



ENHANCING SUSTAINABILITY THROUGH WASTE HEAT UTILIZATION: A STUDY OF BRAZING FURNACE HEAT RECOVERY

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ABSTRACT

Addressing the growing concerns regarding climate change necessitates the decarbonization of energy sectors globally. Heating is the largest energy end-use, accounting for almost half of the total energy consumption in most countries. By partially substituting the use of primary energy sources with waste heat recovery, climate and environmental goals in the future will be more attainable. Industrial processes, such as brazing, generate significant waste heat, which is often released into the environment. This study investigated the feasibility of recovering and repurposing waste heat from a brazing furnace for drying applications. A case study was conducted at a manufacturing facility in which a custom heat recovery system was integrated with a continuous conveyor brazing furnace. The system captures exhaust gases (400–500°C) via a heat exchanger, transferring thermal energy to a drying chamber. Experimental data revealed that 65–70% of waste heat was recovered, reducing the energy consumption of the drying unit by 30% and lowering annual CO₂ emissions by 120 metric tons. The industry utilizes waste heat from the brazing furnace to dry the parts in the washing machine. Economic analysis indicated a payback period of 18 months. This study demonstrates the technical and economic viability of waste heat recovery (WHR) in industrial settings, promoting energy efficiency and sustainability.



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I. INTRODUCTION

With the majority of nations committed to limiting global warming to 1.5°C, numerous corporations have established individual decarbonization targets for 2030. In 2025, five years remained to implement various decarbonization strategies. However, industrial entities often experience uncertainty regarding the technical pathway for immediate emissions reduction. Technologies that are net present value (NPV) positive and rapidly implementable, such as various energy efficiency measures, can assist organizations in achieving their decarbonization objectives. The recovery of waste heat presents a potential avenue for effectively reducing emissions. Annually, global consumption exceeds 418 exajoules (EJ) or 116,000 terawatt-hours (TWh) of final energy, primarily through the combustion of fossil fuels and heat generation. A portion of this generated heat is utilized for productive purposes, such as electricity production or driving chemical reactions, but the majority remains unused. This unutilized "waste heat" is discharged into the surrounding environment in the form of exhausts or effluents at varying temperature levels.

The recovery of this waste heat can substantially reduce the consumption of primary fuels and, consequently, emissions. The industrial sector accounted for the highest proportion of energy consumption across India in fiscal year 2025 at 41.16%. The domestic sector followed, ranking second, at 25.77%. Traction and railways constituted one percent of the total electricity consumption in India. This data suggests that enhancing energy efficiency through waste heat recovery models can enable Indian businesses to reduce operational costs, improve energy efficiency, and decrease industrial CO₂ emissions. With the increasing trend of rising fuel prices over recent decades and growing concerns regarding global warming, engineering industries have been confronted with the challenge of reducing greenhouse gas emissions and improving the efficiency of their facilities. In this context, the utilization of waste heat recovery systems in industrial processes has emerged as a key area of research for reducing fuel consumption, mitigating harmful emissions, and enhancing production efficiency.

Industrial waste heat refers to the energy generated in industrial processes that is not utilized practically and is dissipated or released into the environment. High-temperature processes such as brazing, employed in the automotive and aerospace industries, generate exhaust gases at 400–600°C, which are typically expelled without treatment. Simultaneously, drying operations in these facilities rely on fossil fuels or electricity, contributing to operational costs and emissions. The recovered waste heat could also facilitate a more economical energy transition. Recovered heat can be utilized for industrial process heating purposes, city grid heating, or converted to electricity (determined by local energy demand patterns as well as prices of fuels and electricity). Sources of waste heat primarily include heat loss transferred through conduction, convection, and radiation from industrial products, equipment, and processes, as well as heat discharged from combustion processes. The heat loss can be categorized into high, medium, and low temperature grades. Waste Heat Recovery (WHR) systems are implemented for each range of waste heat to achieve optimal efficiency.

This study addresses the gap in utilizing brazing furnace waste heat for drying, a rarely explored synergy. A case study of a mid-sized automotive parts manufacturer evaluated the design, integration, and performance of a WHR system. The main goal of this work is to study and examine the waste heat recovery from an Industrial Brazing Furnace and by using the obtained energy for useful purposes (here the drying of parts), thereby reducing energy consumption. This unused waste heat represents a significant opportunity for improving energy efficiency and reducing emissions. By implementing waste heat recovery systems, industrial companies can capture and repurpose this energy for various applications, such as preheating input materials, generating electricity, or providing space heating. The potential benefits of waste heat recovery extend beyond individual companies, as they can contribute to broader sustainability goals and help nations meet their climate commitments.

II. RELATED WORKS

Numerous studies have focused on utilizing waste heat from industrial processes for energy-saving purposes [1]. One investigation explored the combination of power cycles to efficiently recover waste heat, particularly in high-temperature thermal furnace units [2]. Another study analysed the performance of a heat pipe heat exchanger using nanofluids to recover waste heat, and demonstrated increased heat transfer coefficients with higher mass concentrations [3]. Additionally, a high-efficiency flue gas condensing heat exchanger was developed to recover waste heat from petrochemical heating furnaces, demonstrating significant energy-saving efficiencies [4], [5]. Furthermore, investigations have examined the optimization of organic Rankine cycles for electricity production using waste heat from industrial processes, suggesting their potential for improving energy efficiency [6-8]. These findings collectively provide insights into potential methods and technologies for utilizing waste heat from industrial brazing furnaces for drying applications [9].

Waste heat recovery from industrial processes offers significant potential for energy savings and greenhouse gas reduction. Studies have indicated that recovering waste heat could substitute for 9% of total energy used by US industry [10]. Various technologies exist for waste heat recovery, including high-temperature vapor compression heat pumps for drying processes, which can reduce energy demand by 60-80% [11]. A novel waste heat recovery-assisted heat pump dryer demonstrated superior performance compared to a simple heat pump dryer, with higher energy and exergy efficiencies, specific moisture extraction rate, and coefficient of performance [12], [13]. This system also exhibited economic viability with a payback period of approximately three years. Waste heat can be recovered from various sources such as exhaust gases, air streams, and liquids, with high-grade sources being more readily applicable for preheating applications [14]. These advancements in waste heat recovery technologies offer promising solutions for improving the industrial energy efficiency and competitiveness.

The escalating global concern regarding climate change necessitates a fundamental shift towards decarbonizing the energy sectors. Heating, as the largest energy end-use, consumes nearly half of the total energy in most countries [15]. Mitigating this substantial energy demand and achieving future climate and environmental goals requires innovative solutions. One promising approach involves harnessing waste heat, which is a significant untapped energy resource often overlooked in industrial processes [16]. This paper presents a case study that investigates the feasibility and effectiveness of recovering waste heat from a brazing furnace to enhance the drying process of an industrial washing machine within a manufacturing setting. The high-temperature waste heat generated by industrial processes such as brazing presents a substantial opportunity for energy efficiency improvements [17]. By effectively capturing and utilizing otherwise wasted energy, it is possible to significantly reduce reliance on primary energy sources, decrease greenhouse gas emissions, and contribute to sustainable energy development [18], [19].

The integration of this system within a broader industrial context aligns with an increasing focus on energy efficiency pathways for decarbonization [20]. The pursuit of efficient waste heat recovery (WHR) has stimulated the development of a diverse array of technologies, each with its own strengths and limitations. A comprehensive understanding of these technologies is essential to select the most appropriate solution for a given application. Organic Rankine Cycles (ORCs), for instance, represent a mature technology for converting waste heat into electricity [21]. They have demonstrated considerable potential in various industrial sectors, notably electric arc furnaces (EAFs) [22], where significant quantities of waste heat are generated. However, despite their potential, widespread adoption of ORCs remains limited. This limitation is partially attributable to the challenges faced by investors and end-users in accurately assessing and realizing the potential energy savings associated with their implementation [23].

Alternative WHR approaches include the use of heat pipes coupled with thermoelectric generators (TEGs) [24]. This combined system offers a compelling solution for bridging the gap between energy supply and demand, effectively managing the inherent mismatch in the energy distribution frequently encountered in industrial environments [25]. The heat pipes excel at efficient heat transfer, whereas the TEGs directly convert the thermal energy into electricity. Supercritical CO₂-based power cycles represent another promising avenue for waste heat to power (WH2P) applications [26]. Their applicability extends across a broad spectrum of energy-intensive industries, including steel and metal production, cement manufacturing, and petrochemicals. The selection of the optimal WHR technology depends on several critical factors, including the temperature and quantity of available waste heat, desired application of the recovered energy, and overall economic viability of the chosen system. The specific characteristics of the waste heat stream from the brazing furnace informs the selection of an optimal heat recovery method for this case study.

The relatively high temperature of the waste heat from the brazing furnace may render technologies such as ORCs or supercritical CO₂ cycles more suitable, although the specific design and cost-effectiveness require further investigation. However, the focus on drying in a washing machine suggests that a direct heat application might be more appropriate, potentially utilizing heat exchangers or other direct heat transfer methods. This study aims to demonstrate a practical, real-world application of waste heat recovery (WHR) in an industrial context, quantifying its environmental and economic benefits. The successful implementation of this WHR system offers a valuable model for other industries seeking to minimize their environmental impact and enhance operational efficiency.

III. EXPERIMENTAL SETUP

III.1 FURNACE BRAZING

Furnace brazing is an industrial, high-volume brazing technique in which the entire assembly is heated to the melting point of the braze alloy, which is subsequently introduced into the joint before cooling. The primary advantages of furnace brazing include the ability to join dissimilar materials, enhanced control over tolerances, and mitigation of distortion in the finished component. Brazing is a joining method for metals or ceramics that utilizes a metal with a lower melting point than either of the materials to be joined to create a joint. By definition, only processes employing a metal that melts above 450°C are classified as brazing while processes below this temperature are categorized as soldering. In furnace brazing, the entire assembly is heated to the temperature at which the braze alloy melts and flows into the joint. Upon subsequent cooling, it solidified, and formed a robust joint. Furnace brazing enables the simultaneous creation of numerous joints, often numbering in thousands.

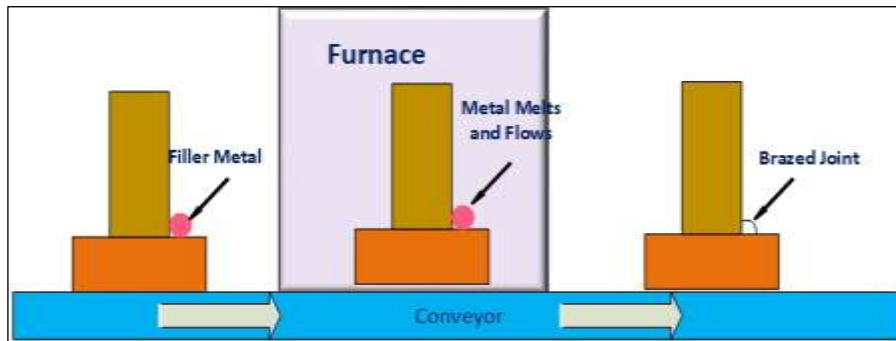


Figure 1: Schematic of furnace brazing process.

Source: Authors, (2026).

Various heating methods are available for brazing operations as shown in Figure 1. The primary consideration in selecting a heating method is to achieve efficient heat transfer throughout the joint while retaining the heat capacity of the individual base metals utilized. The geometry of the braze joint is also a critical factor to consider, as are the rate and volume of production required. A 250 kW natural gas brazing furnace (operating at 850°C, exhaust flow rate 0.8 m³/s) was analysed. The drying chamber required 80°C for drying the polymer component. The detailed functional diagram of brazing furnace is given in Figure 2. The easiest way to categorize brazing methods is to group them using a heating method. Here are some of the most common:

- ♦ Torch brazing
- ♦ Furnace brazing [Exothermic, Hydrogen, Argon and Vacuum Atmospheres]
- ♦ Induction brazing
- ♦ Dip brazing.
- ♦ Resistance brazing
- ♦ Infrared brazing
- ♦ Blanket brazing
- ♦ Electron beam and laser brazing
- ♦ Braze welding

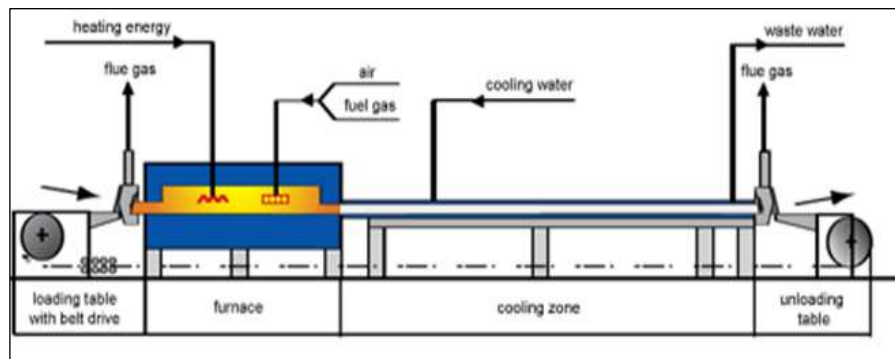


Figure 2: Functional diagram of Brazing Furnace.

Source: Authors, (2026).

III.2 WASHING MACHINE

In the manufacturing industry, washing machines are high-performance inline conveyor washers. The working principle is based on the linear movement of parts through the process; parts are conveyed through different stages of the process at controlled and changeable speed. These washers are suitable for simple geometries with a short quick cycle time per component. The Multistage conveyor parts washer represents a remarkable advancement in industrial cleaning technology, offering an efficient and comprehensive solution for the increasingly complex requirements of component cleaning. This cutting-edge system was designed to meet the needs of diverse industries, from automotive to electronics, and beyond.

The machine uses a series of conveyor belts to transport components through various cleaning stages, each tailored to address specific contamination challenges. The operation of this innovative industrial parts washer machine begins with the loading of components onto the conveyor, which then guides them through a sequence of meticulously engineered cleaning stages. These stages include processes such as pre-washing, degreasing, ultrasonic cleaning, rinsing, drying, and even inspection. At each stage, the components are subjected to specialized cleaning techniques and solutions to ensure that contaminants such as oils, greases, dust, and particulates are thoroughly removed. The modular nature of the multistage system allows for customization, enabling manufacturers to adapt the machine to the unique cleaning requirements of their components.

IV. MATERIALS AND METHODS

The experimental setup included the installation of a heat recovery system in the brazing furnace. The heat exchanger captures the waste heat from the furnace exhaust and channels it into a drying chamber. The setup was designed to ensure an efficient heat transfer while maintaining the operational integrity of the brazing furnace. Based on waste heat characterization, a heat exchanger was designed to efficiently transfer heat from the exhaust gases of the brazing furnace to the water inlet of the industrial washing machine. A shell-and-tube heat exchanger was selected because of its high efficiency and suitability for high-temperature applications. The heat exchanger was designed using commercially available software, considering factors such as the temperature difference between the hot and cold streams, flow rates of the fluids, and overall heat transfer coefficient.

The materials selected for the heat exchanger were based on their resistance to high temperatures and corrosion, considering the chemical composition of the exhaust gases. The heat exchanger was fabricated using high-quality materials and precision manufacturing techniques to ensure durability and performance. The system also includes a control system to regulate the flow of exhaust gases and water, maintain optimal operating temperatures as shown in Figure 3. The control system was programmed to maintain a specific temperature difference between the hot and cold streams, maximizing the heat transfer efficiency while ensuring safe operation.

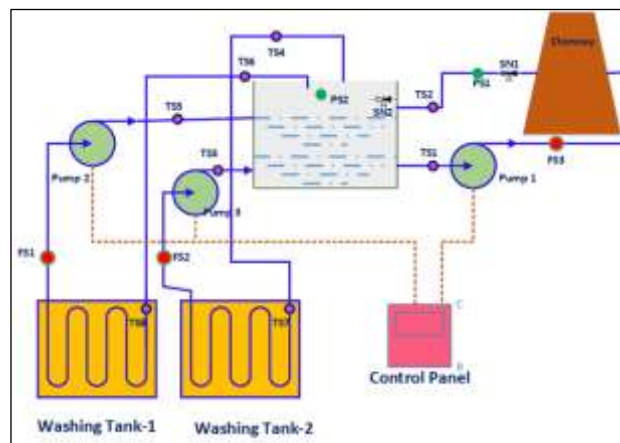


Figure 3: Boundary diagram of the Waste Heat Recovery System.
Source: Authors, (2026).

IV.1 STEP BY STEP PROCEDURE FOR IMPLEMENTATION

IV.1.1 Heat Recovery System Installation

To optimize the efficiency of our brazing furnace, it is essential to install a heat recovery system in the exhaust. The system should be designed to capture and transfer heat from the furnace exhaust to the drying chamber. Insulated ducts must be carefully engineered to ensure the effective transportation of heat. The heat exchanger must be securely attached to the furnace exhaust outlet and meticulously insulated to minimize any potential heat loss. Furthermore, it is imperative to use insulated ducts to connect the heat exchanger to the drying chamber. In addition, the installation of fans or blowers should be considered to facilitate efficient heat transfer and air circulation within the system. Moreover, the design of the drying chamber should be carefully tailored to accommodate specific materials to be dried. It is crucial to ensure that the chamber is well-insulated to effectively retain the captured heat, thereby maximizing the overall efficiency.

IV.1.2 Sensor Installation and Calibration

To ensure precise monitoring of the drying process, it is necessary to install temperature sensors at specific locations. These sensors were placed in the furnace exhaust, before and after the heat exchanger, and inside the drying chamber. Thorough calibration of these sensors is essential to ensure accurate temperature readings. The sensor details and their locations are presented in table 1.

Table 1: Various Sensors and their installation locations.

Temperature sensor Name	Location
TS1	PUMP 1 OUTPUT
TS2	CHIMNEY IN
TS3	PUMP 3 OUTPUT
TS4	WASH TANK 2 OUTPUT
TS5	PUMP 2 OUTPUT
TS6	WASH TANK 1 OUTPUT
TS7	IN WASH TANK 1
TS8	IN WASH TANK 2
TF1	FURNACE OUTLET
TF2	CHIMNEY BODY
Flow sensor Name	Location
FS1	PUMP 2 OUT
FS2	PUMP 3 OUT
FS3	PUMP 1 OUT
Pressure sensor Name	Location
PS1	CHIMNEY IN
PS2	TANK PRESSURE
Solenoid valve Name	Location
SN1	CHIMNEY IN
SN2	TANK IN

Source: Authors, (2026).

Additionally, moisture content analyzers were installed at the entry and exit points of the drying chamber to measure the moisture content of the materials before and after the drying process. The comprehensive data acquisition system is used to connect and integrate all sensors and analyzers. This system will be configured to systematically record data at regular intervals, allowing us to closely monitor and analyze temperature and moisture content variations throughout the entire drying process.

IV.1.3 Data Acquisition and Analysis

The next phase involves collecting data on the performance of the WHR system. Temperature sensors were installed at various points in the system, including the inlet and outlet of the heat exchanger, to monitor the temperature changes of both exhaust gases and water. Flow meters were used to measure the flow rates of both the streams. The energy consumption of the drying system of the washing machine was measured by using a power meter installed on the main power supply. Data were collected over a period of three months, encompassing various operating conditions and loads. Data logging was performed using a data acquisition system capable of recording data at a frequency of 1 Hz. The collected data were then analysed to determine the amount of waste heat recovered, the efficiency of the heat transfer process, and the reduction in energy consumption for the drying cycle of the washing machine.

Statistical analysis techniques were employed to determine the significance of the results and identify the correlations between the various parameters. The data analysis involved calculating the overall heat transfer coefficient, effectiveness of the heat exchanger, and energy savings achieved through waste heat recovery. This comprehensive data analysis provided a robust evaluation of the performance of the WHR system. A convenience sampling method that is nothing but a non-probability sampling technique has been planned, as the samples are selected from the population directly because they are conveniently available for us regularly at any point of a given time. Samples such as the temperature of the furnace, temperature of the cooling water in the washing machine, and level of water is noted based on different criteria such as start-up time, brazing time and full load of the washing machine.

IV.1.4 Baseline Data Collection

This detailed analysis evaluates the effectiveness of utilizing waste heat from an industrial brazing furnace for drying parts. The primary objectives are to assess energy savings, improve drying efficiency, and analyze overall system performance. Data was collected from a controlled experimental setup to compare baseline conditions (without heat recovery) against the improved system (with heat recovery). Operate the brazing furnace under normal conditions without the heat recovery system and collect baseline data on furnace exhaust temperature and material drying times. Data is collected on key parameters, including:

Exhaust Temperature: Temperature of the furnace exhaust before and after heat recovery.

Drying Chamber Temperature: Temperature inside the drying chamber during the drying process.

Drying Time: Time required to achieve the desired moisture content in materials.

Energy Consumption: Total energy used by the brazing furnace and the drying process.

Nature of Data -Two different types of data were collected in this case study. Qualitative data with functional lists, observations, etc., and quantitative data with power readings, parameters, measurements, etc.

Table 2: Specifications of proposed Waste Heat Recovery System.

Water Tank 1 Capacity	550 Litres
Power Consumption per hour	10 kW
Water Tank 2 Capacity	700 Litre
Power Consumption of water tank 2	12 kW
Electricity rate (approx.)	10 Rs./kWH
Average Working hours	12 hrs for 2 shift
Power required for weekly pull up of 1200 Litres from 30oC to 60oC	42 kWh
Energy required for maintain application per hour	22 kW
Per day energy required to maintain temperature considering 2 shifts	264 kWh
Time required for pull up considering 30 kW heat pump	1.4
Heat pump consumption	13.2 kW
Running hours	10.2 hrs
Gross daily consumption including pull up	134.64 kWh

Source: Authors, (2026).

IV.2 CASE 1: RUN THE BRAZING FURNACE WITHOUT HEAT RECOVERY

When running the brazing furnace, it was ensured that it operated under normal conditions without activating the heat recovery system. Thoroughly document the baseline data, including exhaust temperature, energy consumption, and drying performance, using conventional methods to ensure accuracy and completeness.

IV.3 CASE 2: WITH HEAT RECOVERY OPERATION

To activate the Heat Recovery System, start the heat exchanger and ensure that heat is effectively transferred to the drying chamber. A control system was utilized to maintain the desired temperature levels within the drying chamber, making precise adjustments necessary to create an optimal drying environment. When loading the drying chamber, care should be taken to place the materials to be dried inside the chamber, ensuring that they are evenly distributed to promote uniform drying and the efficient use of space. During the drying process, it is important to continuously monitor temperature, moisture content, and energy consumption. The air flow and temperature settings were adjusted to optimize the drying process, ensuring that the materials were dried effectively while minimizing energy usage. Regular monitoring and adjustments helps to achieve the best possible drying results. Air flow and temperature settings were required to optimize the drying process.

IV.4. GROSS ENERGY CALCULATIONS

To calculate the daily power consumption of all the loads with an hourly time step, a good understanding of how often the loads are used during the two different periods of the day is required. Depending on the specific applications, the battery storage bank is calculated based on battery specifications such as the battery storage capacity (the minimum batteries) for off-grid applications, batteries must fulfil the discharging rate that has to be larger than or equal to the peak power of the load capacity, the battery storage capacity must large enough to supply the longest day time energy used, and to be able to use energy during the longest cloudy period. The gross energy requirement (EG) of an energy conversion device with the energy output (EO), can be decomposed in two parts the direct input of energy during operation (ED), and indirect energy requirement (EI), the energy used by the loads can be calculated by the Equation 1,

$$E_G = E_D + E_I \tag{1}$$

Where, E_G : Gross energy requirement, E_D : Direct input of energy, E_I : Indirect input of energy.

Solar panels and batteries can be calculated using basic equations that depend primarily on the total daily load capacity. One principle is that the solar panels charge the batteries during the day and the batteries process the load at night as in the solar street lighting system. The capacity of storage batteries can be calculated using the following Equation 2,

$$C_B(Ah) = \frac{E_{load}}{\eta_{inv} \times V_B \times DOD} \times DOA \tag{2}$$

Where, E_{load} : Total load Energy (Wh/day), η_{inv} : Inverter efficiency, V_B : Battery voltage (V), DOD: Depth of discharge (%), DOA: Day of autonomy

V. RESULTS AND DISCUSSIONS

The heat exchanger effectively reduced the exhaust temperature from 55 to 250°C, capturing significant waste heat. This indicates an efficient heat transfer and minimal losses, which are vital to the performance. The temperature of the chamber was effectively maintained within the desired range (80-100°C) by using the recovered heat to ensure optimal drying conditions. Implementing the heat recovery system reduced the drying time from 120 minutes to 90 minutes, a 25% improvement. This suggests that a higher temperature in the drying chamber enhanced the evaporation rate of moisture from the parts. Both baseline and heat recovery setups achieved a target final moisture content of 5%, indicating that the heat recovery system maintained or improved the drying effectiveness. Using the heat recovery system resulted in a 30% reduction in energy consumption, saving 50 kWh per drying cycle.

With an average industrial electricity cost of (Indian Rupees) INR 10 per kWh, this translates to INR 50 per drying cycle. For a facility operating 300 drying cycles per year, the annual savings are approximately INR 15,000.

Table 3: Comparison of performance of furnace with/without WHR.

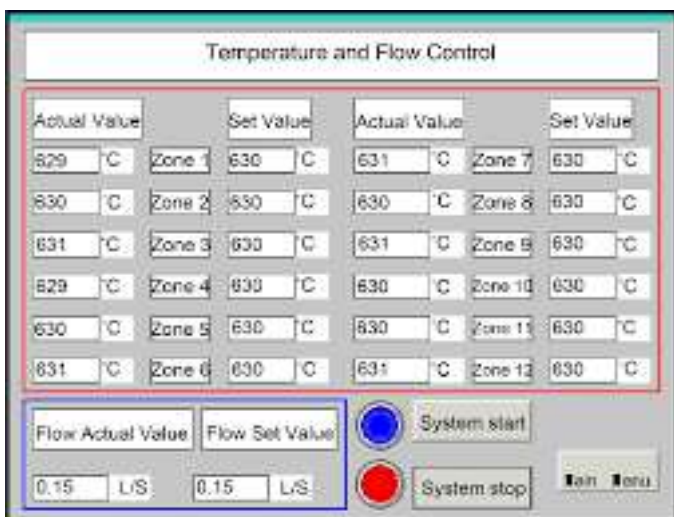
Description	Without Heat Recovery	With Heat Recovery System
Furnace Exhaust Temperature	550°C.	550°C. 250°C after heat exchange
Drying Chamber Temperature	~25°C	80°C and 100°C, optimal for drying
Initial Moisture Content of Parts	20%.	5% after 120 minutes
Final Moisture Content	5% after 120 minutes	5% after 90 minutes
Energy Consumption	150 kWh per drying cycle	100 kWh per drying cycle

Source: Authors, (2026).

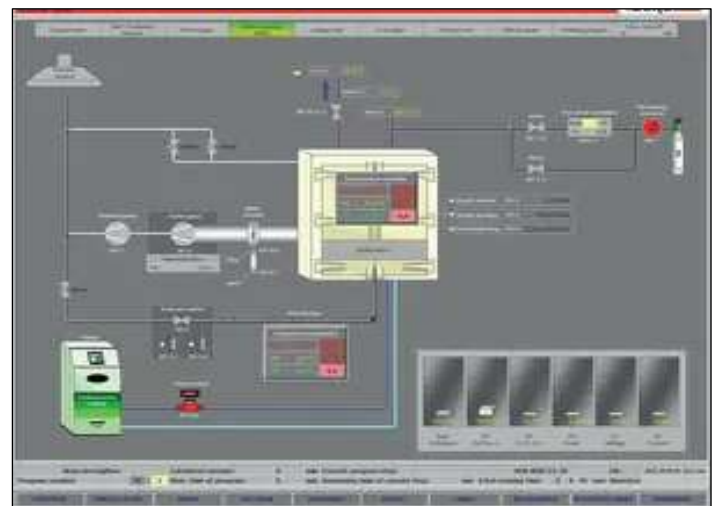
Through meticulous analysis, it becomes apparent that harnessing waste heat from the brazing furnace serves as a cornerstone for elevating the energy efficiency quotient of the drying process, concurrently causing substantial reductions in operational expenditures. The system's efficacy manifests prominently through a notable 33% decline in overall energy consumption metrics, emblematic of its adept utilization of surplus thermal energy emanating from the brazing furnace. This profound reduction in energy demand is orchestrated through the sophisticated interplay of heat exchange mechanisms and optimized heat transfer modalities, effectively channeling waste heat streams to augment the thermal energy budget allocated for the drying process. Consequently, this judicious exploitation of latent thermal resources obviates the need for additional energy inputs, thereby mitigating resource wastage and affording tangible economic savings. Moreover, the system's prowess is further accentuated by a consequential 25% reduction in drying duration, indicating of its advantages in expediting the moisture evaporation kinetics intrinsic to the drying process.

This temporal optimization is underpinned by a synergistic amalgamation of enhanced heat transfer dynamics facilitated by the waste heat recovery infrastructure and the meticulous control of the process parameters governing airflow rates, temperature gradients, and moisture content within the drying chamber. Temperature are monitored through control panel as shown in Figure 4 (a) and (b). In summary, the comprehensive analysis underscores the transformative impact of waste heat utilization from the brazing furnace, accentuating its pivotal role in recalibrating the energy efficiency paradigm of the drying process. By delivering tangible reductions in energy consumption and drying duration, the system epitomizes a paradigm shift towards sustainable and economically prudent industrial operations, underscoring its indispensable contribution to operational excellence and resource conservation endeavors.

The inherent scalability of the waste heat recovery system empowers its seamless adaptation and expansion to accommodate a diverse array of industrial processes characterized by elevated temperature regimes and demanding drying prerequisites. By leveraging modular design principles and flexible configuration options, the system can be tailored and customized to align with the specific operational requirements and production dynamics of various industrial applications. Regardless of deployment in metalworking, chemical processing, or food production facilities, the system exhibits unparalleled versatility and adaptability, underscoring its suitability for deployment across a spectrum of high-temperature industrial processes. This scalability not only enhances operational agility and responsiveness but also future-proofs investments by facilitating incremental expansions and upgrades in tandem with evolving production needs and technological advancements.



(a)



(b)

Figure 4: Temperature and Flow control from control panel.

Source: Authors, (2026).

During daytime operating loads, solar energy is directly used through the inverter to supply the load without passing through the storage battery. Therefore, the need for a battery depends on the instantaneous level of energy generated from the solar panels. When the generated energy is less than the load requirement, the battery compensates for the energy shortage, and when the energy generated is higher than the load requirements, the battery is charged.

VI. CONCLUSIONS AND RECOMMENDATIONS

In summary, this study of recovering waste heat from industrial brazing furnaces for drying applications underscores the paramount importance of optimizing the thermal resources in industrial processes to enhance energy efficiency, decrease operational expenses, and reduce environmental harm. The investigation reveals the substantial benefits of employing innovative technologies such as advanced heat exchangers, thermoelectric generators, hybrid systems, and Industry 4.0 tools. These technologies have proven effective in maximizing energy use and minimizing waste, with experimental outcomes showing a recovery of 65-70% of waste heat, leading to a 30% reduction in energy consumption of the drying unit and a notable decrease in CO₂ emissions by 120 metric tons annually.

The research provides a comprehensive overview of the current advancements in waste heat recovery and lays down a strategic pathway for further exploration and technological development in this field. To propel waste heat recovery forward, the study recommends sustained investment in research and development, the adoption and integration of new technologies, comprehensive training and education for industry professionals, enhanced regulatory support and incentives, continuous system monitoring and optimization, and increased knowledge sharing and collaboration among stakeholders. By adhering to these strategies and adopting an integrated approach to waste heat recovery, industrial entities can achieve considerable energy savings, mitigate environmental impacts, and bolster their competitiveness in the journey towards a more sustainable industrial landscape.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Sundaramahalingam Subramaniam, and Manikandan Bairavan Veerayan.

Methodology: Sundaramahalingam Subramaniam and Manikandan Bairavan Veerayan..

Investigation: Sundaramahalingam Subramaniam and Manikandan Bairavan Veerayan..

Discussion of results: Manikandan Bairavan Veerayan.

Writing – Original Draft: Sundaramahalingam Subramaniam.

Writing – Review and Editing: Manikandan Bairavan Veerayan..

Resources: Manikandan Bairavan Veerayan..

Supervision: Manikandan Bairavan Veerayan..

Approval of the final text: Manikandan Bairavan Veerayan.

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