropha is the best alternative fuel to be used. Looking to the cost aspect of the castings, Jatropha is blended with LDO for reducing the cost of the castings and evaluating the performance of furnace.

Jatropha has been cultivated in Dayalbagh Educational Institute (DEI) in 10 acres. Jatropha seeds obtained from the plants are used to produce bio-diesel in the laboratory. Some of the Jatropha oil is obtained from Churu (Rajasthan) for experiments. Natural gas is also used as a fuel to produce the casting in the rotary furnace.

From literature survey it has been found that the rotary furnace is not very energy efficient. So, certain modifications in the design of existing rotary furnace have been made to enhance the performance of the furnace and make it more energy efficient. There is a need for heat recovery devices to increase the efficiency of the furnace by raising the temperature of air entering into the furnace. Two heat recovery devices have been designed and used for raising the temperature of air entering in to the furnace. A compact heat exchanger has been designed, fabricated and used in the furnace and found to give 470°C as temperature of the air coming out of the exchanger and entering in to furnace with efficiency of 45.36%.

After deciding the resources and design there is always a need for looking at the practical viability of the design, this requires a vast experimentation, the results are then optimized to bring forward a technically feasible, economically viable and environment friendly furnace for the foundry.
It is observed that not much literature is available about the major parameters influencing the melting process using rotary furnace. The standardization of melting parameters for rotary furnace either has not been done or particular foundry have not made it public with a fear of leakage of trade secrets. So it is imperative to conduct experimentation on rotary furnace with modified design and standardize the parameter influencing the melting rate and to make them available to all small scale foundries across the nation to benefit them.

Lot of experiments are conducted to determine the effect of various parameters of the furnace such as speed of rotation of the furnace, percentage of excess air, pre-heat air temperature, melting time, flame temperature, fuel consumption and melting rate of the furnace using blends of bio-diesel with LDO and natural gas.

Considering the parameters which influence the melting of the charge in the modified rotary furnace, it has been observed that the use of self designed circular shape burner with six holes on the periphery in place of conventional single hole burner results in substantial amount of fuel saving. It has been further observed that with the supply of 10% excess air preheated to 400°C with an optimal rotation speed of 1 Rotations per minute (RPM) and 10% of blending of bio-diesel with LDO yields lowest fuel consumption and highest melting rate. Similarly experiments are performed using different percentage of excess air and varying preheat temperatures and different speed of rotation of the furnace using natural gas as fuel. Almost similar results are obtained. The reasonably good amount of cost saving and profit is obtained using the modified Rotary furnace. By adopting the Rotary furnace for iron melting, high flame temperature is obtained that enabled production of high quality Spheroidal Graphite (S.G.) iron during experimentation. The melting parameters are standardize with design modification and enabled to produce S.G. iron during experimentation in both the fuels (bio-fuels blended with LDO and natural gas). Large number of experiments are conducted to standardize the input percentage of carbon during the melting process to obtain the required percentage of carbon in the castings. The study of micro-
structures and mechanical properties of the casting produced by modified rotary furnace using natural gas and blends of bio-fuel with LDO show that quality of the castings meets the specification desired. Micro-structure studies of the samples produced during experiments also confirm at amount of graphite ranges between 14 – 20% in S.G. iron and grey cast iron. Melting in modified rotary furnace also enables production of grey flakes of different sizes covering up to 20% of area. Sulphide and oxide inclusion are totally avoided.

The results of experiments are used for the purpose of modeling and optimization of furnace parameters. State-of-the art soft computing technique are employed for determining the value of input parameters viz., percentage of excess air, speed of rotation, degree of air preheat and melting time for optimizing each of the outputs i.e. melting rate, flame temperature and fuel consumption. The experimental observations of all the seven parameters influencing the melting process have been used to develop three models using Artificial Neural Network (ANN). The models accepts four input parameters and generates three output parameters viz., fuel consumption, melting rate and flame temperature. Model developed gives estimated values very close to experimental value with a variation less than 5%. Similarly from Neuro Fuzzy model estimated values obtained are very close to experimental value with a variation less than 5%. Neuro Fuzzy modeling is also used to develop a model for input and output parameters. The input parameters are then optimized using the Guided Evolutionary Simulated Annealing (GESA). Neural Network model (trained using a series of experimental results), serves as fitness function and applied here as input to GESA. It is observed that the optimal process parameters and melting rate closely resemble with the experimental values. GESA determined the optimal process parameters while maximizing the melting rate. Similar results are obtained while Neuro fuzzy model is used as fitness function. Interactive ANN is also used for optimizing the parameters in forward and reverse direction.
Good performance of the furnace alone cannot be the criterion for adoption of the melting technique by the small-scale foundries, cost of the melting also plays an important role. The cost of melting is influenced by the capital cost, operating cost including the maintenance and labor cost. The cost of melting, which is of crucial importance, has been studied in detail. Therefore, the economics of four possible alternatives of melting viz., LDO-fired Cupola furnace, Gas-fired Cupola furnace, Coke-fired Cupola and Bio-Diesel fired Rotary Furnace has been studied. Economic analysis has shown that modified bio-diesel fired Rotary furnace is most suitable as the cost of the casting produced is lowest. Considering the initial cost of furnace it is observed that if the amount to be invested for purchase of gas fired cupola in place of modified rotary furnace is deposited in bank, a substantial amount per annum can be earned. Also melting with modified rotary furnace requires less skilled manpower and utilization of the furnace is very high as number of heats per day and number of days of melting can be increased or decreased according to the requirement. This facility is not available in cupola (Gas fired or Coke fired) so, modified rotary furnace is most suitable on account of reasons above including cost of installation and operation.

Air pollution that caused the closure of the foundries in Agra to save Taj-Mahal is addressed in detail. Many experiments at varying levels of input parameters are conducted using blends of bio diesel with LDO and natural gas. It is observed that by adopting modified rotary furnace for iron melting the air polluting elements i.e., Sulphur dioxide (SO₂), Nitrogen dioxide (NO₂), SPM and Carbon Monoxide (CO) was found at levels much below the norms laid by CPCB. When the optimum input parameters of melting to achieve high melting rate are considered, the pollutants are totally controlled. While using natural gas the pollutants are found lower than in the case of bio-diesel blended with LDO.

Hence, it has been concluded that a modified rotary furnace fired with blends of bio-diesel and LDO is energy efficient, eco-friendly and proposed for small-scale foundries of India based on technical and economic considerations.
Results from the experimentation are analyzed and validated using statistical analysis. Regression analysis has been done to study the effect of rotational speed, melting time, preheat air temperature, excess air and flame temperature on fuel consumption. Test of significance (student ‘t’ test) is used to test the hypotheses in all the above cases. It has been found that all the hypotheses favour our results. The affordability and ease of adaptability is also considered while proposing the alternate melting technique for small-scale foundries of India and Agra in particular.

Present research will also be of great use if its outcome could help the government and concerned authorities to develop guidelines that are more specific. This thesis is based on the self-designed, developed and modified rotary furnace, using innovative features in comparison to the conventional rotary furnace presently found in literature.