Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 97 (2014) 267 – 276

Procedia Engineering

www.elsevier.com/locate/procedia

12th GLOBAL CONGRESS ON MANUFACTURING AND MANAGEMENT, GCMM 2014

Waste heat recovery from metal casting and scrap preheating using recovered heat

Selvaraj.J[a,]*, Varun V.S.[a], Vignesh[a], Vishnu Vishwam[a]

[a]Department of Mechanical Engineering, Amrita Vishwa Vidya Peetham, Coimbatore 641112, India.

Abstract

In metal casting, after solidification of the molten metal in the mold cavity, the knocked out casting has heat energy stored it and is wasted into atmosphere as the casting cools down in the shop floor. If this heat energy can be absorbed by the raw materials by a suitable arrangement, it will reduce energy consumption during melting, resulting in savings in economy and environment. This paper discusses an innovative approach to implement such a methodology. In a basic set up, when this preheating was achieved, the scrap was found to take 2.83 % less energy than it would take to melt without this preheating set up. This technique has been improvised by keeping aluminum powder in between the scrap and the hot casting to have better heat recovery, resulting in an increase of heat recovery to the tune of 5.7 %. When this savings are applied to global castings produced, which run into millions, the total energy and emissions saved amounts to a substantial figure. The calculations indicate energy savings as high as 419 GWh, which translates roughly to Rs 377 crores a year for Indian foundries in one year.

Selection and peer-review under responsibility of the Organizing Committee of GCMM 2014

Keywords: Metal casting; Environment; Scrap preheating; Energy saving; Cost reduction; Productivity improvement;

1. Introduction

Energy Conservation is unquestionably of great importance, since the current energy resources are diminishing fast and the renewable resources' ability to provide to the extreme energy needs of the society in a dependable way is limited. Metal casting is one of the most energy-intensive industries in the world [1, 2], carrying immense potential for conservation.

* Corresponding author. Tel.: +91-994-493-1947; fax: +0-000-000-0000 .
E-mail address: j_selvaraj@cb.amrita.edu

1877-7058
Selection and peer-review under responsibility of the Organizing Committee of GCMM 2014
doi:10.1016/j.proeng.2014.12.250

As conventional energy resources are diminishing and at the same time polluting, global warming in raise, and more catastrophic weather extremes are occurring worldwide, the responsibility on the human beings to find methods of conservation is high [3]. Hence it is highly important to reduce the wastage of energy in all possible ways. Motivated by the need of energy savings, a new technique is proposed to utilize the huge amount of heat energy which was wasted from knocked out casting in the conventional casting process

Nomenclature

V_c	Volume of the casting (m^3)
V_s	Volume of the scrap (m^3)
E	Energy required for melting the cast iron (kJ)
L	Latent heat of fusion (kJ/kg)
ΔT_1	Difference between melting point and initial temperature of Cast iron when it is charged into the furnace (K)
ΔT_2	Difference between the maximum temperature to which the metal is raised for pouring and the melting point (K)
C	Specific heat capacity of cast iron (kJ/kg-K)
P	Density of cast iron (kg/m^3)
M	Mass of cast iron (kg)
h	Enthalpy (kJ/kg-K)
ε	Emissivity of surface

Recovering industrial waste heat can be achieved via numerous methods. Combustion air preheating, Boiler feed water preheating, Load preheating, Power generation, Transfer to liquid or gaseous process streams, etc are some of the typical waste heat recovery options [4]. The selection of heat recovery method will depend on key factors such as the temperature, phase, and chemical composition of the exhaust stream, as well as the nature of the desired end use for recovered heat. The Energetics study conducted in 2004 evaluates energy losses at multiple stages of manufacturing. It does not only quantify waste heat losses, but also acknowledges that these losses may total 2050 % of energy delivered to plants [5].

Various technologies have been developed so far to reduce energy consumption by preheating the scrap in steel making industries. Typical techniques include Bucket Scrap Preheating Systems, Rotary Kiln Preheater, Shaft Furnaces, EcoArc Shaft Furnace, etc. After conducting an in-depth analysis of the conventional waste heat recovery system (WHRS), it is observed that studies and practices in waste heat recovery of knocked out casting has not been done so far. Hence, this paper proposes a novel WHRS, in which waste heat recovered from the knocked out casting, is used for preheating the scrap

2. Methodology and Experimental Set up

The methodology is to bring the cast iron raw material (virgin billets or scrap) close to the hot cast iron castings that are just knocked out from the mold and keep them together closely, thereby preheat the raw material using the sensible heat of the knocked out castings. Since the preheated material is going to act as a next charge for the furnace, the heat recovered by raw material through this method reduces the energy consumption in the furnace. Fig.1. shows the process flow of conventional casting and the proposed method. The shaded blocks and dashed arrows in the Fig.1 represent the steps involved in the proposed method, whereas other blocks are applicable to any conventional casting. From this flow chart, it can be understood that in conventional method of casting, the knocked out castings (from the stage ‘casting shake out’ in the flow chart) are directed to cleaning and inspection without extracting their heat; whereas in the proposed method, the knocked out castings are directed to a preheating apparatus that mixes raw material and castings, facilitating transfer of waste heat from the casting to the raw material.

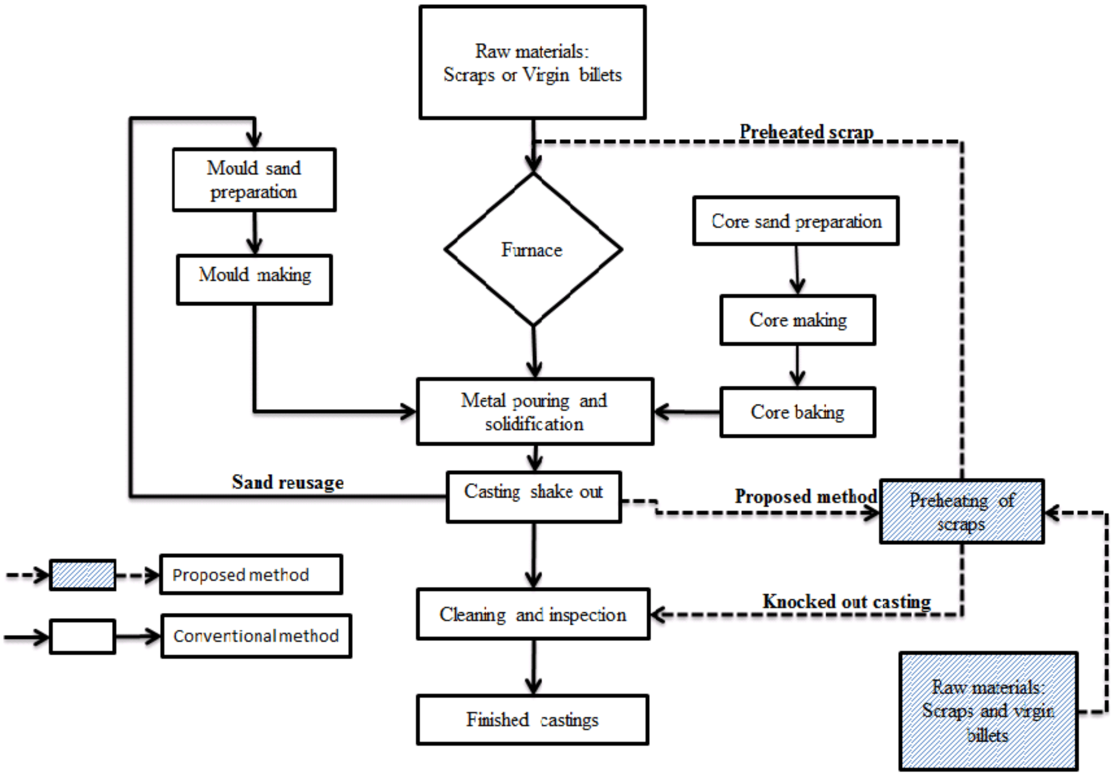

Fig. 1. Process flow of conventional and proposed casting industry.

2.1. Basic experimental set up

The basic experimental set up is shown in the Fig.2. The knocked out casting is kept in the middle, surrounded by the raw materials that absorbs the waste heat from the castings. In this set up, uniform shaped raw material and casting has been used for simplicity, but in reality, there will be variability in shapes; nevertheless, the principles remain same. Modifications on this basic experiment set up were done to improvise the heat absorbed by the raw material in two ways: a) by introducing aluminum powder as a medium of heat transfer between the raw material and casting and b) by re-using the aluminum powder that was used in the heat exchanger set up. These modifications were done on the basic experimental set up to prevent the heat loss due to convection and radiation. K type thermocouples were used to measure the temperature history and the data is logged using data acquisition system following the standard practices [6, 7]. For each experiment, calculations were made on energy savings, and graphs were plotted to find out the maximum temperature achieved by raw materials in each method. The temperature is measured using K type thermo couples. The reason for keeping raw material at different distances is to gain knowledge of the heat transfer phenomena when the distances differ. The temperatures against time graph were plotted for the scraps at different distances and also of the knocked out casting.

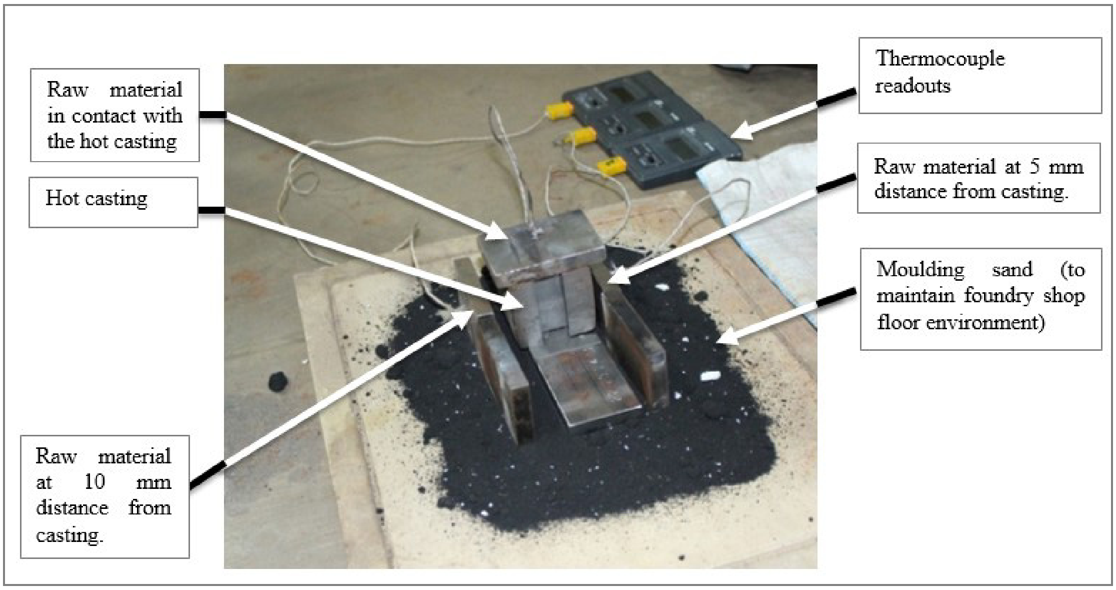

Fig. 2. Basic experimental set up

2.2. Experiment with incorporation of aluminum powder

In the basic experiment, the air gap between scrap materials and knocked out casting causes an obstacle to heat transfer since the air has poor thermal conductivity. To alleviate this, aluminum powders were introduced into the gaps between the knocked out casting and the scrap material. This improves the heat transfer between casting and raw materials. The experimental set up for the new method is as shown in the Fig.3.

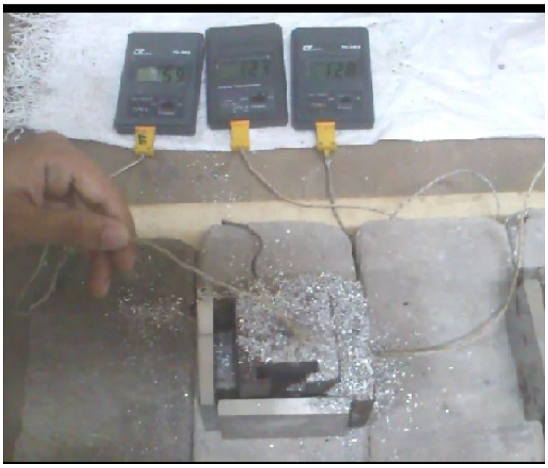

Fig. 3. Experimental set up with aluminum powder

2.3. Experiment with re-usage of aluminum powder for heat recycling

To extract the heat gained by the metal powder during the first preheating experiment, the metal powder is being reused for second experiment after getting it separated from the scrap materials of first experiment. By performing this, significant amount of heat that goes waste in the powder is minimised since the heat is recycled. Experimental set up is shown in the Fig.4.

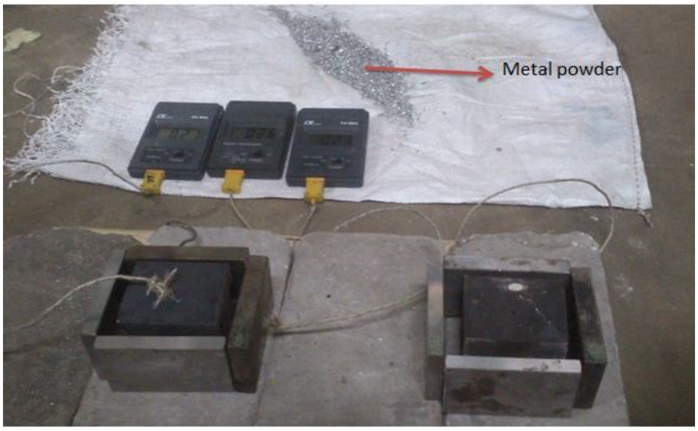

Fig. 4. Experimental set up with heat recycled aluminum powder

3. Results and Discussions

In this section, results are presented starting from basic experiment, then with aluminium powders and with the re-usage of aluminium powder for heat-recycling. It should be noted here that these experimental results are of preliminary nature in such a novel process without any prior data available. Deeper levels of research and experimentation are needed to ensure the standardisation and repeatability of these experimental results.

3.1. Results of the basic experiment without aluminum powder

The temperature distribution observed in the raw materials which are in contact with knocked out casting and which were kept at a distance of 5 mm is shown in Fig.5. By examining the temperature distribution of scraps at both locations, it is observed that the maximum temperature achieved in the scrap kept at a distance of 5 mm is 346 K and the maximum temperature achieved by the scrap in contact with knocked out casting is 498 K; these temperatures are reached at 15 minutes at 12 minutes respectively, from the beginning of the pre heating process.

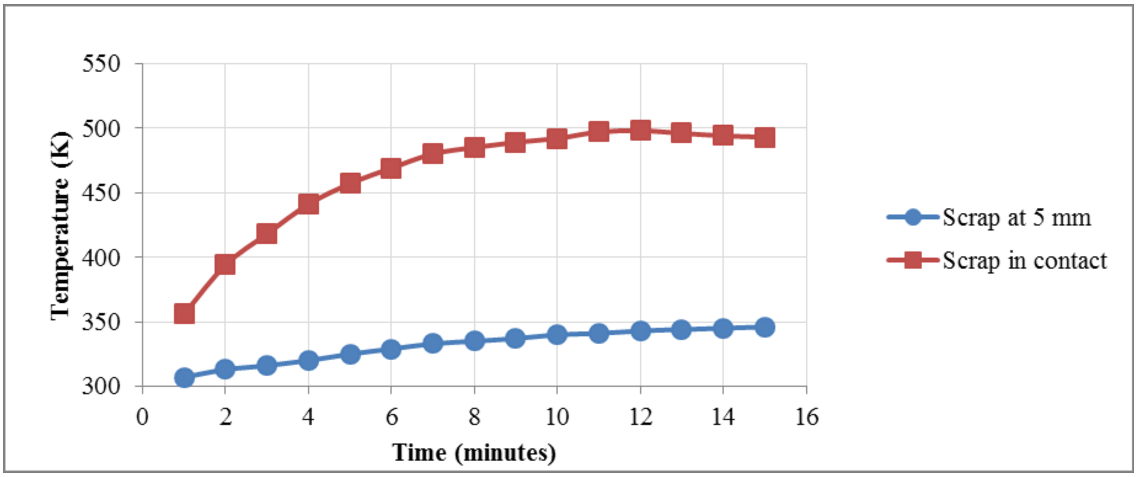

Fig. 5. Temperature distribution of raw material preheating process without aluminum powder

These results indicate a simple fact: complete physical contact between the scrap and casting is highly desirable from the stand point of maximum heat recovery; when it is not possible to achieve complete contact between the scrap and casting due to dissimilarities of shapes and sizes between them, it should be ensured that they are as close as possible to enhance heat transfer. In the above mentioned case, the heat transfer is primarily governed by conduction (for contacting scraps) and radiation for scraps with 5 mm offset. The general differential equation of heat conduction for the transient nonlinear state that describes this phenomenon is as follows [8]:

$$K\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}+\frac{\partial^2 T}{\partial Z^2}\right)=\frac{dh}{dt} \quad (1)$$

Where the enthalpy, $h = \int \rho c dT$

The governing equation for radiation heat transfer is given as follows: For a grey body with only two surfaces, the heat transfer is equal to:

$$Q=\frac{\sigma\left(T_1{}^4-T_2{}^4\right)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1}+\frac{1}{A_1F_{1\rightarrow 2}}+\frac{1-\varepsilon_2}{A_2\varepsilon_2}} \quad (2)$$

Where, ε is the respective emissivity of each surface. However, this value can easily change for different circumstances and different equations should be used on a case per case basis

The role of convection is very minimal since air current was restricted in the set up. The role of radiation is high at high temperatures and low as temperature drops. In the beginning, the temperature gradient is high and hence the heat transfer is high, resulting in steady rise in temperature of the scrap; but as time progresses, temperature difference between the scrap and the casting diminishes, causing progressively lesser heat transfer from the casting to the scrap. This trend is clear from the equations and the temperature rise curves in the Fig.6

3.2. Results of the experiment with aluminum powder

The temperature distribution observed in the raw materials which were kept at a distance of 5 mm from and in contact with the castings with the introduction aluminum powders in the gap is shown in Fig.6. The Aluminum powders used are of size varying from 0.2 mm to 0.8 mm. It is observed that the maximum temperature achieved in the scrap kept at a distance of 5 mm and in contact are 369 K and 498 K respectively. When compared to the case without powder, there is a clear improvement in heat transfer for the case with powder: Moreover, it has also taken only 11 minutes to reach this peak compared to 15 minutes in the previous case. So, by introducing Aluminum powder in the air gap, waste heat recovery is improved and also the time taken is reduced both leading to energy efficiency and productivity, respectively. The calculations in section 4 reveals the amount of heat recovery made possible by this method.

The reason for improvement of waste heat recovery because of the addition of Aluminum powder is because of improvement of thermal conductivities: Pure Aluminum has a thermal conductivity of 237 W m^{-1} K^{-1}, Aluminum foam (can be treated on par with powder used in this experiment) has a thermal conductivity of 218 W m^{-1} K^{-1} and air has a thermal conductivity of 0.0265 W m^{-1} K^{-1} [9]. Air gap with a very low thermal conductivity obstructs the flow of heat and hence the peak temperature is lesser. When Aluminum powder which possesses high thermal conductivity was introduced, it aids in better heat transfer.

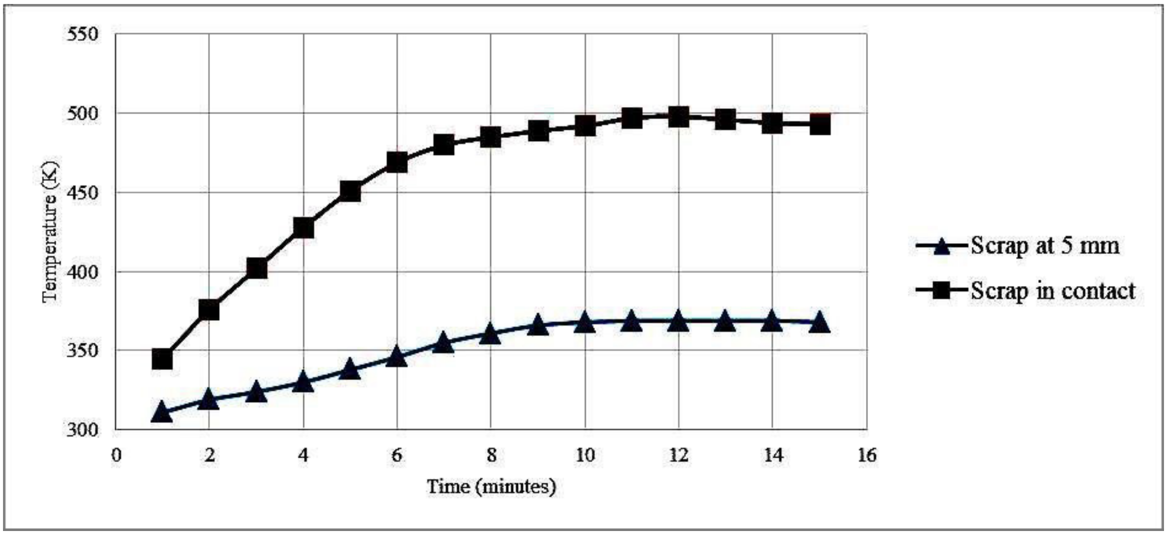

Fig. 6. Temperature distribution of raw material preheating process with aluminum powder

3.3. Results of the experiment with re-used aluminum powder

In this experiment, the aluminum powder is reused after completing one heating cycle, resulting in heat-recycling: before its heat is wasted by cooing down, it is taken to the next heating cycle and hence, the heat retained by it from the previous cycle further enhances the heat recovery. The maximum temperature attained by the scarp at 5 mm from the casting is 392 K which is the highest temperature obtained of all the three experiments. Temperature distributions of the raw materials at a distance of 5 mm and in contact are shown in the Fig.7.

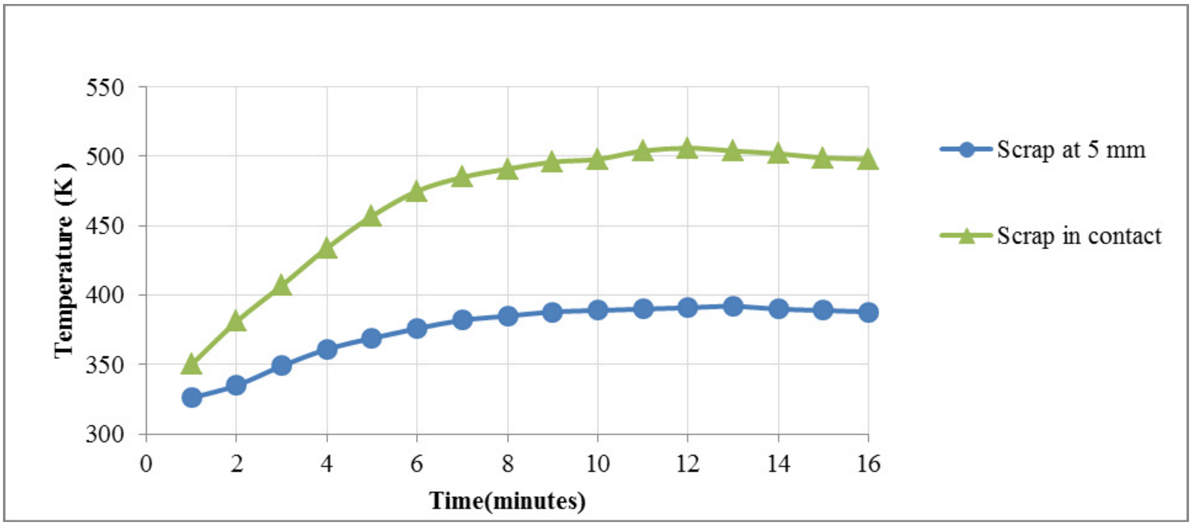

Fig.7. Temperature distribution of raw material preheating process with heat-recycled aluminum powder

4. Energy savings calculation

For each of the case discussed above, savings in energy has been calculated by calculating the energy consumed for melting the scraps in conventional and proposed methods.

4.1. Energy required for melting the cast iron block

E = Sensible heat + Latent heat + Superheat

$$E = m \times c \times \Delta T1 + m \times L + m \times c \times \Delta T2 \quad (3)$$

For Cast Iron, the following parameters are applicable:

c = 0.5 kJ/kg K
L = 126 kJ/kg
ρ = 7,200 kg/m^3
Vc = 2.8×10^{-4} m^3 (This volume corresponds to the mold cavity used)

$$m = 1.4 \times (Vc * \rho) \quad (4)$$

m = 2.9 kg (60 % yield assumed).
Melting point : 1473 K
Pouring temperature : 1673 K (200 K of super heat is allowed to account for the energy loss in the molten metal while it is carried from the furnace, till the point of pouring)
Room temperature : 300 K

The energy required for melting the cast iron block can be calculated by using all the above values in the equation (3)
E = 2.9×0.5× (1473-300) + 2.9×126 + 2.9×0.5× (1673-1473)
= 1700.85 + 365.4 + 290
= 2356.25 kJ

By applying the value of temperature gained by scrap in equation (3), Energy consumed for melting the metal in each method can be calculated. Let E1, E2 & E3 be the energy consumed for melting the material in the methods 1, 2 & 3 respectively.

Percentage energy saved in the three proposed methods can be calculated using the equation (5)

$$\% Ei = (E - Ei/ E) * 100 \quad (5)$$

Where i is the method number (1-3)

4.2. Energy savings in method 1 (i.e., without usage of Aluminum powder)

For the calculation of energy saving by waste heat recovery, the peak temperature attained by scrap has to be considered. Scraps that are in contact with the casting achieve high peak temperature and scraps that are far away from the casting achieve low preheat temperature. Now, to get an average figure, let us consider the peak temperature achieved by the scrap kept in between the far off position and contact position. We shall follow the same for all calculations.

E1 = 2.9×0.5× (1473-346) + 2.9×126 + 2.9×0.5× (1673-1473)
= 1634.15 + 365.4 + 290
= 2289.55 kJ
% E1 = (2356.25-2289.55)*100/2356.25
% E1 = 2.83 %

4.3. Energy savings in method 2 (i.e., with the usage of Aluminum powder)

E2 = 2.9×0.5× (1473-369) + 2.9×126 + 2.9×0.5× (1673-1473)
= 1600.8 + 365.4 + 290
= 2256.2kJ
%E2 = (2356.25-2256.2)*100/2356.25
%E2 = 4.25 %

4.4. Energy savings in method 3 (i.e., with the usage of energy-recycled Aluminum powder)

E3 = 2.9×0.5× (1473-392) + 2.9×126 + 2.9×0.5× (1673-1473)
= 1567.45 + 365.4 + 290
= 2222.85 kJ
%E3 = (2356.25-2222.885)*100/2356.25
%E3 = 5.7%

The energy savings and maximum temperature obtained by scraps in all the three methods are shown in the Table.1. It is observed that the maximum energy saved is in the third method where preheated aluminum powders have been used.

Table 1. Peak temperature of the scrap (°C) and % saving in energy

Method	Scrap at a distance of 5 mm	Scrap in contact	% energy savings
1	346	498	2.83
2	369	498	4.25
3	392	506	5.7

4.5. Economic gain calculations

Economical viability of the proposed method can be calculated as follows: India produces 9,994,000 tons of castings per year [10]. Majority of them is from the ferrous materials sector. According to reports [11], to melt one ton of ferrous material, on the average, the furnace takes 650 kWh to 750 kWh of electricity. If the proposed method is applied, it will take 6% less that is 42 kWh less, assuming 700 kWh/ton. Extending this to the total production, assuming the same trend to non-ferrous castings also, a saving of around 419 GWh of energy is realizable, which translates roughly to Rs 377 crores a year for a typical industrial tariff rates of Rupees 9 per unit. Hence, there is a strong economical reason to adopt this method.

4.6. Environmental gain calculations

Energy generation by any means has its environmental impacts and hence any attempt to conserve energy it readily cuts down the emission various stages in the life cycle of the process. There are different ways to assess the carbon foot print related to energy: Resource input-output methods[12, 13], Componential methods with wider accounting[14], etc. Using a generic carbon foot print calculators[15] to calculate the impact of this work on emissions, it was found that the proposed method of waste heat recovery that resulted in 419 GWh of energy has the potential to save 211130 tons of CO_2. This number of trees that would be required to be planted to produce this effect would be around 1266780, based on the assumption that each tree absorbs 1.1 kg of CO_2 per year over 25 years.

5. Conclusions and future work

Based on the studies conducted in this research, the proposed approach of scrap preheating from the waste heat recovered provides a significant energy savings in the casting operation. When this method is implemented in Indian foundries, it will save around 6 % energy consumption, which will give a cumulative annual savings of 419 GWh in the total energy demand in India, translating roughly to Rs 377 crores of savings in monetary terms and 211130 tons of CO_2. This novel and simple method of waste heat recovery and scrap preheating does not require any major infrastructural investment in foundries, except one extra flow line and a few extra whop floor workers. Refinements can be done in the method to prevent more heat loss due to radiation by enclosing the whole set up in a box, which can be considered for future scope. There is an urgency now to promote such simple and innovative solutions of energy conservation that requires fewer resources as energy scarcity and energy-related environmental problems are threatening the sustainability of the planet.

References

[1] Zheng Jiliang and L. I. Junting, "Study on the Ecologic Network System of Energy-intensive Industries," vol. 5, pp. 1987-1992, 2011.

[2] EPA. (2007, Energy Trends in Selected Manufacturing Sectors. *(19-09-2012)*. Available: http://www.epa.gov/sectors/pdf/energy/report.pdf

[3] Hui Zhang, Hong Wang, Xun Zhu, Yong-Jun Qiu, Kai Li, Rong Chen, and Qiang Liao, "A review of waste heat recovery technologies towards molten slag in steel industry," *Applied Energy,* vol. 112, pp. 956-966, 12// 2013.

[4] DoE-USA. (2008, 25-09-2012). *Waste Heat Recovery: Technology and Opportunities in US Industries.* . Available: http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf

[5] JPM Florez, GGV Nuernberg, MBH Mantelli, RSM Almeida, and AN Klein, "Effective thermal conductivity of layered porous media," in *Proceedings of 10th International Heat Pipe Symposium, Taipei, Taiwan*, 2011.

[6] Hsien-Chi Sun and Long-Sun Chao, "Analysis of interfacial heat transfer coefficient of green sand mold casting for aluminum and tin-lead alloys by using a lump capacitance method," *Journal of heat transfer,* vol. 129, pp. 595-600, 2007.

[7] Jacob O Aweda and Michael B Adeyemi, "Experimental determination of heat transfer coefficients during squeeze casting of aluminium," *Journal of Materials Processing Technology,* vol. 209, pp. 1477-1483, 2009.

[8] MM Pariona and AC Mossi, "Numerical simulation of heat transfer during the solidification of pure iron in sand and mullite molds," *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* vol. 27, pp. 399-406, 2005.

[9] K. Boomsma and D. Poulikakos, "On the effective thermal conductivity of a three-dimensionally structured fluid-saturated metal foam," *International Journal of Heat and Mass Transfer,* vol. 44, pp. 827-836, 2// 2001.

[10] Modern Casting. (2011, 31-12-2012). *46th Census of World Casting Production*. Available: http://www.afsinc.org/files/25-28censusdec12.pdf

[11] V.R. Gandhewar, S.V. Bansod, and A.B. Borade, "Induction Furnace-A Review," *International Journal of Engineering and Technology,* vol. 3, pp. 277-284 2011.

[12] T. Wiedmann, J. Minx, J. Barrett, and M. Wackernagel, "Allocating ecological footprints to final consumption categories with input–output analysis," *Ecological Economics,* vol. 56, pp. 28-48, 2006.

[13] R.A. Begum, J.J. Pereira, A.H. Jaafar, and A.Q. Al-Amin, "An empirical assessment of ecological footprint calculations for Malaysia," *Resources, Conservation and Recycling,* vol. 53, pp. 582-587, 2009.

[14] GJ Li, Q. Wang, XW Gu, JX Liu, Y. Ding, and GY Liang, "Application of the componential method for ecological footprint calculation of a Chinese university campus," *Ecological Indicators,* vol. 8, pp. 75-78, 2008.

[15] Ecoforests. (2012, 25-12-2012). *Carbon foot print calculator*. Available: http://carbon.ecoforests.org/