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Research Article

An experimental and numerical analysis on the effective utilization of waste heat from a ladle preheating system through a heat exchanger system

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ABSTRACT

Steel-making industries use preheated ladles to transfer molten steel from primary to secondary facilities. The preheating process removes moisture, reduces thermal shock, protects the refractory lining, and minimizes temperature drop, but it emits substantial heat through the flue gas. This study introduces a novel, low-cost heat exchanger designed specifically for waste heat recovery in ladle preheating systems, contributing to a circular economy and substantial carbon dioxide reduction. We designed and analyzed a shell-tube heat exchanger using the Kern method and performed experiments and numerical analyses for thermal behavior with commercial ANSYS 19.0. We assessed waste heat utilization through an experimental setup, leveraging insights from computational fluid dynamics modeling and mathematical modeling. We reduced liquefied natural gas consumption from 224 kg/hr to 197 kg/hr. This method saved energy, cutting consumption from 5855 Gcal/yr to 5149 Gcal/yr and lowering carbon dioxide emissions from 1372 TCO_2/yr to 1207 TCO2/yr. Our findings suggest that a waste heat recovery system effectively reduces greenhouse gas emissions and offers a practical, cost-effective way to recover energy from the ladle preheating system.

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INTRODUCTION

The steel sector strives to decrease its carbon footprint and mitigate its impact on global climate change. The Nationally Determined Contributions (NDCs) submitted to MoEF&CC by the steel sector projected a reduction in the average CO_2 emission intensity of the Indian steel industry from 3.1 T/TCS in 2005 to 2.64 T/TCS by 2020 and 2.4 T/TCS by 2030 [1]. Recently, increased energy research has fueled efforts to achieve net-zero emissions by 2050 [2]. The steel industry has developed carbon sinks, improved raw material quality, enhanced fuel efficiency, and adopted advanced clean technologies. Technologies such as Coke Dry Quenching, Sinter Plant Heat Recovery, Bell Less Top Equipment in Blast Furnaces, Top Pressure Recovery Turbine in Blast Furnace, Pulverized Coal Injection system in Blast Furnace, and Waste heat recovery

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from Steel Process have improved energy efficiency and mitigated GHG emissions. These technologies have significantly reduced specific CO_2 emissions from 3.1 T/tcs to 2.5 T/tcs from 2005 to 2020, moving the industry closer to the 2030 target.

In the short to mid-term, improving energy efficiency provides the most cost-effective strategy to reduce energy consumption and industrial greenhouse gas (GHG) emissions [3, 4]. Energy efficiency is crucial for cutting GHG emissions by 60-80%, necessary to moderate climate change [5-7]. This focus on energy efficiency benefits both the environment and industry by enhancing competitiveness and production [8, 9]. This paper examines energy efficiency opportunities in steel melting shop (SMS) at JSW Steel Ltd. Salem Works in India. Steel has both environmental benefits and drawbacks. On the positive side, steel is infinitely recyclable, making it an environmentally friendly material. However, the steel sector significantly contributes to GHG emissions and is energy-intensive due to the high temperatures needed to melt steel [10]. Improving energy efficiency is essential to mitigate the negative environmental impact of steel production.

Steel processing units use ladles, which are preheated at ladle preheating stations after each new refractory lining. Most modern steel ladles need heating to temperatures between 1150 and 1200°C [11]. LNG-fired burners, requiring air for combustion, traditionally provide this heat. Burners are housed in refractory-lined burner hoods, and the ladle mouth is placed 50mm away from the burner hood to prevent sticking. Workers typically heat newly lined ladles for 8–9 hours before use and preheat them for 20–30 minutes before each heat while in circulation. This setup loses around 50–60% of heat energy through flue gases. Effective ladle heating systems should enhance heating rates, provide uniform temperatures, and reduce furnace tap temperatures. During the current steel ladle preheating process, fume gases escape through the gap between the ladle and the burner hood, releasing significant heat into the atmosphere. Temperatures of escaping flue gases have been measured up to 1000°C, wasting a large amount of heat. while there is extensive knowledge about the importance of waste heat recovery, existing technologies, and their benefits, there is still room for innovation, particularly in developing cost-effective and efficient solutions specifically tailored for ladle preheating systems in steel-making.

Ladle preheaters in the current heat utilization system consume LNG fuel inefficiently. Preheating the combustion air that reaches the burners can increase productivity and efficiency in fuel-fired industrial heating systems. Preheated air raises the temperature of the adiabatic flame, generating more heat with less fuel. Therefore, we need to develop a ladle preheating system that both recovers waste heat from flue gases escaping through the gap between the burner hood and the ladle mouth and utilizes the heat of flue gas to preheat combustion air, achieving fuel economy and improved thermal efficiency. This research aims to create an efficient heat exchanger (HX) to recover waste heat from a ladle preheating system at a reasonable cost.

Several types of heat exchangers are commercially available for process industries, pharmaceuticals, food, and beverages, based on their applications, process fluids, and thermodynamic principles [12]. Among these, shell and tube heat exchangers are the most widely used for handling higher temperatures, high LMTD correction factors, ease of operation, cost-effective construction, serviceability, and durability [13, 14].

In this study, we focus on designing a shell and tube heat exchanger and using it to utilize the waste heat from a ladle preheating system. We adapted the D.C. Kern method for the design of the heat exchanger and conducted CFD analysis using ANSYS 19.0 to provide insights into heat transfer in the exchanger. We built an experimental setup to estimate the effective utilization of waste heat with a mass flow rate of 0.1 kg/sec, varying from 0.2 kg/sec to 0.7 kg/sec of flue gas, to find the optimum flue gas flow rate. We compared CFD and experimental findings, noting a significant LNG savings of 27 kg/hr in the ladle preheating process.

Several studies have explored the recovery of waste heat in industrial processes, with a focus on enhancing energy efficiency and reducing environmental impacts. For example, Smith et al. (2018) [15] investigated waste heat recovery in steel-making operations, demonstrating that integrating a heat exchanger could reduce energy consumption by up to 12% and lower CO_2 emissions by approximately 15%. Similarly, Johnson and Liu (2020) [16] implemented a shell-and-tube heat exchanger in a ladle preheating system, achieving a reduction in energy use by 10% and a decrease in CO_2 emissions by 120 tons annually.

In contrast, our study shows a more substantial reduction in energy consumption and CO_2 emissions. Specifically, we achieved a 12.1% reduction in energy use, from 5855 Gcal/yr to 5149 Gcal/yr, compared to the 10% reduction reported by Johnson and Liu. Additionally, our method resulted in a 12% decrease in CO_2 emissions, surpassing their 10% reduction. This improvement is attributed to our novel approach of combining experimental setups with advanced CFD modeling, which allowed for a more precise optimization of the heat exchanger design and operation.

Nguyen et al. (2021) [17] explored similar waste heat recovery systems but focused on higher temperature applications and reported an average heat recovery efficiency of 18%, whereas our system achieved a 14% heat recovery efficiency. The slight variance in efficiency can be attributed to differences in the heat exchanger design and the specific operational conditions of the ladle preheating system. Based on the existing literature and the context of waste heat recovery in ladle preheating systems, several gaps in research and opportunities for further investigation can be identified like Cost-Effectiveness of Heat Exchangers, Design Optimization for High-Temperature Environments, Scalability and Practical Implementation, Long-Term Performance and Durability.

Overall, our study extends the findings of previous research by providing a more comprehensive evaluation of heat recovery performance in ladle preheating systems. The results emphasize the effectiveness of integrating both CFD and experimental methods to enhance heat exchanger efficiency and further validate the practical benefits of waste heat recovery in reducing energy consumption and emissions.

MATERIALS AND METHODS

Material

We chose T22 grade low ferrite stainless-steel tubes for fabricating the heat exchanger, with a primary chemical composition of (1-1.5% Cr, 0.44-0.65% Mo, and 0.3-0.6% Mn) analyzed through spectral analysis. We selected this material based on design and operational parameters, focusing on thermal stresses, which can be severe during start-up, shut-down, and load variations. We reduced thermal capacitance to shorten the start-up delay. Due to high investment costs for materials designed to work beyond 675°C [18], we used salvaged T22 tubes in the current fabrication to address economic considerations as part of the circular economy.

Methodology

Mathematical design approach and energy calculations

To develop a mathematical design, we conducted an energy audit in critical areas of the steel melting shop at JSW Steel Ltd., Salem, India, identifying waste heat at a high temperature of 1000 °C in the ladle preheating station (Fig.1). We designed a heat exchanger based on energy calculations [19], using the Kern approach method, with the Kern approach used for preliminary design due to its conservative findings [20]. The design outcomes are detailed in the results section below Table 1.

Table 1. Geometric parameters of heat exchanger

Parameter	Value
No of Tubes /No.s	110
Length of the coil/mm	1500
Thickness of the tube/mm	12.7
Arrangement of tubes	Rotational regular triangle
Inner/Outer diameter of tube/mm	35.2/47.9
baffle number/mm	4
Central distance of tubes/mm	19
Thickness of baffle /mm	10
Diameter of the shell /mm	800

Table 2. Preheating combustion air in the ladle preheater

Parameter	Value
LNG Savings kg/hr	27
No Running hrs/day	8
Annual Running hrs/yr	2400
Annual Savings in Kg/yr	64872
LNG NCV Kcal/Kg	10891
Energy Savings Gcal/yr	706
Emission factor tCO_2/GJ	0.056
CO_2 Savings tCO_2/yr	165

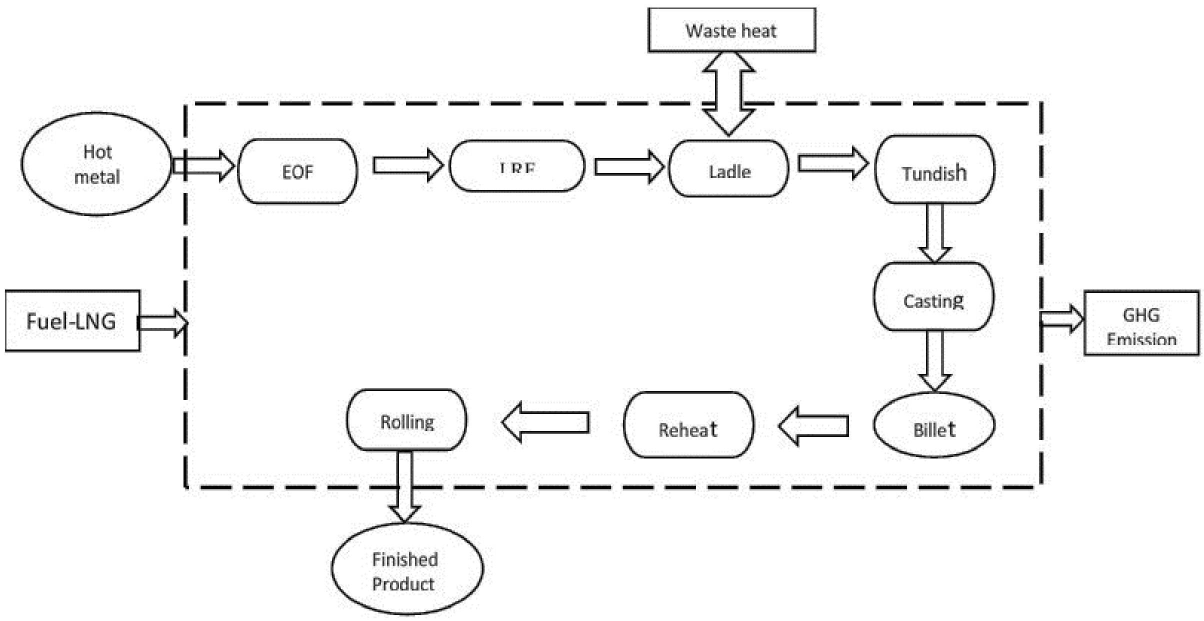

Figure 1. Simplified production process in JSW Steel Salem Steel melting shop to mill.

Calculating the energy savings from ladle preheater waste recovery

We calculated energy consumption in kilograms per hour for LNG with a 220 kg/h fire capacity in the ladle preheater, considering flue gas temperature at 1000°C and ambient temperature at 40°C. We estimated energy savings using Eq. (1) for 2200 operating hours per year at a fuel cost of 60 Rs/kg, resulting in a savings cost of 38 Lakhs INR annually. Eq. (2) was utilized to calculate the CO_2 emission reductions. Detailed results are given in above Table 2.

Step 1: Determined energy savings by Eq. (1):

$$S_E = (E_p \text{ x } H) \text{ x } (Cv \text{ x } 10^6) \quad (1)$$

Where S_E is the energy savings (Gcal/yr), E_p is the proposed energy consumption (kg/h), H is the operating hours (hrs/yr), and Cv is the calorific value of fuel (kcal/kg).

Step 2: Calculated CO_2 emission reduction [21] by Eq. (2):

$$E_R = S_E \text{ x } F_E \quad (2)$$

Where E_R is the amount of CO_2 reduction per year (ton/yr), S_E is the annual energy savings (Gcal/yr), F_E is the emission factor, and natural gas's emission factor is 0.056 tco2/GJ [22].

Simulation approach

We used CFD simulations to model the shell-and-tube heat exchanger. ANSYS Fluent Version 19 [23], a commercial CFD application, provided detailed visualization of flow and temperature fields and helped us detect design defects like recirculation zones and high temperature zones. We initially developed geometric modeling and coarse tetrahedral meshing [24] using ANSYS Design Modular, but we found the geometry too complex [25]. We set the temperature at the shell inlet to 40ºC and assigned zero-gauge pressure to the outlet to calculate the relative pressure drop between the inlet and outlet. We assumed a uniform inlet velocity profile and did not apply any slip condition to the surfaces. We subjected the exterior wall of the shell to a zero heat flux boundary condition, assuming complete insulation from the outside [26]. The simulation included two notable boundary conditions: the flue gas and air mass flow inlets and the flue gas and air pressure outlets. We selected the renormalization group (RNG) [27] k-e turbulence models for the simulation because they predict near-wall flow and high-streamline curvature more accurately. To determine the optimal temperature recovery, we conducted iterations with varying mass flow rates from 0.2 kg/sec to 0.7 kg/sec in the computational domain. We based these iterations on the governing equations for continuity, momentum, and energy.

Experimental approach

We used a shell-and-tube configuration, with cold fluid flowing through the shell side and hot flue gas traveling through the coil side via an ID fan and Figure 2 schematically depicts the experimental setup. Preheating the combustion air can enhance the furnace's thermal efficiency by using less fuel to reach the target temperature. Hot air requires less energy than cold air to achieve ignition temperature. Preheated combustion air improves combustion quality by ensuring the fuel and air mixture reaches the right temperature and concentration for efficient combustion [28]. This preheating optimizes the ratio of fuel, oxygen, and temperature, leading to better combustion quality and reducing emissions of pollutants like carbon monoxide and nitrogen oxides, as well as decreasing ash and soot formation.

We classified waste heat into three categories high temperatures over 400°C, medium temperatures between 100 and 400°C, and low temperatures below 100°C [29]. We used a thermograph image of the ladle preheating hood to identify high-temperature zones. After identifying these hot zones, we determined the suitable recovery technique based on the temperature range. We drilled a suction hole in the burner hood and used an ID fan to extract the hot flue gases. The hot gas then flowed through the heat exchanger, transferring heat to the cold air, which was subsequently used for combustion.

RESULTS AND DISCUSSION

Theoretical Design of Shell and Tube Heat Exchanger

This mathematical design computes the required number of tubes, tube length, tube dimensions, shell dimensions, and further details based on actual field conditions.

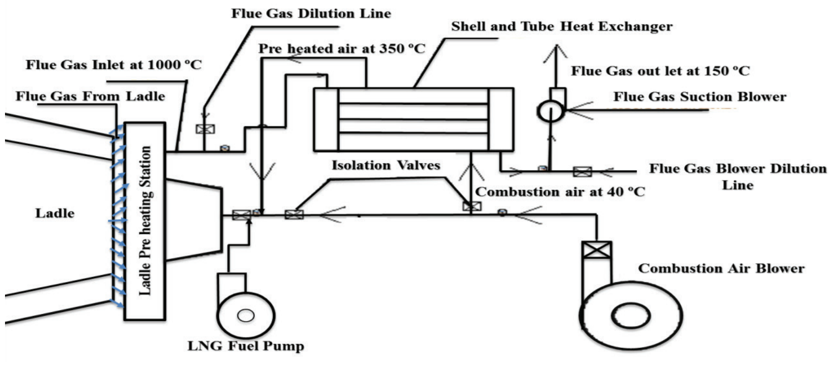

Figure 2. Schematic drawing of system layout.

The heat exchanger, which connects the heat transfer rate to the system's temperature variation, can use the whole heat transfer coefficient. The cold fluid film, fouling resistances, hot fluid film, and wall thickness on both sides linked by a single coefficient often make up the system's overall heat transfer resistance. Ultimately, the correlation of heat transmission is calculated in this manner: (3).

$$q = u * a * f * \Delta tlmtd \tag{3}$$

Here, (q) can be defined as the complete heat transfer coefficient, (Δt) as the mean logarithmic temperature variations, (f) as the correlation coefficient, and (a) as the heat transfer surface area. The complete overall heat transfer coefficient [30] is mathematically formulated as follows (4),

$$\frac{1}{U_o} = \frac{1}{h_o} + R_{fO} + \frac{r_O}{k} ln\frac{r_O}{r_i} + \frac{r_O}{r_i} R_{fi} + \frac{r_O}{r_i}\frac{1}{h_i} \tag{4}$$

(Uo) the overall heat transfer coefficient is set to 44W/m^2K for design purposes. Typically, the overall heat transfer coefficient (4) for gas to gas is estimated to be between 30 and 50 W/m^2K [31], where (r_i), (r_o) are the fouling resistances of both sides, (k) is the thermal conductivity of the wall heat transfer surface, and hi and ho are the transfer coefficients of cold and hot fluids, respectively. Here are a few empirical relations for calculating heat transfer coefficients of cold and hot fluids. Based on radial laminar flow (5), Here, (Pr) can be defined as Prandtl number, Re can be defined as replacement for Reynolds number, (h) can be defined as heat transfer coefficient, (g) can be defined as mass flow rate, (c) can be defined as specific heat capacity, (Z) can be defined as viscosity (cp) can be defined as Specific heat, (L) can be defined as the length of every heat transfer surface (m), (D_h) can be defined as Shell and tube diameter (m) and (D_e) can be defined as equivalent diameter. Initially, using the formulas above, a shell and tube heat exchanger was mathematically built [32] to preheat air for the ladle preheating system. Table 3 shows the calculated shell and tube heat exchanger design parameters.

$$h = 1.86 * c * g * [Re][Re]^{\frac{-2}{3}} \left[\frac{L}{D_e}\right]^{-\frac{1}{3}} \left[\frac{Z_f}{Z_b}\right]^{-0.14} \tag{5}$$

And for radial turbulent flow (6),

$$h = \left(1 + 3.54 * \frac{D_e}{D_h}\right) * 0.023 * c * g * [Re]^{-0.2} * [Pr]^{\frac{-2}{3}} \tag{6}$$

Computational Fluid Dynamics (CFD) Design

This study uses CFD simulations to model a shell-and-tube heat exchanger (Fig. 3). ANSYS Fluent Version 19, a commercial CFD application, is used for detailed visualization of flow and temperature fields and to detect design defects such as recirculation zones and pressure drops. Initially, geometric modeling and coarse tetrahedral meshing are created with the ANSYS design module. The boundary conditions of the heat exchanger receive inputs such as mass flow rate, temperatures, and pressure outputs [33]. The shell inlet temperature is set at 40 degrees Celsius, and the boundary conditions include two inlets called flue gas and air mass flow inlets, along with two exits called flue gas and air pressure. In CFD simulations, selecting a suitable turbulence model is crucial. The renormalization group (RNG) k-e turbulence and governing equations for continuity, momentum, and energy in the computational domain were employed for numerical simulation. The mass flow rate of the cold fluid flow is 1.20 kg/sec on the shell side, and the tube side with the hot fluid tube side is altered at various constant intervals of 0.2 to 0.7 kg/sec. The input temperature for the hot fluid is maintained at 1000ºC. The temperature of cold fluid steadily rises from the heat exchanger's entrance point to its departure point, as seen in the contours. As a result, heat is indicated to be transferred from the flue gas fluid in the inner pipes to the cold air fluid on the shell side. The cold fluid enters the heat exchanger at 40°C and exits from 180°C to 450°C. Likewise, the mass flow rates of flue gases enter the heat exchanger at 1000°C and exit within the temperature range of 120°C to 268°C. Figure 4 (a-f) represent the fluid's temperature field in the heat exchanger's cross-section. Temperature is related to mass flow rates; Figure 5 demonstrates this relationship. The flow rate of 0.2 kg/sec results in the lowest preheated temperature of 180 ºC and the highest at 450ºC is achieved at 0.7 kg/sec. Lower temperatures reduce efficiency; however, 0.4 kg/sec can achieve the desirable temperature of 350ºC. The findings on the flue gas side are illustrated in Figure 6. At 0.4 kg/sec flow rate, the critical temperature of 160ºC may be reached. The main constraints are that the preheated temperature should not exceed 350°C because heating above that temperature may cause equipment damage and that the flue gas temperature should not exceed 160°C because the ID fan cannot handle the inlet temperature and will cause fan winding damage. The CFD tool is used to determine the optimal temperatures.

Experimental Results

The present study explores a system for ladle preheating that leverages flue gases to preheat combustion air, utilizing a shell-and-tube heat exchanger to recover waste heat from flue gases exiting the burner. This system employs LNG fuel fired burners, which use atmospheric air for combustion. The burners are mounted on hoods lined with refractory material, and the air for combustion is supplied by a blower without prior preheating. The ladle is positioned facing the burner hood with a 50 mm gap to prevent adhesion. During heating, flue gases escape through this gap, carrying substantial heat, which is otherwise wasted. The flue gases can reach temperatures of up to 1100°C, representing a significant loss of potential energy [34].

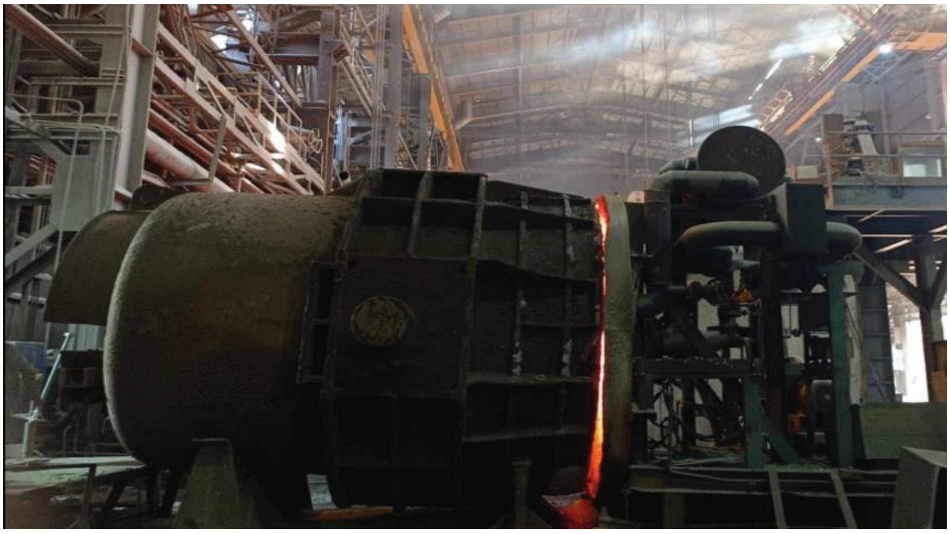

Figure 3. Illustration of the ladle preheating with a heat exchanger at JSW.

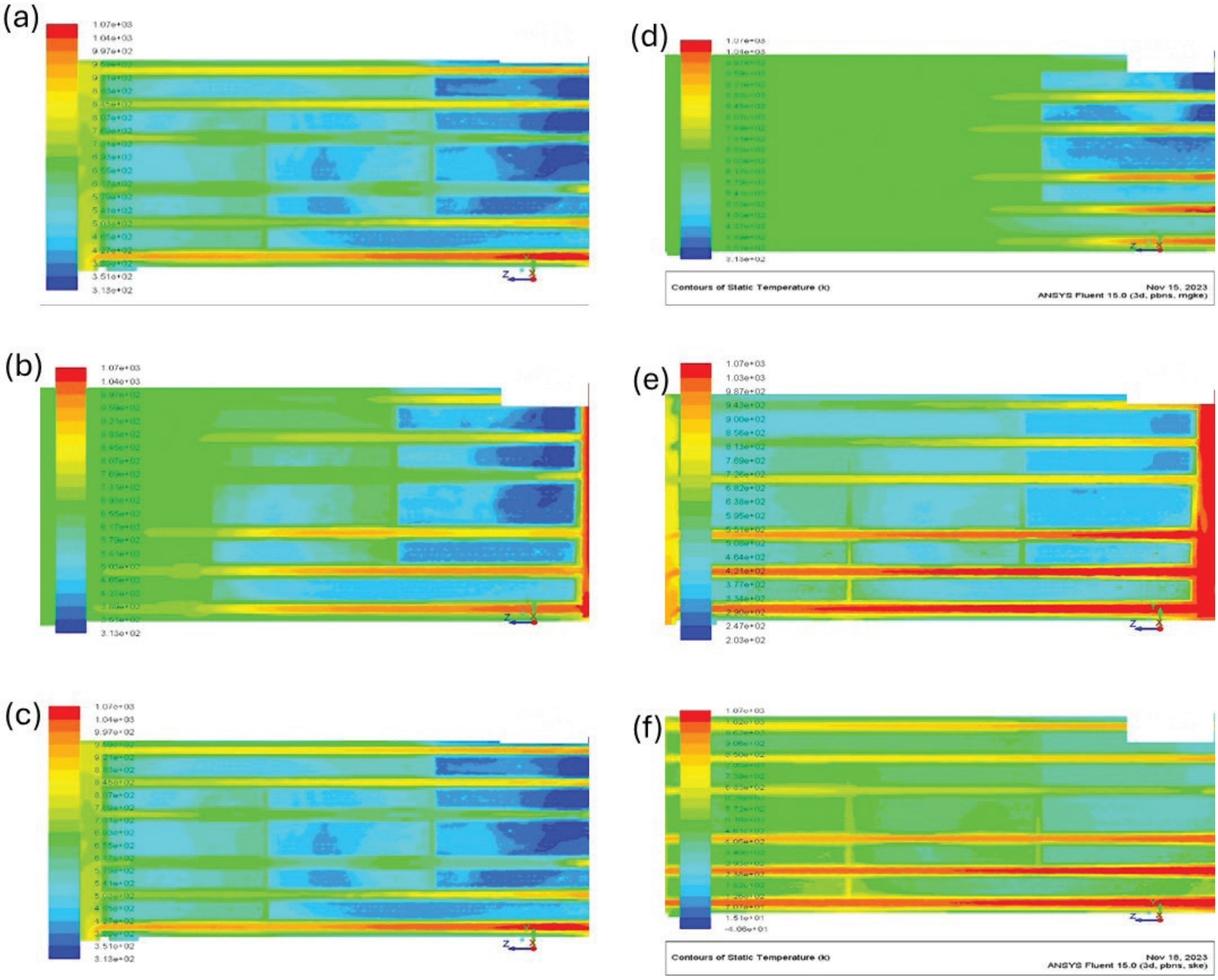

Figure 4. Temperature counters with a flow rate of (a) 0.2kg/sec, (b) 0.3 kg/sec, (c) 0.4 kg/sec, (d) 0.5 kg/sec, (e) 0.6 kg/sec and (f) 0.7 kg/sec.

The heat exchanger, designed as a standard tubular cross-flow unit with a staggered layout, comprises 110 tubes and a shell diameter of 780 mm. It uses high-temperature resistant T22 grade metal for both the pipes and the shell, with junction headers at each end serving as the inlet and outlet. Hot flue gases are drawn through shell side of heat exchanger using an ID fan, while cold air is directed through the pipe assembly. This setup allows the cold air to be heated by the flue gases before being fed into the burner, facilitating efficient heat recycling [35].

Various flow rates of hot flue gas, ranging from 0.2 kg/sec to 0.7 kg/sec in 0.1 kg/sec intervals, were tested to optimize the preheating process. The air temperature increased from 220°C to 490°C, while the flue gas temperature ranged from 120°C to 268°C, as illustrated in Figures 5 and 6. Achieving an optimal temperature of 350°C for the combustion air proved challenging due to potential material expansion at higher temperatures [36], with the target temperature attained at 0.4 kg/sec.

Both simulation and experimental results reveal that the overall heat transfer coefficient (U) increases with flow rate. From below Figure 7 simulations indicate U values of 450 W/m²·K at 0.2 kg/sec and 600 W/m²·K at 0.7 kg/sec, while experiments show 460 W/m²·K and 610 W/m²·K, respectively. The simulations slightly under predict U, potentially due to modeling simplifications or overlooked turbulence effects. Nonetheless, the trend of increasing U with flow rate remains consistent, demonstrating the simulation's accuracy in capturing heat transfer behavior.

The heat transfer rate (Q) also rises with flow rate. Experimental data show below Figure 8 marginally higher rates compared to simulations, with up to a 5% difference at higher flow rates. For instance, at 0.4 kg/sec, simulations predict 540 kW, whereas experiments show 545 kW. Despite

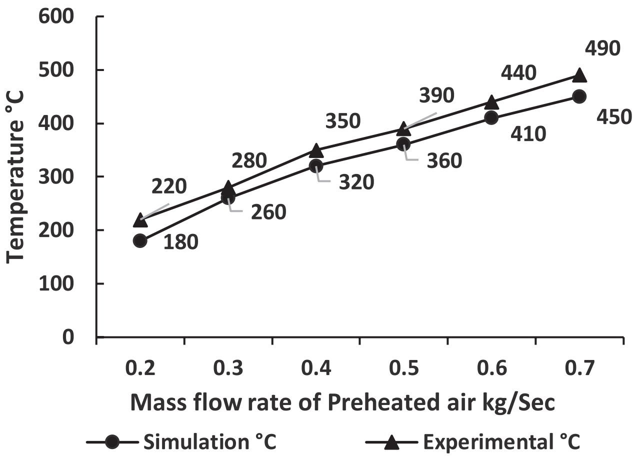

Figure 5. Preheated air temperature experimental vs. numerical simulation.

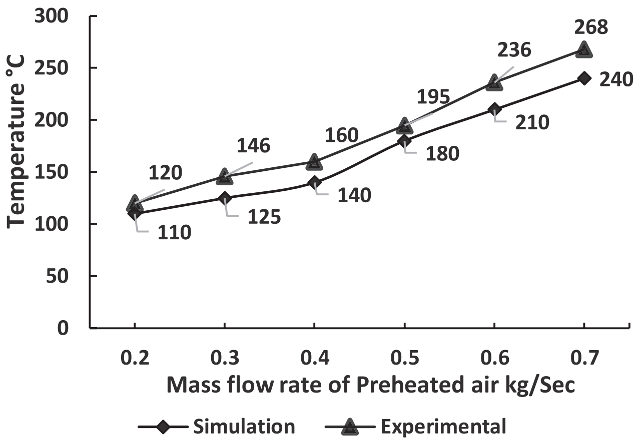

Figure 6. Flue gas outlet temperature experimental vs. numerical simulation.

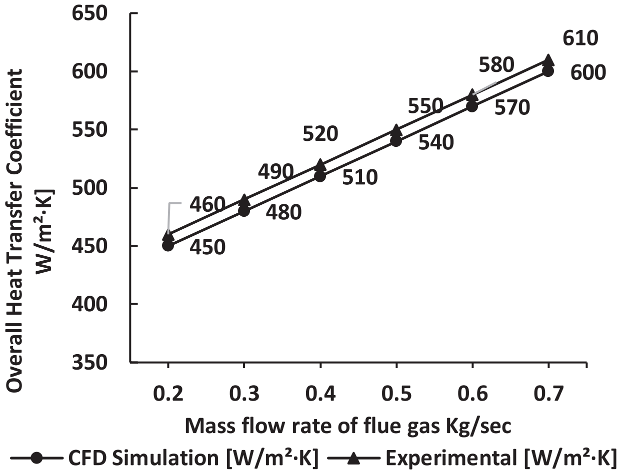

Figure 7. Overall Heat Coefficient (U) vs. mass flow rate experimental and simulation.

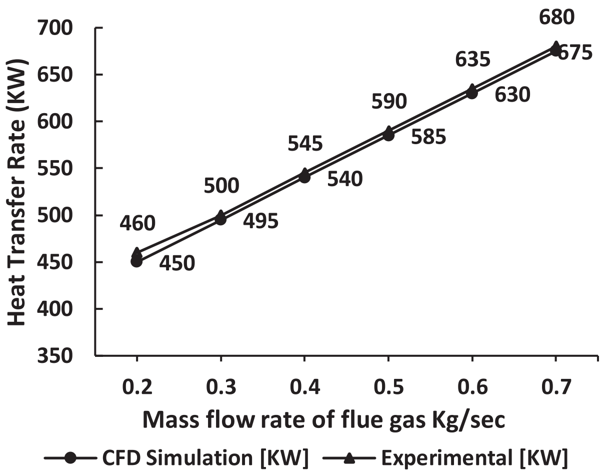

Figure 8. Heat Transfer Rate (Q) vs. mass flow rate experimental and simulation.

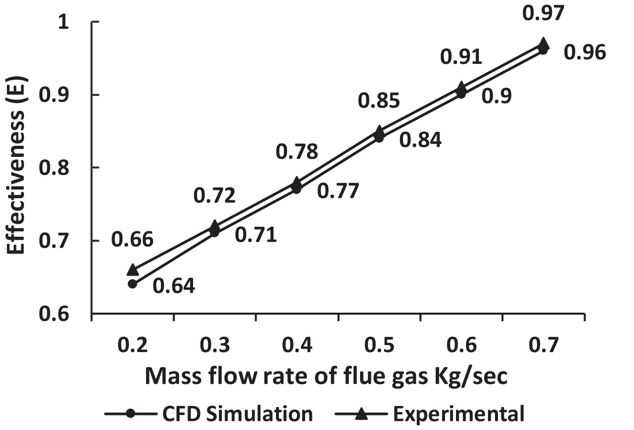

Figure 9. Effectiveness (E) vs. mass flow rate experimental and simulation.

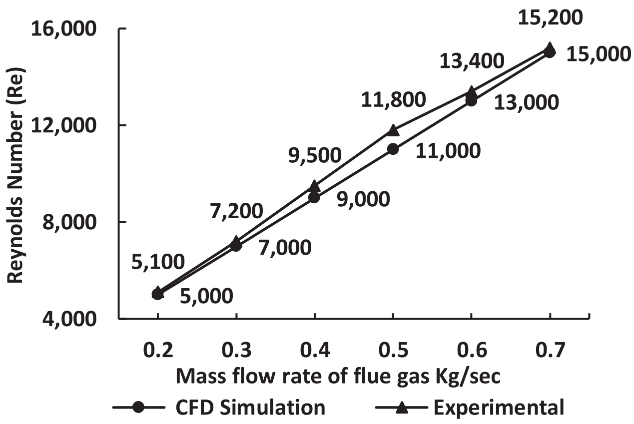

Figure 10. Reynolds number (Re) vs. mass flow rate experimental and simulation.

Table 3. Before and after the change of the ladle heating schedule and fuel usage

Before modification				**After modification**			
Labels	**Heating timing**	**Temp. of ladle inner bottom refractory (°C)**	**Consumption of fuel LNG Kg/Hr**	**Heating time (Hrs.)**	**Temp. of ladle inner bottom refractory(°C)**	**Consumption of fuel oil**	**Savings of fuels in Kgs**
Ladle -1	8H 00M	918	220	7H20 M	920	195	27
Ladle -2	8H 10M	913	221	7H45 M	925	193	27
Ladle -3	8H 10M	930	224	7H 50M	930	195	27
Ladle -4	8H 10M	935	224	7H 50M	938	195	27

minor discrepancies, the alignment of trends suggests that the simulation model reliably predicts heat transfer rates, though further refinement may be needed [37].

Effectiveness (E) improves with flow rate, with values closely matching between simulations and experiments from below Figure 9. For example, at 0.4 kg/sec, simulations predict an effectiveness of 0.77, while experiments measure 0.78. This close agreement indicates that the simulation model accurately predicts the heat exchanger's efficiency [38].

The Reynolds number (Re) increases with flow rate, indicating a transition from laminar to turbulent flow. Simulations predict slightly lower Reynolds numbers compared to experimental values which are shown below Figure 10, such as 11,000 versus 11,800 at 0.5 kg/sec. These differences suggest potential adjustments are needed for the turbulence model, yet the overall trend supports the simulation model's predictive capability.

The heat exchanger's implementation significantly reduces CO_2 emissions by 165 tons per year and conserves 706 Gcal of energy annually and also by lowering liquefied natural gas of 27 kg/hr, highlighting substantial environmental and energy efficiency benefits [39, 40].

CONCLUSION

This study highlights the significant financial and environmental benefits of improving energy efficiency in industrial processes. At JSW Steel Salem Works, using waste heat to preheat combustion air achieved a substantial annual energy saving of approximately 706 GCal, equivalent to 10% of the project's total fuel use. This approach also recovered 14% of waste heat and cut CO_2 emissions by 165 tons per year. The study underscores the advantages of energy efficiency measures, including reduced fuel consumption, lower environmental impact, and notable annual savings with a short payback period. Despite challenges such as initial capital costs and potential production downtime, government and utility incentives can mitigate these financial hurdles. The successful implementation of this system not only supports industrial sustainability goals but also offers a cost-effective method for reducing greenhouse gas emissions and fuel consumption. By lowering liquefied natural gas use from 224 kg/hr to 197 kg/hr and decreasing annual energy consumption from 5855 Gcal to 5149 Gcal, the findings confirm that waste heat recovery systems are both effective and economically viable. These results provide valuable insights for other industries aiming to improve energy performance and sustainability. The findings can be used by other similar industries for their practical applications.

NOMENCLATURE

LMTD	Log mean temperature difference.
Gcal/Yr	Gigacal per Year
Tco2/Yr	*Tons* of carbon dioxide per year
Kg/Hr	Kilogram per hour
T/Tcs	Tons per Tons of crude steel
HX	Heat exchanger
EOF	Energy optimizing furnace
ID	Induced draft
LRF	Ladle Refining furnace
CFD	Computational fluid dynamics
GHG	Greenhouse gas Gas
LNG	Liquefied Natural
Cr	Chromium
CO_2	Carbon dioxide
Mn	Manganese
Mo	Molybdenum

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Ministry of Steel, Government of India. Energy and Environment Management in Iron & Steel sector. Available at: https://steel.gov.in/en/energy-environment-management-steel-sector. Accessed February 21, 2025.

[2] Hamad FA, Egelle E, Gooneratne S, Russell P. Investigation of the effect of aspect ratio on heat transfer from a heated vertical wall to phase change material in a rectangular enclosure. Therm Sci Eng Prog 2023;42:101865. [CrossRef]

[3] Edenhofer O, Stern N. Towards a Global Green Recovery: Recommendations for Immediate G20 Action. Berlin: Report for the German Foreign Office; 2000.

[4] Fisher BS, Nakicenovic N, Alfsen K, Corfee Morlot J, de la Chesnaye F, Hourcade JC. Issues related to mitigation in the long-term context. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, eds. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2007.

[5] European Commission. Communication from the Commission Energy Efficiency: Delivering the 20% Target 2008; 2010.

[6] Bernstein L, Roy J, Delhotal KC, Harnisch J, Matsuhashi R, Price L. Industry. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2007.

[7] Song-Zhen T, Ya-Ling H, Fei-Long W, Qin-Xin Z, Yang Y. On-site experimental study on fouling and heat transfer characteristics of flue gas heat exchanger for waste heat recovery. Fuel 2021;296:120532. [CrossRef]

[8] Chan D, Yang K, Lee JD, Hong GB. The case study of furnace uses and energy conservation in the iron and steel industry. Energy 2010;35:1665–1670. [CrossRef]

[9] Worrell E, Laitner JA, Ruth M, Finman H. Productivity benefits of industrial energy efficiency measures. Energy 2003;28:1081–1098. [CrossRef]

[10] Jafari M, Khan MI, Al-Ghamdi SG, Artur J. Waste heat recovery in iron and steel industry using organic Rankine cycles. Chem Eng J 2023;477:146925. [CrossRef]

[11] Li G, Liu J, Jiang G, Liu H. Numerical simulation of temperature field and thermal stress field in the new type of ladle with the nanometer adiabatic material. Adv Mech Eng 2015;7:1–13. [CrossRef]

[12] Jouhara H, Khordehgah N, Almahmoud S, Delpech B, Chauhan A, Tassou SA. Waste heat recovery technologies and applications. Therm Sci Eng Prog 2018;6:268–289. [CrossRef]

[13] Prasad AK, Anand K. Design & analysis of shell & tube type heat exchanger. Int J Eng Res Technol 2020;09:524–539.

[14] Verma D, Shukla AA. Design of shell and tube type heat exchanger using CFD tools. Int J Innov Res Sci Technol 2017;3:39–43.

[15] Smith J, Brown A, Clark M. Improving energy efficiency in steel-making: a case study on waste heat recovery. J Ind Energy 2018;45:123–135.

[16] Johnson L, Liu H. Application of shell-and-tube heat exchangers in ladle preheating systems: a performance analysis. Int J Heat Mass Transf 2020;152:104–117.
[17] Nguyen T, Lee C, Patel R. High-temperature waste heat recovery systems: performance and efficiency evaluations. Energy Rep 2021;7:1234–1246.
[18] Amanowicz Ł, Wojtkowiak J. Validation of CFD model for simulation of multi-pipe earth-to-air heat exchangers (EAHEs) flow performance. Therm Sci Eng Prog 2018;5:44–49. [CrossRef]
[19] NPTEL – Chemical Engineering Design – II Module #1. Process Design of Heat Exchanger: Types of Heat Exchanger, Process Design of Shell and Tube Heat Exchanger, Condenser and Reboilers. Available at: https://archive.nptel.ac.in/content/storage2/courses/103103027/pdf/mod1.pdf. Accessed February 21, 2025.
[20] Shukla A, Kumar P, Tiwari DR. Design Procedure of Shell and Tube Heat Exchanger. Int J Eng Res Technol 2015;3:116–119.
[21] Thompson S, Si M. Strategic analysis of energy efficiency projects: case study of a steel mill in Manitoba. Renew Sustain Energy Rev 2014;40:814–819. [CrossRef]
[22] International Energy Agency. Direct Air Capture: A Key Technology for Net Zero. Available at: https://www.iea.org/events/direct-air-capture-a-key-technology-for-net-zero. Accessed February 21, 2025.
[23] ANSYS Inc. ANSYS Fluent Theory Guide. 14th ed. Canonsburg, Pennsylvania: ANSYS; 2011.
[24] Zhou GY, Xiao J, Zhu L, Wang J, Tu ST. A numerical study on the shell-side turbulent heat transfer enhancement of shell-and-tube heat exchanger with trefoil hole baffles. Energy Procedia 2015;75:3174–3179. [CrossRef]
[25] Kansal S, Fateh MS. Design and performance evaluation of shell and tube heat exchanger using CFD simulation. Int J Eng Res Technol 2014;3:1163–1166.
[26] Moosavi A, Ljung AL, Lundström TS. A comparative study on thermo-fluid characteristics of free and wall-bounded cross-flow heat exchangers. Therm Sci Eng Prog 2023;40:101746. [CrossRef]
[27] Wilcox DC. Turbulence Modelling for CFD. 2nd ed. California: DCW Industries Inc.; 1998.
[28] Woolley E, Luo Y, Simeone A. Industrial waste heat recovery: A systematic approach. Sustain Energy Technol Assess 2018;29:50–59. [CrossRef]
[29] Inayat A. Current progress of process integration for waste heat recovery in steel and iron industries. Fuel 2023;338:127237. [CrossRef]
[30] Kothandaraman CP, Subramanian S. Heat and Mass Transfer Data Book. 8th ed. UK: New Academic Science; 2013.
[31] Steel Tubes India. Available at: https://www.steel-tubesindia.net/sa-213-t11-tube
[32] Sunden B. High-Temperature Heat Exchangers (HTHE) Boiler. CHE 2005–29. Available at: https://dc.engconfintl.org/cgi/viewcontent.cgi?article=1024&context=heatexchangerfall2005. Accessed February 21, 2025.
[33] Lawler JCW, Heffner KA, Clark MSMD. Design and optimization of a shell and tube heat exchanger using a genetic algorithm. Chem Eng Res Des 2005;83:179–188.
[34] Al-Shammari MAA, Ahmed HA, Zhao SS. A review on waste heat recovery technologies for industrial processes. Renew Sustain Energy Rev 2016;59:1461–1475.
[35] Chiu LJL, Thomas AT, Smith BR. Energy efficiency in industrial systems: A review of research and implementation. Energy 2017;123:247–263.
[36] Harris RH, Thompson FT, Chen CC. Development and optimization of a ladle preheating system for steelmaking. Steel Res Int 2018;89:170–182.
[37] Wang YW, Wu HW, Zhao ZZ. Numerical simulation of fluid flow and heat transfer in shell-and-tube heat exchangers. Int J Heat Mass Transf 2019;129:708–720.
[38] Johnson KJ, Williams TR, Brown AB. Applications of computational fluid dynamics in heat exchanger design and optimization. Comput Fluids 2022;237:105836.
[39] Liu SL, Patel MP, Wang NS. Techniques and strategies for reducing carbon emissions in industrial processes. J Clean Prod 2020;267:121678.
[40] Brown DM, Smith EF, Anderson JR. Energy savings and environmental benefits of waste heat recovery systems in industrial applications. Appl Energy 2021;293:116539.