International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 7 (2015) pp. 16693-16708

http://www.ripublication.com

Solar Thermal Preheating of Metallic Scraps in Foundries

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ABSTRACT

Foundries consume enormous amounts of fossil fuel energy for melting the raw materials to produce molten metal for casting. While doing so, the emission of greenhouse gases and resulting climate change are serious problems. This paper attempts to utilise concentrated solar thermal energy using parabolic troughs to preheat raw materials so that the energy consumed in the furnace for melting the raw materials is reduced. The experiments were conducted on aluminium raw materials of various thicknesses under different times in a day to measure the energy absorbed by the raw materials. The results show that the raw materials absorb maximum energy when they are surrounded by fine aluminium turnings to act as heat transfer medium between the scraps and receiver of the trough. As high as 106 ºC of temperature rise could be achieved by this method. This result in the energy savings of 6.77 % of the total energy required for melting the scrap. When this saving is extended to global production for casting, it saves 1.17 billion units of electricity. Extending this to the total casting production in India, assuming the same trend to all types of castings also, cumulative savings of around 111.86 million kWh is realizable, which translates roughly to a saving of Rs. 1174.54 million per year. Hence this novel approach has immense potential for exploration and implementation.

Keywords: Parabolic trough collector; scrap preheating; solar thermal energy; environment; economics;

I. INTRODUCTION

Solar thermal power is one of the promising renewable energy options to substitute the increasing demand for conventional energy. The International Energy Agency (IEA) report, 2011[1] reveals that solar energy is the prime illimitable energy available to all; the use of solar energy will also enhance sustainability, reduce pollution, lower the costs of mitigating climate change and keep fossil fuel prices lower. In India, the potential for solar energy is huge with about 5000 TWh of solar insolation every year with most parts receiving 4-7 kWh per square metre per day.

Concentrating solar power (CSP) technology is used for high and medium heat applications. The energy is optically concentrated before being converted into heat. The optical collection can be obtained by reflection of solar radiation employing reflectors. The sunlight is concentrated in the focal plane, with the aim of maximizing the energy flux on the absorber surface [2]. For such concentrating purposes, parabolic trough collector (PTC) is one of the technologies to deliver high temperature with good performance and better efficiency. The system can produce up to 400 ˚C [3]. The applications of PTC include industrial process heat such as cleaning, drying, evaporation, distillation, sterilization, desalination, thermal power plants, heat driven refrigeration, space heating and cooling, etc.[4].

In foundries, for melting raw materials which might consist of either virgin billets or metallic scrap, various types of furnaces such as coke-fired copula, electric arc, rotary and induction are used. Every year, the energy consumption by foundries across the globe is 59.87 billion kWh and in India, for the total production of 9.81 million metric tons, a simple calculation shows that the amount of energy consumed will be 5.69 billion kWh [5].

Various technologies have been developed to reduce the energy consumption in foundries. They include: regenerative methods to utilise waste heat from stack gases [6], waste heat recovery from slags [7], by preheating the scraps using the heat available in the casting [8, 9], etc. Techniques which are already implemented for preheating scraps are shaft furnace scrap preheating, consteel technique, rotary kiln, vertical kiln, and scrap bucket charge technique [10], etc. Solar thermal preheating of metallic scraps with the help of parabolic trough collector is a field that has not been explored so far by the research fraternity in this field of energy conservation in foundries. Hence this research focuses on that technique with an objective of experimentally calculating the amount of preheat achieved by the metal scraps when PTC is used and assessing its economic and environmental benefits.

II. EXPERIMENTAL SETUP

Fig. 1 shows the flow chart of both conventional method and proposed method. The dashed lines and shaded blocks in the flow chart represent the steps involved in the proposed method whereas the other blocks are applicable to any conventional casting method. Manual tracking mechanism is used in this experimental setup. The semi-circular absorber tray is placed in the focal line of the PTC, where all the reflected, focused light is concentrated. In this setup, three different sized Aluminium raw materials have been used to study their heat absorption potential: 6 mm, 10 mm and 20 mm. In actual foundry practice, there will be high variability in sizes and shapes of scraps, but by studying the heat absorption characteristics of these scraps which have progressively increasing in size, some generalisation can be made about the relationship between size of the scrap and heat saving potential. Justification for 6 mm, 10 mm and 20 mm scrap is simply it is an industrial average, based on the observation and classification into small, medium and large, neglecting sheet metal scrap and extra-large scraps whose occurrences are relatively minimal.

The basic experimental set up is simple, consisting of PTC and its stand, absorber tray, aluminium scraps and instrumentation measures for the full temperature rise history. The next sophistications for improving heat transfer between the tray and the scrap are as follows: a) to use the Aluminium cut wire shots of 2 mm diameter and 3-5 mm length; b) to use the Aluminium turnings of 0.3 mm thickness and 1-2 mm length. These cut wire shots and turnings act as a medium to effectively conduct the heat from the tray to the scrap, minimizing the gaps between them preventing heat transfer.

For each method, calculations were made for useful energy gain, collector efficiency and energy savings. Graphs were plotted to depict the heat gain pattern and maximum temperature achieved by the scrap of various thicknesses in these experiments. The main parts of the experimental set up are briefed here:

1. *Parabolic Reflector:* The reflector is one of the vital parts of the parabolic trough collector as it reflects the fraction of solar light intensity to be accumulated by the absorber tray. The reflector used in this setup is a polished aluminium reflecting sheet with a reflectivity of 90 % of the immaculate surface.
2. *Absorber tray:* The semicircular absorber tray is placed at the focal line of the parabolic trough collector. The diameter and length of the absorber tray are 0.23 m and 1.10 m. The reflected solar radiation is concentrated on the absorber tray and the scraps are placed in the tray.
3. *Temperature measuring device:* The K type thermocouple is used to sense the temperature gain in the scraps. A digital temperature indicator connected with the thermocouple shows the temperature value within the range of -50 °C to 1300 °C.

To calculate the solar radiation, "solar power meter" is used with the accuracy typically within ± 10 W/m^2 in sunlight and resolution of 0.1 W/m^2. The solar power meter is calibrated in the temperature of 25 ± 2.5 °C and relative humidity of 3 % to 70 % and the standards used to calibrate are multi product calibrator (± 8 PPM), 7 ½ digital multimeter (± 25 PPM) and 4 ½ digit meter (0.025 %).

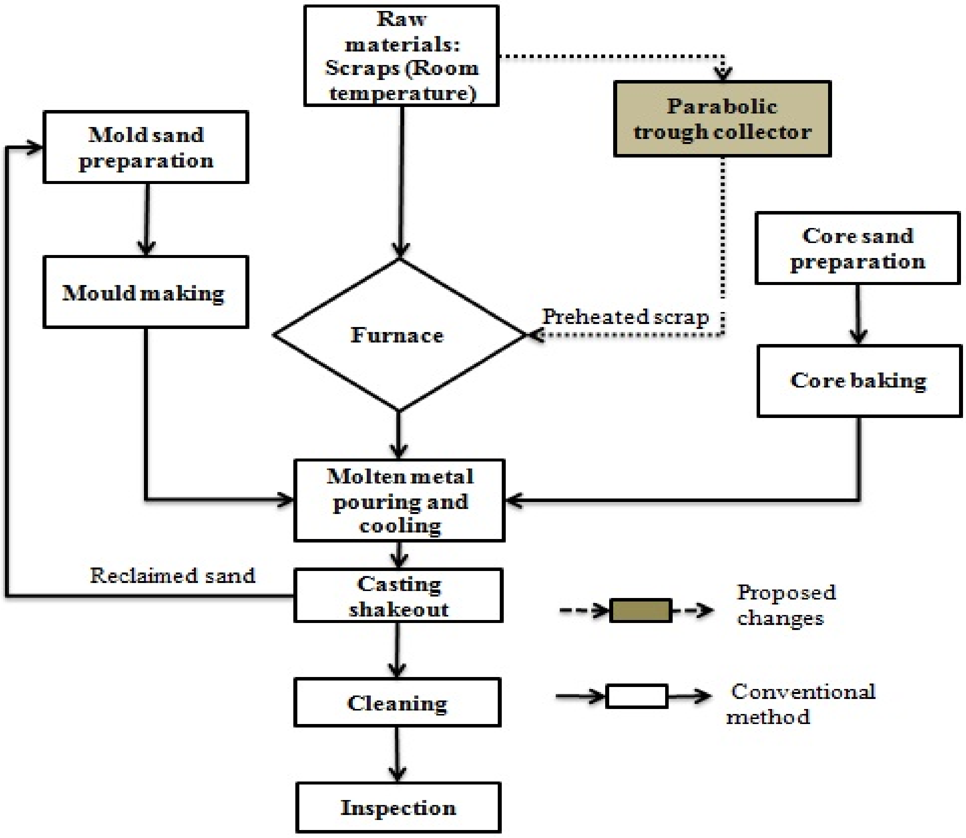

Fig. 1 Process flow chart of conventional foundry practice and proposed changes

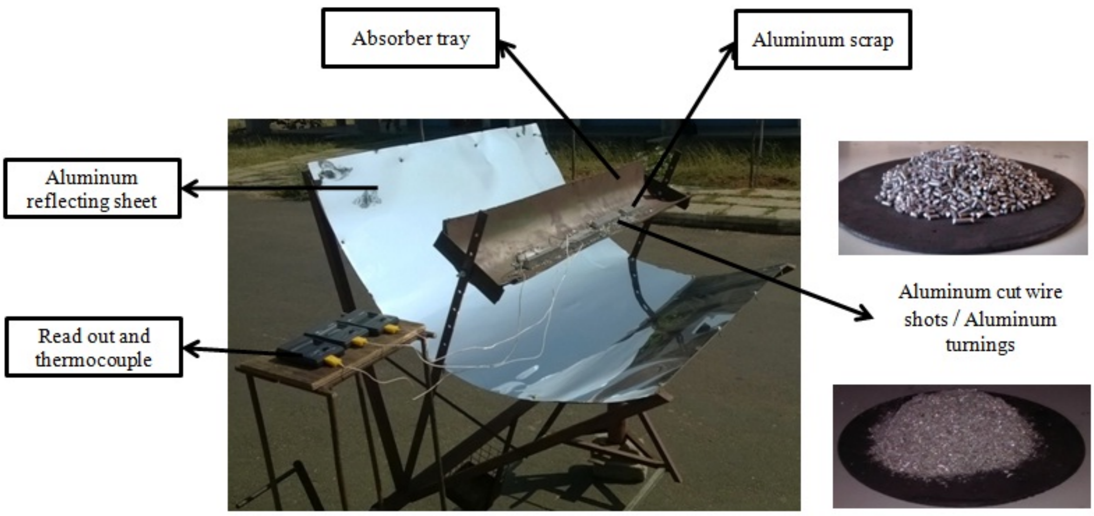

Fig. 2 Improvised experimental setup with heat transfer enhancers

A. Basic experimental setup without heat transfer enhancers

In the basic experimental setup, the semicircular absorber tray, which collects the radiation from parabolic concentrator, carries metallic scraps of various sizes. The scraps are in direct contact with the tray, but the air pockets present between the setup and absorber tray obstructs the flow of heat from the tray to the scrap, since the thermal conductivity of air (0.02593 W/m·K) is too far low than that of aluminium (204.2 W/m·K).

B. Improvised experimental set up with heat transfer enhancer

To overcome the above- mentioned problem of limited heat conductivity, the basic setup is improved by incorporating solid heat transfer media that are loose enough for flexibility of handling and flowability between the scraps. Such media used are: (i) aluminium cut wire shots and (ii) aluminium turnings. This setup is shown in Fig. 2. Aluminium cut wire shots have better flow ability since they are cylindrical. But they are heavy, accumulating heat in themselves; so aluminium turnings that are lighter were also used to check their performance for this purpose.

III. GOVERNING EQUATIONS

The governing equation shows the relationship between various useful energy gains per unit area at any time period to measure the thermal efficiency of parabolic trough collector. The solar PTC's collection efficiency is defined by following equation [11]:

$$\eta_c = \frac{Q_u}{A_t \cdot H} \tag{1}$$

The useful heat energy gain (Q_u), shows the amount of light intensity converted into useful heat energy in the given area. The useful energy gain can be expressed in terms of equation below:

$$Q_u = H \cdot \alpha \cdot \varepsilon \cdot \gamma \cdot A_t - U_l \cdot A_r \cdot (T_r - T_{amb}) \tag{2}$$

Where $A_r = \pi D_r L/2$ is the area of the absorber which absorbs the reflected light from the collector $A_t = (W - D_r) \cdot L$, is the area of aperture

The overall heat transfer coefficient is expressed by Duffie and Beckman [12] in the following equation:

$$U_l = h_{conv} + U_{cond} + h_{rad} \tag{3}$$

The heat transfer coefficient of natural convection [12] is defined as

$$h_{conv} = \frac{Nu_n k_a}{L_c} \tag{4}$$

The radiation heat transfer coefficient between the receiver and atmosphere is expressed by Garg and prakash [13] in the following form:

$$h_{rad} = \varepsilon \cdot \sigma \cdot \left(T_r^{\,2} + T_{amb}^{\,2}\right) \cdot \left(T_r + T_{amb}\right) \quad (7)$$

The general heat conduction equation [14] is expressed below:

$$Q = -KA\frac{\Delta T}{\Delta x} \quad (8)$$

Conduction heat transfer coefficient, U_{cond} is defined as,

$$U_{cond} = \frac{k}{x} \quad (9)$$

IV. RESULTS AND DISCUSSIONS

Experiments were conducted to measure temperature variation history in different thicknesses of scrap material in PTC. Since the solar radiation is dependent on weather condition, the temperature variation history in raw material also varies. The experiments were conducted at the time range of 11.30 am to 3.30 pm (4 hrs) to make use of the maximum solar insolation. In this section, results are presented starting from basic experiments, then with aluminium cut wire shots, followed by aluminium turnings.

A. Results of basic experiments

The temperature variation history observed in the raw materials of 6 mm, 10 mm and 20 mm thickness in the basic experiment are shown in the Fig. 3, Fig. 4 and Fig. 5 respectively. Different thicknesses are used to understand the variation of temperature gain with the thickness. The maximum temperature reached by 6 mm, 10 mm and 20 mm are 89 ˚C, 83 ˚C and 80 ˚C respectively. It is observed that the maximum temperature obtained by the scraps reduces with the increase of scrap thickness. This because of two reasons: (a) when the scrap size increases, the distance between the outer surface of the scrap and inner core (where thermocouple junction is placed) increases, resulting in increased thermal resistance offered by the metal. (b) As the size of scrap increases, the external surface area increases; this increased surface area increases heat transfer losses of conduction and convection types and heat gain by scrap can’t match the losses since losses occur in all areas whereas gain occurs only in the areas in contact with hot absorber tray. The random variations in the trend is attributed to factors such as sudden winds causing convective heat losses from the scrap and passing clouds reducing the solar irradiance. Such randomness is common for all the forthcoming results also.

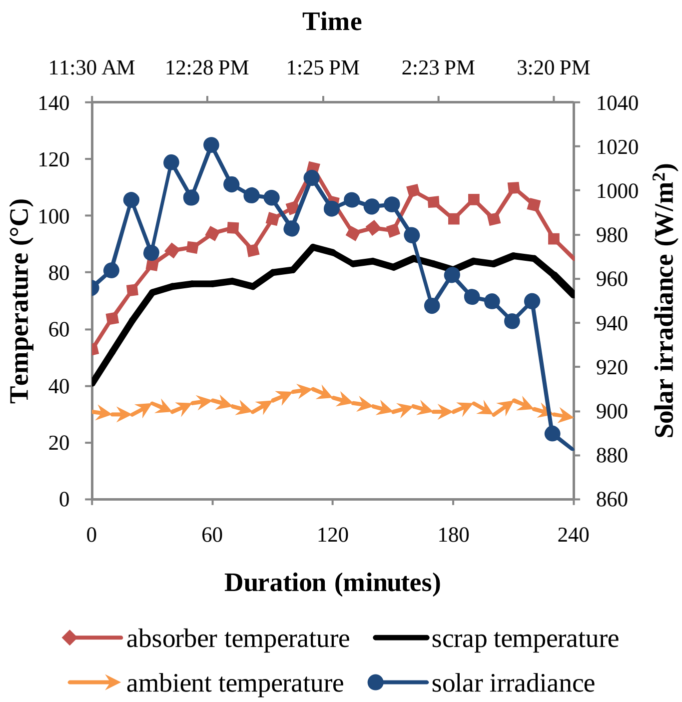

Fig. 3 Temperature variation history of 6 mm aluminium scraps without heat transfer enhancers

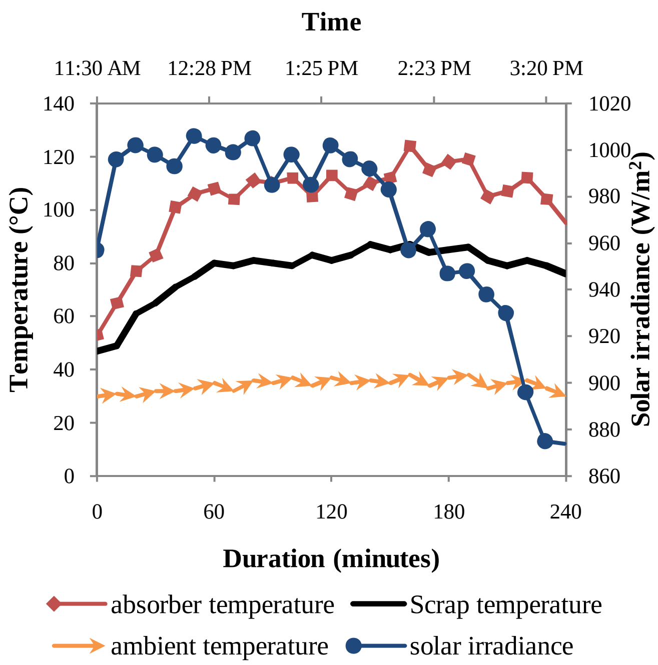

Fig. 4 Temperature variation history of 10 mm aluminium scraps without heat transfer enhancers

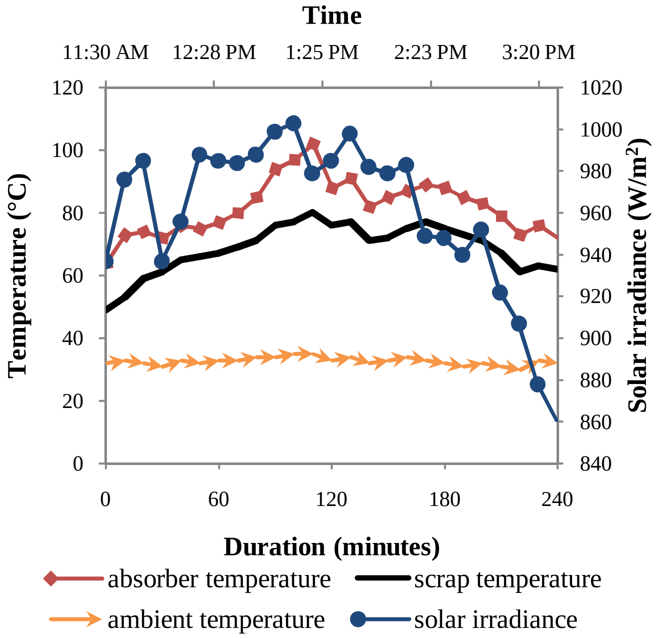

Fig. 5 Temperature variation history of 20mm aluminium scraps without heat transfer enhancers

In actual practice, even for two scraps that mate on their plain surfaces, the contact won't be perfect due to the air voids in the surface roughness. This introduces some thermal resistance in the contact surfaces. This should not be confused with the big air pockets created by the space between two irregularly shaped scraps whose surfaces can't fully mate. The heat conduction is calculated by the ratio of the temperature difference and the total thermal resistance of the raw material. The total thermal resistance [15] can be obtained by the following equation:

$$R_T = R_{c_1} + R_{interface} + R_{c_2} + R_{conv} \quad (10)$$

$$R_T = \frac{L_1}{k_1 A_c} + \frac{1}{h_a A_s} + \frac{L_2}{k_2 A_s} + \frac{1}{h_1 A_s} = \frac{1}{UA}$$

B. ***Results of improvised experiments***

1) *Results with aluminium cut wire shots:* The temperature variation history of aluminium scraps of different thicknesses, surrounded by cut wire shots is presented in Fig. 6 through Fig. 8. As the plots reveal, the maximum temperature reached by scraps of 6 mm, 10 mm and 20 mm are 95 °C, 94 °C and 85 °C respectively. There are two important observations that can be made here: (a) the peak temperature of scrap in the core is inversely proportional to its size, when all other conditions such as solar irradiance are kept constant. The reason for this is the increased resistance for conduction of heat for increased thickness of the scrap. (b) The cut wire shots have filled into the air pockets between the scraps and thus have effective heat transfer from absorber tray to the scrap. This is a desired phenomenon.

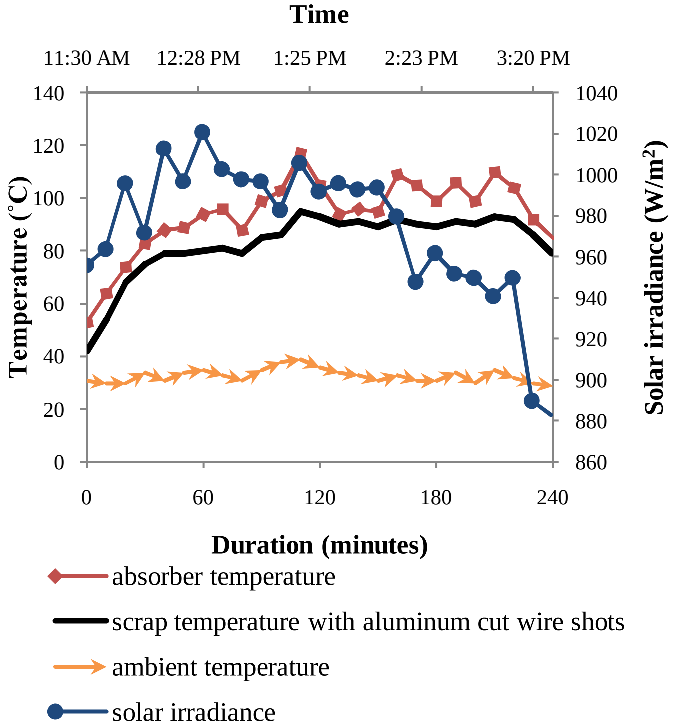

Fig. 6 Temperature variation history of 6 mm aluminium scrap with aluminium cut wire shots

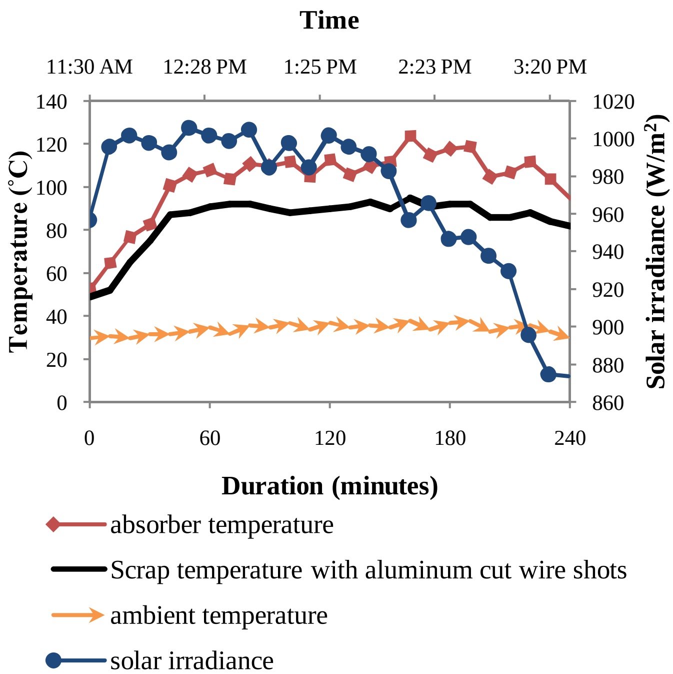

Fig. 7 Temperature variation history of 10mm aluminium scrap with aluminium cut wire shots

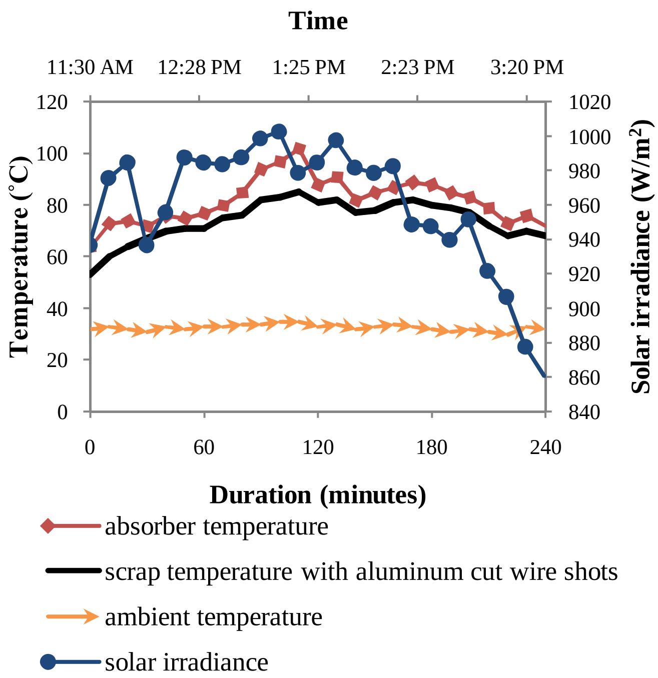

Fig. 8 Temperature variation history of 20 mm aluminium scrap with aluminium cut wire shots

2) *Results with aluminium turnings:* The temperature variation history observed in the raw materials of 6 mm, 10 mm and 20 mm thickness are shown in the Fig. 9, Fig. 10 and Fig. 11 respectively. The maximum temperature reached by 6 mm, 10 mm and 20 mm thickness scrap is 106 °C, 101 °C and 97 °C respectively. A reasonable amount of increase in the value of maximum temperature obtained is found in this experiment when compared with the basic experiment. The aluminium turnings have done well in conducting the heat to scrap, when compared to the cut wire shots because of the reasons cited in this section: The surface area by volume ratio are more for turnings than for cut wire shots. Because of this, there is less accumulation of heat by turnings and more transfer to scrap.

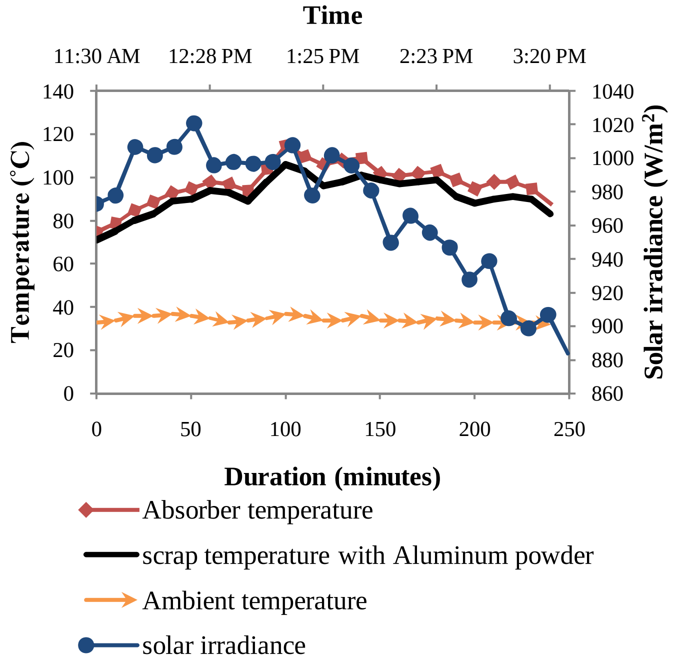

Fig. 9 Temperature variation history of 6 mm aluminium scraps with inclusion of aluminium turnings

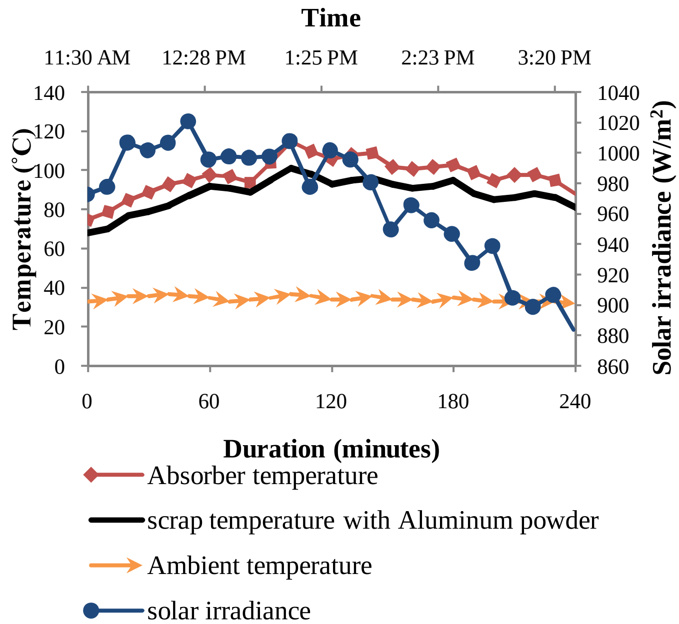

Fig. 10 Temperature variation history of 10 mm aluminium scraps with inclusion of aluminium turnings

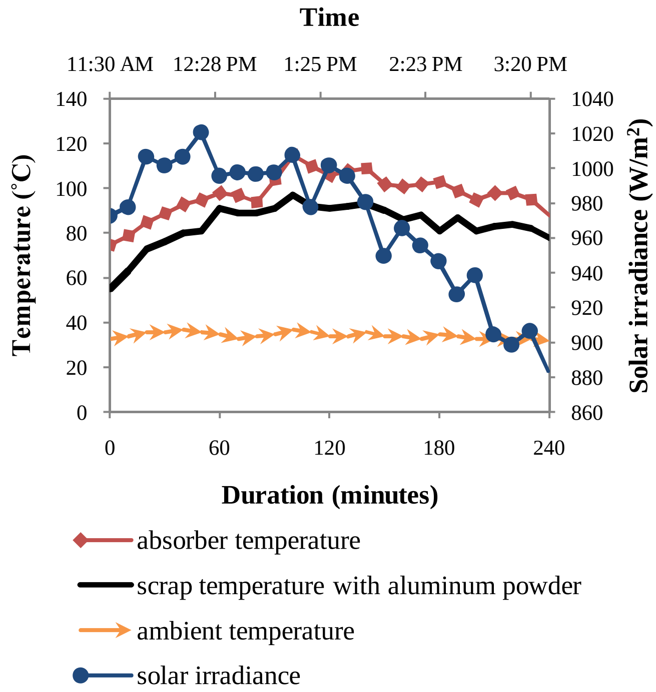

Fig. 11 Temperature variation history of 20 mm aluminium scraps with inclusion of aluminium turnings

V. ENERGY GAIN CALCULATIONS

A. Energy required for melting

The energy required for melting can be expressed as:

$$E_m = m \cdot c_p \cdot \Delta T_1 + m \cdot L + m \cdot c_p \cdot \Delta T_2 \qquad (11)$$

The energy required for melting 1.15 kg (total scrap weight) aluminium using the conventional method can be calculated as follows:

$E_m = 1.15 \times 0.896 \times (932 - 300) + 1.15 \times 3.98 \times 10^5 + 1.15 \times 0.896 \times (1023 - 932)$

$E_m = 1202.68$ kJ

The energy gained by the scrap using PTC for a maximum preheat of 106 °C as shown in Fig. 10 can be calculated by following equation [15]:

$$E_g = m \cdot c_p \cdot \Delta T \qquad (12)$$

$E_g = 1.15 \times 0.896 \times (379 - 300)$

$E_g = 81.4$ kJ

The percentage of energy gained calculation are given below

$$\% \, energygained = \frac{E_g}{E_m} \times 100$$

$$= (81.4/1202.68) \times 100$$

$$\% \text{ energy gained} = 6.77$$

TABLE: 1 PEAK TEMPERATURE OF SCRAP AND % ENERGY GAINED

	Raw materials without heat transfer enhancers			Raw materials with the usage of aluminium cut wire shots			Raw materials with the usage of aluminium turnings		
Thickness (mm)	6	10	20	6	10	20	6	10	20
Peak temperature of scrap (°C)	89	83	80	95	94	85	106	101	97
% energy gained	5.3	4.8	4.54	5.83	5.74	4.97	6.77	6.34	5.9

B. Economic benefits

A simple calculation reveals the potential of the economical savings of the proposed method: in India, there are 4700 foundries which produce 9,810,000 metric tons of all types of castings and for aluminium 950,000 tons of casting per year [5]. The energy saved by using proposed method for aluminium casting is 10.83 million kWh, which roughly translates to Rs. 113.715 million per year for typical industrial tariff rates of rupees 10.50 per unit (kWh). To melt one ton of aluminium, on the average, an induction furnace takes 520 kWh – 700 kWh [16] of electricity. If the proposed method is applied in foundries, it would take 6.77 % less, i.e., 40 kWh less per ton, for a specific energy consumption of 580 kWh/ton (assumed within the valid range). Extending this to the total casting production in India, assuming the same trend to all types of castings also, a saving of around 111.86 million kWh of energy is realizable, which translates roughly to Rs. 1174.54 million per year. Hence, there is a strong economical reason to adopt this method.

C. Ecological benefit calculations

Energy conserved by utilizing the solar resources mitigates the emission of greenhouse gases, which are called carbon foot print. Some approaches used to explore the carbon foot print are: process based life cycle assessments methods, environmental input output methods, discrete event simulation method [17] and hybrid method [18, 19]. According to a literature, the emission of CO_2 per kWh of power consumption is 1.13 kg [20]. The total amount of electricity savings in the proposed method is found to be 10.83 million kWh, which in turn reduces CO_2 emissions in the range of 12,237 tons. The above calculation shows only to aluminium castings; if we extend this to total casting productions in the world, the savings in economy and environment would be enormous.

VI. CONCLUSION

From this work, it can be clearly understood that the proposed method of solar thermal preheating of metallic scraps have very large potential for implementation in foundries. The experiment in this report shows that by utilizing the solar thermal preheating concept, 6.77% of melting energy is saved. This saving when applied to global casting production leads to saving of 1.18 billion kWh. Ecological foot print savings for India shows that this method can save 12,237 tons of CO_2. If such simple yet effective methods are promoted in all industries, the current energy and environmental crises can be mitigated to a reasonable degree. Considering the need of energy conservation, industries can easily come forward to perfect this method by further development and implement the same.

Nomenclature:

A_t	Aperture area (m^2)
A_r	Receiver area (m^2)
A_s	Scrap area (m^2)
c_p	Specific heat of material, 0.896 (KJ/Kg.K)
C	Constant coefficient (dimensionless)
D_r	Receiver diameter (m)
E_m	Energy required for melting (kJ)
E_g	Energy gained (kJ)
Gr_L	Grashof number (dimensionless)
g	9.81 m/s^2
h_{conv}	Convective heat transfer coefficient ($W/m^2.K$)
h_{rad}	Radiative heat transfer coefficient ($W/m^2.K$)
H	Solar irradiance (W/m^2)
k	Thermal conductivity (W/m.°C)
L	Length (m)
L_c	Characteristic length (m)
m	mass, 1.15 (Kg)
Nu	Nusselt number (dimensionless)
Pr	Prandtl number (dimensionless)
Q_u	Useful heat gain (W)
R_T	Total thermal resistance (°C/W)
Ra_L	Rayleigh number (dimensionless)
T_r	Receiver temperature (°C)
T_{amb}	Ambient temperature (°C)
U_{cond}	Conductive heat transfer coefficient ($W/m^2.K$)
U_l	Overall heat transfer coefficient (W/m^2)
W	Collector width (m)

α	Absorptance (dimensionless)
ε	Emittance (dimensionless)
γ	Shape factor (dimensionless)
σ	Stefan- Boltzmann law, 5.6704×10^{-8} ($W/m^2.K^4$)
$\frac{\Delta T}{\Delta x}$	Temperature gradient (°C/m)
ΔT_1	Temperature difference between the melting temperature and room temperature of aluminum (°C)
ΔT_2	Temperature difference between the pouring temperature and melting temperature of aluminum (°C)
B	Volume expansivity (1/K)
υ	Kinematic viscosity (m^2/s)
η_c	Collector efficiency

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