Design and Development of an Energy-Efficient Oil-Fired Tilting Furnace with an Innovative Recuperator and Burner

Doctoral Thesis

by

"Prabhjot Singh"

(2015MEZ0016)

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY ROPAR

August, 2023

Design and Development of an Energy-Efficient Oil-Fired Tilting Furnace with an Innovative Recuperator and Burner

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Prabhjot Singh: *Design and Development of an Energy-Efficient Oil-Fired Tilting Furnace with an Innovative Recuperator and Burner*

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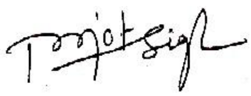

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Prabhjot Singh

Certificate

This is to certify that the thesis entitled **Design and Development of an Energy-Efficient Oil-Fired Tilting Furnace with an Innovative Recuperator and Burner**, submitted by **Prabhjot Singh (2015MEZ0016)** for the award of the degree of **Doctor of Philosophy** of Indian Institute of Technology Ropar, is a record of bonafide research work carried out under my (our) guidance and supervision. To the best of my knowledge and belief, the work presented in this thesis is original and has not been submitted, either in part or full, for the award of any other degree, diploma, fellowship, associateship or similar title of any university or institution.

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Lay Summary

The heat energy going to waste in the environment might be used efficiently to obtain maximum fuel combustion by using the proposed recuperator design. The application of hot air to the burner resulted in a considerable improvement in fuel oxidation. Moreover, the proposed recuperator reduced the furnace's exergy loss and enhanced thermal efficiency by 50%. The scientific research might fulfill the technological objective of minimizing the consumption of fuel without jeopardizing the furnace's functionality. Specific fuel consumption could indeed be successfully lowered through a recuperator since preheating the primary air resulted in efficient combustion and fuel savings. Because of the air and fuel preheating, a larger volume of metal may be melted with the same amount of input energy. Furthermore, the environmental considerations were adequately taken care of since the unique features of the developed recuperator resulted in efficient fuel combustion.

Abstract

During the melting of metals, it is reported that around 50% of the total energy is lost in flue gases. Therefore there is always a need to improve the efficiency of the furnaces. In the first phase of the thesis work, the design and development of an energy-efficient oil-fired tilting furnace with an innovative recuperator are reported. The internal hollow pipe of the proposed recuperator is so designed that at its exterior cylindrical surface, multiple turns of a guideway are welded in a spiral fashion. This increases the heat transfer between the flue gas and ambient air to the burner. The study shows that the efficiency of the oil-fired tilting furnace got enhanced by 50% after implementing the proposed recuperator. Specific fuel consumption without the recuperator was 0.166 kg/kWh, which was reduced to 0.138 kg /kWh with the recuperator. A channel for flue gases is provided in the developed furnace, which helps to divert hazardous gases away from the working environment. The second phase of the thesis work presents an experimental study to evaluate the influence of air swirl vane angles on pollutants in a heavy oil fuel-fired furnace with a recuperator. A novel burner system with a range of concentric air swirl generators (vane angles of 15°, 20°, 30°, 45°, 60°, and 90°) was ultimately incorporated to the combustion chamber of the furnace. This study examined the thermal efficiency and the polluting emission parameters of CO_2, HC, CO and NOx. According to the results, preheated air-fuel and air swirl generators with vane angles of 45° and 30° emit the least HC and CO, whereas air swirl vane angles of 90° emit the most. A preheated primary air swirl vane angle of 45° results in the lowest NOx emission (25 ppm) value. Furthermore, larger air swirl vane angles of 45° result in increased temperature, premixed combustion, and a rise in NOx emission. The results showed that when the temperature of the preheated primary and secondary air and heavy oil fuel combination increased, so did the mean effective temperature of the combustion gases.

Keywords: Heavy oil combustion, Air swirl burner, NOx emission, Swriler vane angle, Flame stability, Burner design, Crucible furnace, Recuperator

List of Publications from Thesis

Journal

1. **Prabhjot Singh**, Harpreet Singh and Anoop Kumar Singh, “Design and Development of an Energy-Efficient Oil-Fired Tilting Furnace with an Innovative Recuperator”. *International Jouranl of Metalcast*, vol. 16, pp. 1745–1757, Nov. 2021.

2. **Prabhjot Singh**, Harpreet Singh and Anoop Kumar Singh, “Experimental investigation on combustion characteristics of novel preheated air swirl burner operating on the heavy oil fired furnace for reducing NOx emission”, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 45:1, pp. 96-110, Jan 2023.

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Chapter 1
Introduction

The foundry sector has a significant effect on the economic growth of any nation since metal smelting is the first stage in a vast amount of subsequent metal shaping activities. It is the principal sector in the world and the products used in nearly every area of modern industrialized society. The casting industry is often responsible for the expansion of engineering industries. The Foundry is among the most significant production techniques for fabricating metallurgical components. Although castings are in high demand, industrialized nations are increasingly finding it difficult to fulfil the market[1]. Given strict environmental standards and a lack of trained labour seeking an improved workplace environment, only a few nations are well placed to take a large part of the global castings industry. To accommodate the rising foundry industry's labour demands, technical education institutes and academic institutions developed specialised degrees in this subject. Researchers from universities and associations focused much of their research on metal-casting technology's operational and related issues[2].

Furnaces are the fundamental building blocks of our industrial civilization and form the cornerstone of society. The primary goal of a furnace is to achieve a higher melting temperature than is possible in the open air. Although some operations might be performed in the open air, the efficiency would be significantly lower, the energy consumption would be much more significant, and the process management would be much more complex[3]. Applications such as melting contain a wide range of operating temperature that are governed in part by the metals getting heated and in part by the purpose of the thermal process and consequently processes. The highest furnace temperature in any heating operation is higher than the temperature at which the load will be heated[4].

This thesis explores the requirements and solutions for technological advancement and modernization in metal-casting production and engineering. Melting of ferrous and non-ferrous metals and their alloys are age-long practice. Methods of melting the metals were different in the initial years of casting, and there are continuous signs of progress in the process. Now a day, there is a burning demand for non-ferrous and their alloys in the market of almost every field of engineering. Hence different methods of melting non-ferrous alloys are in practice. The foundry and metal casting industries use a lot of energy. The energy cost contributes 10%–15% of a foundry's operational costs[5]. The furnace is the equipment used for metal casting. It has an essential role in engineering; about 80 % of work is involved in metal casting. As per the report of India Foundry Institute, 14% of total casting is used in automobile parts. Thus metal casting has a vital role in engineering[6]. It has been demonstrated that at least six significant examples of possible energy savings exist. These categories are as follows: (1) melting techniques, (2) power-factor control, (3) induction motor utilisation, (4) auxiliary equipment, (5) core ovens, and (6) air compressors. Because melting can account for 50% to 75% of total energy usage, it is critical to employ effectiveness and optimization measures[7].

1.1 Classification of Furnaces

In industrial furnaces heat is produced to elevate their temperature to a range slightly beyond the needed operational temperature, either by combustion of fuel or conversion of electric heating. Although fuel-fired furnaces are the most popular, electrically heated furnaces are utilized in situations where the benefits cannot forever be quantified in terms of fuel expenditure[8]. The type of fuel may influence furnace design in fuel-fired furnaces; however, this is not a significant issue with industry 4.0 furnaces and combustion technology. Additional categorization grounds may be related to the point at which combustion starts and the mechanisms for directing combustion results[9].
Furnaces are widely classed into two categories based on heat generation: combustion type (using any fuels) and Induction type. Depending on the kind of combustion, combustion-type furnaces are classified as oil-fired, coal-fired, or gas-fired. Moreover, furnaces are classed into two types based on the material charging mechanism: batch-type Intermittent or periodic furnaces and continuous furnaces. Another classification comprised based on waste heat recovery (WHR) mechanisms for instance regenerative and recuperative furnaces. Another type of furnace categorization is defined as the thermal transmission mechanism, charging mode, and heat recovery technique, as

reported in Figure 1. Furnace classification could be done according to the mode of heat transfer, load charging or heat recovery. According to the mode of heat transfer, it can be further classifying as an open fireplace furnace or heated through some medium like a coke bed. According to the charging mode, furnaces are classified as batch or continuous. Batch-type furnaces are used for forging, rolling or bailout purposes. Continuous-type furnaces are called crucible furnaces used in gravity die-casting or pressure die-casting[3].

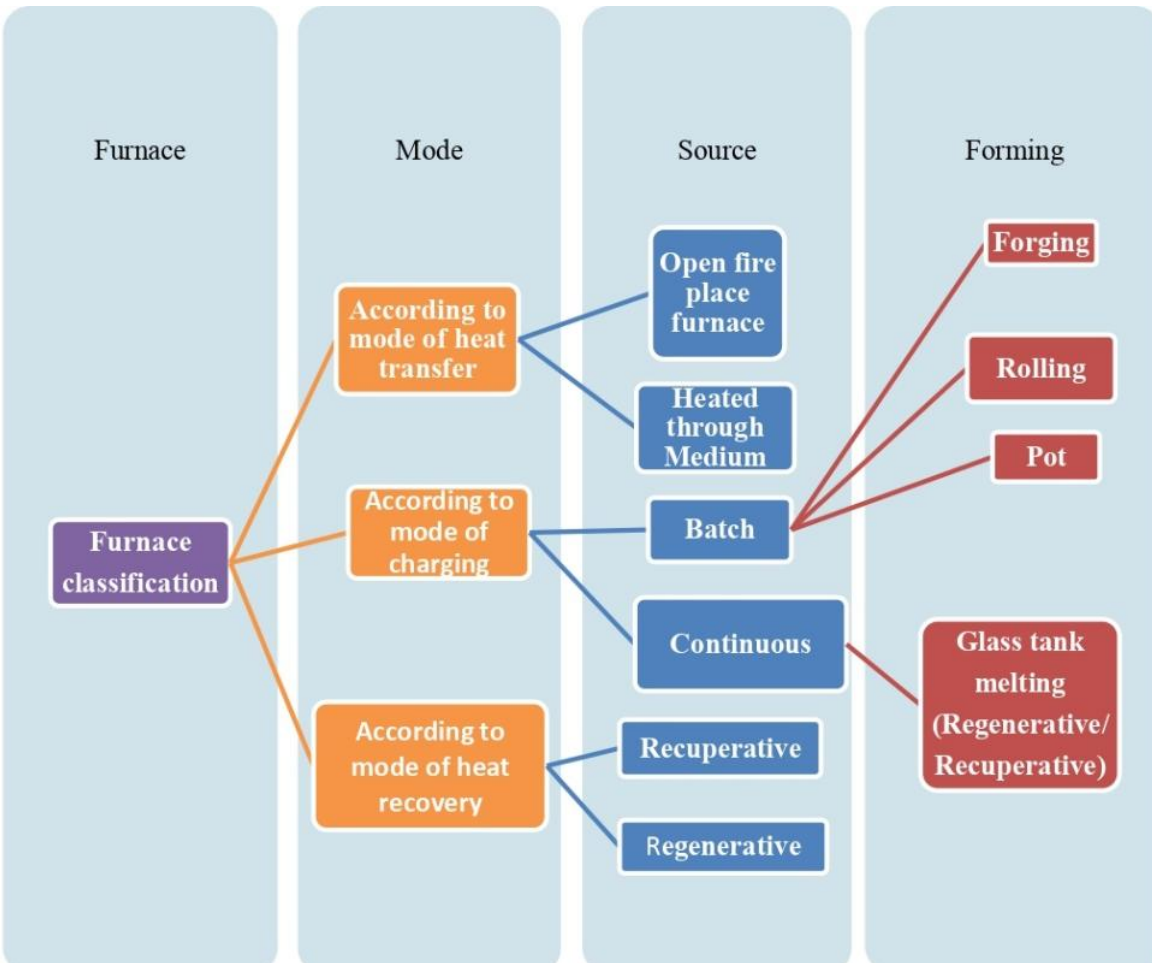


Figure 1.1 General Classification Of Furnaces, According To Mode Of Heat Transfer, Source And Forming[3]

1.2 Classification of Recuperator

A recuperator is a one-of-a-kind counter-flow heat recovery heat exchanger especially designed to recover waste heat commencing an air-handling system's supply automatically and exhaust airflow or process industry exhaust gases[10].

Many processes employ combustion to produce heat, and the recuperator is used to recover or reclaim that heat for reusing or recycling. The recuperators are also air-to-air, liquid-to-liquid or liquid-to-air counter-flow heat exchangers used for waste heat recovery(WHR) in the foundry, refinery and chemical sectors[11].

The recuperators are frequently placed in conjunction with the oil/gas burner section of a furnace or heat generator to improve overall efficiency. The recuperator may considerably enhance the efficiency of a furnace, heat engine or gas turbine by collecting part of the exergy that is habitually wasted as waste heat. Figure 1 depicts a recuperator for waste heat recovery from the exhaust. There are several varieties of recuperators, and the type preferred depends on the application[12].

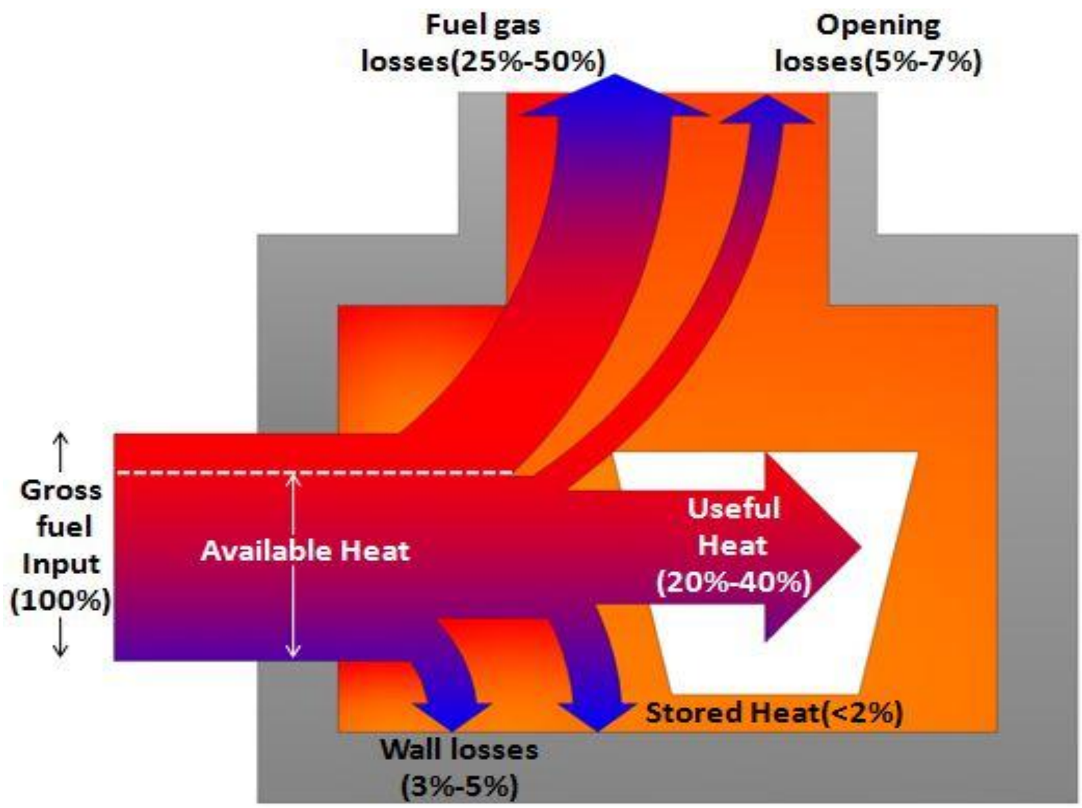


Figure 1.2 heat loss in an oil-fired furnace, illustrated by a sankey diagram[12]

1.2.1 Metallic Radiation type Recuperator

As illustrated in Figure 1.3, the metallic radiation recuperator is one of the simplest forms of a recuperator, consisting two concentric frames of metal tubing.

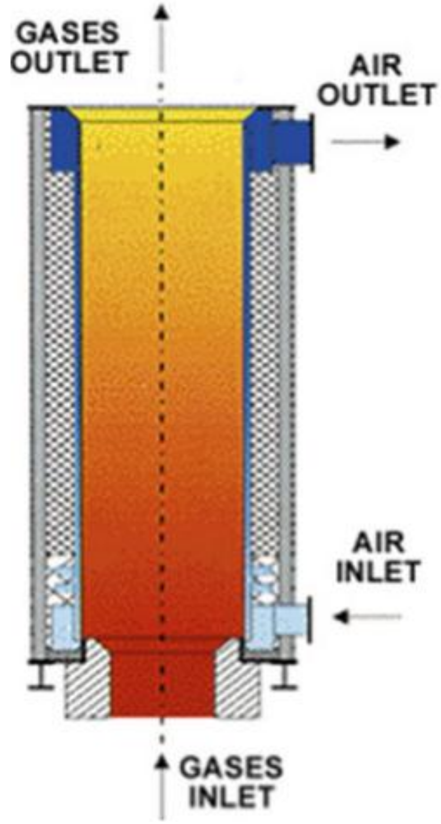


Figure 1.3 illustration of metallic radiation type recuperator in use[13]

The internal tube transports waste heat from exhaust or chimney, whereas the exterior annulus transports ambient air from the surrounding via burner to the furnace air inlet. The entering combustion air picks up waste heat from exhaust or chimney gases and carries more heat into the combustion compartment. This is the heat the fuel does not have to supply; as a result, a lesser amount of oil/fuel is used for a particular furnace raw material loading. Saving of fuel implies a reduction in air used in combustion, so losses from the stack are reduced by decreasing stack gas temperatures and releasing fewer emission gases[10].

The name radiation recuperator derives from the certainty that radiative heat transfer accounts for a significant amount of the heat energy convey from the hot air used in combustion to the exterior of the interior tube. However, because the ambient air in the annulus is apparent to thermal energy, convective heat transfer occurs with the entering air. The hot and the cold stream flows are typically parallel; as indicated in figure 1, the setup would be more straightforward, and the effective heat transfer could be achieved if the fluxes were in opposing directions. The motive for using the parallel flow of the streams is in such recuperators typically provide the added task of cooling down the stack pipe, removing exhaust gases, and increasing its overhaul life[13].

1.2.2 Convective Recuperator

The tube type or convective recuperator is a second typical recuperator form. The hot waste gases are conveyed from beginning to end in small-diameter parallel tubes, as shown in Figure 1.4 below. The inbound ambient or cold air to convey heat enters a shell that encircles the tube arrey and travels one or even more times in the plane perpendicular to their axes.

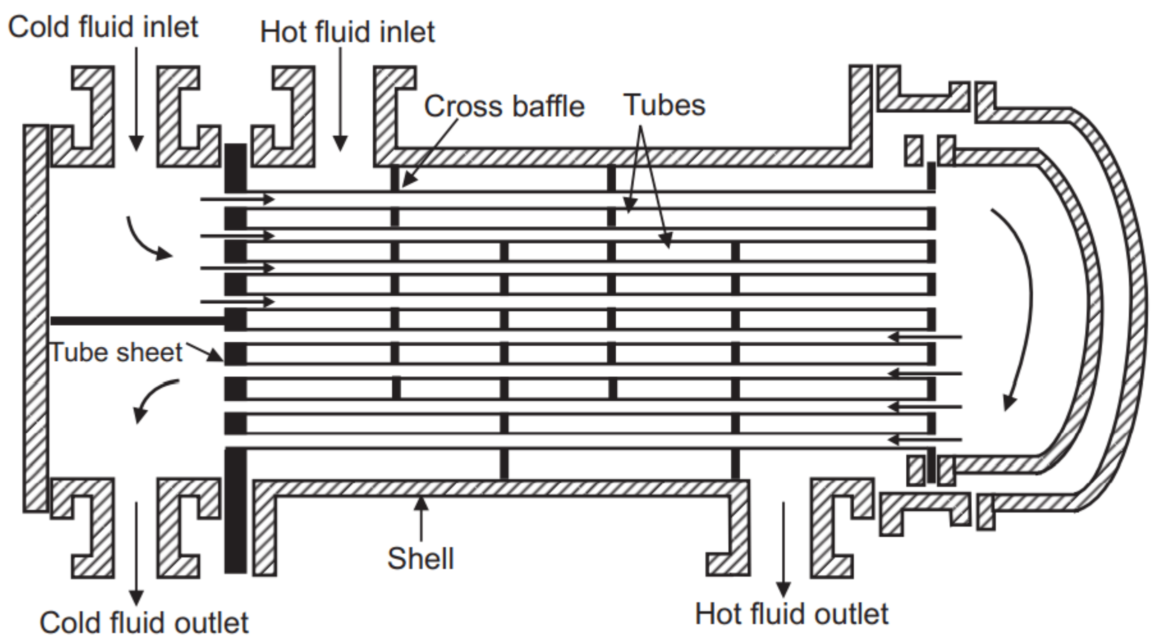


Figure 1.4 convective type recuperator with air flow representation [14]

If the parallel tubes are divided to enable the waste gases to go by over them repeatedly, the recuperator is referred to as a two-pass recuperator. If baffles in the recuperator are two, the recuperator is referred to as a three-pass recuperator, and so on[14].

1.2.3 Hybrid Recuperator

Hybrid recuperators are employed for optimal heat transfer efficiency. These are convective and radiation designs combined, with a high-temperature radiation part and a convective segment, as shown in Figure 1.5. These devices are much more costly than basic metallic radiation-type recuperators; however, they are smaller in size[15].

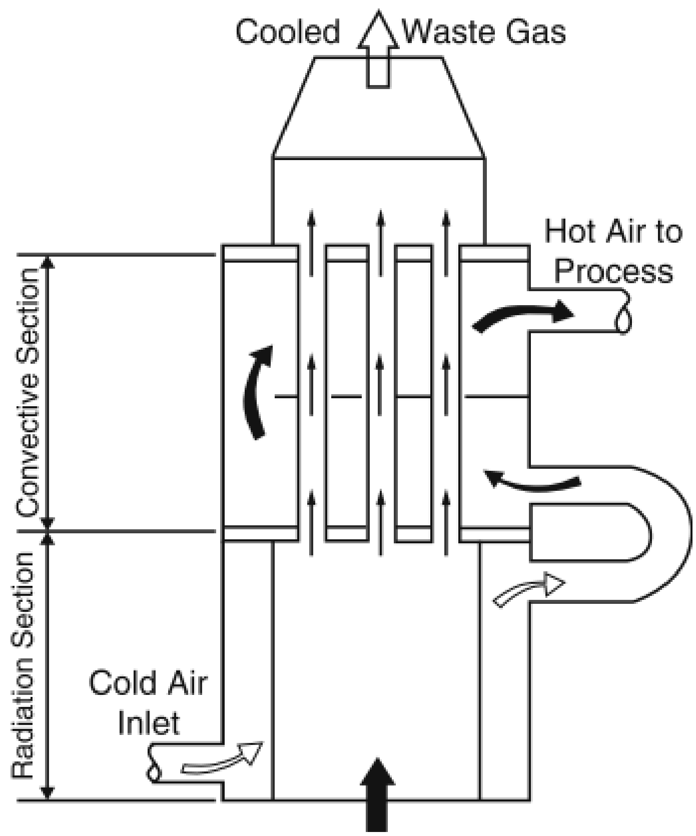


Figure 1.5 illustration of hybrid recuperator with sections of radiation and convective[15]

1.2.4 Ceramic Recuperator

The primary constraint of metallic recuperators' heat recovery is the shortened material life of the inside layer at intake temperature over 1100^{o}C. To resolve the temperature restrictions of of metallic recuperators, ceramic-coated tube recuperators with materials that allow function on the exhaust or chimney at 1500^{o}C and scheduled the pre-heated ambient air at 820^{o}C comparatively on practical basis have been developed, as shown in Figure 1.6. The repeated thermal cycling caused the breaking of welding joint and quick degradation of the tube lining in early ceramic-coated recuperators, which were made of refectory bricks and bonded with fire cement. Later advancements offered a variety of shorter silicon carbide tubing that may be linked by elastic seals positioned in the air pre-headers. Previous types of recuperators exhibited leakage rates ranging from 8% to 60%. The ceramic recuperators are said to survive not more than two years with pre-heated air temperatures reaching 700^{o}C and substantially lower leakage rates[16].

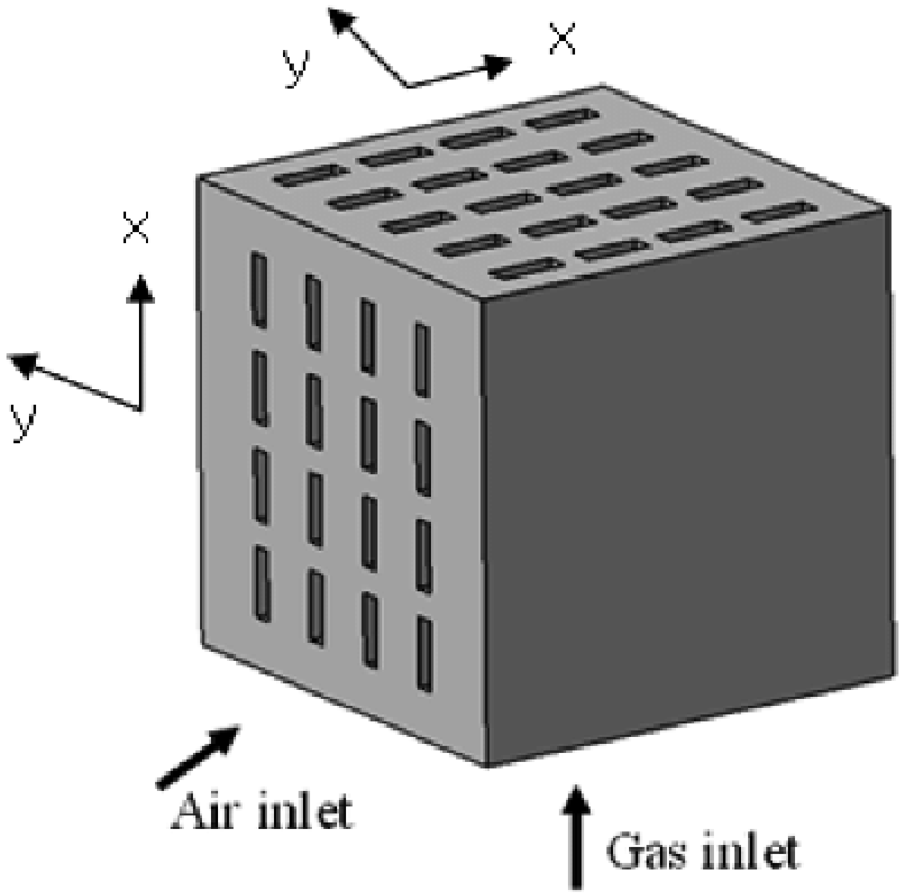


Figure 1.6 illustration of ceramic recuperator reprenting gas flow direction[16]

1.3 Limitations in present furnaces

The foundry sector significantly impacts any country's economy since metal casting is the first step in several subsequent metal-shaping processes. One of the most important production techniques for manufacturing metallic engineering components is foundry. Waste heat recovery is one of the essential areas for possible energy savings in current systems [1][6]. Waste heat recovery is important since reducing the amount of fuel used to create heat in a furnace enhances heating efficiency, which results in lower fuel consumption. This meets the need to boost efficiency while also lowering carbon emissions. It has been observed that continuously working in a hazardous environment, workers/operators are facing severe health issues. The worker/operator cannot work in such conditions for more than 5-6 years. A waste heat recovery unit in place can help to reduce hazardous gas generation by the complete combustion of fuel[17].

1.4 Review of previous work

In its India Vision 2040, the National Institution for Transforming India (NITI Aayog) of India wants to cut industrial energy use by 16%. The NITI Ambition Scenario (NAS) targets energy-efficient opportunities and advancements for Micro, Small & Medium Enterprises(MSME) sectors, which are critical to the predicted 8.1% GDP growth by 2040[18]. Carbon energy usage has become increasingly difficult owing to their ever-increasing expenses, which are exacerbated by their negative environmental consequences, the leading cause of climate change. One of the most severe difficulties is the consequences of climate change on human health[19]. According to reports, worldwide NO_2 and SO_2 emissions may be reduced by 54% and 58%, respectively, by enhancing the effectiveness of energy-generating systems, which could be improved by applying creative development and implementation[20].

India's CO_2 emissions from the commercial units is above the world average, showing possibilities for decarbonisation of the sector, mainly depending on the fossil fuel. India's energy need for the production zone (0.169 kgoe (kilogram(s) of oil equivalent)/$4.9p) is more than the world expected usage (0.139 kgoe/$4.9 p). Today's Indian more for every emission per capita (1.5 tonnes per capita [t/ca]) change with respect to China 36 years ago[21][22].

Several attempts have been made by researchers to create effective recuperators for furnaces. Above 800^{o}C, the principal mechanism of heat transmission from products of combustion to air in a recuperator is radiation. A recuperator's primary role is to minimise fuel consumption while dramatically increasing the efficiency of an industrial furnace[23][24][25]. This is accomplished by pre-heating the entering atmospheric air with the heat of the furnace's exhaust gases. Richard[26] solved the contamination problem by drawing waste exhaust gas via a comparatively larger tubes. Simultaneously, the ambient air was driven throughout a narrower distribution at high air velocity, with no chance of cracks, diversification of ambient air, or compromise of effectiveness.

White[27]recommended an additional circular space route to reduce the severe recuperator external heats. Jacobs[28] projected an unique recuperator concept with rib series to prevent bowing of the tubing objects. Schack[29] proposed a simple framework for overcoming the challenge without risk of failure even without sacrificing process efficiency. Seehausen[30] presented an intelligent design with greater strength at elevated temperatures that was simpler to build. Furthermore, the recuperator structure suffered significant distortion and damage owing to the high working temperatures. Jacobs[31] advocated sending ambient air prior to the entrance to an outer tube through a guide made up of vanes to boost the heat transfer rate. When functioning at the same load condition, previous recuperators were less efficient. Jouhara et al.[10] examined waste heat-recovery(WHR) systems such as Heat Recovery Steam Generator (HRSG), economizers, recuperative burners, regenerative burners, and Rotating cup atomizer (RCA) procedures to reduce the heat differential that drives heat flow from combustion products to ambient air.

1.5 Motivation and objectives

The overall objective is to enhance the efficiency of an fuel-fired furnace for a foundry. Researchers have made various efforts to create effective recuperators for furnaces. Radiation is the principal mechanism of heat transmission from burning hydrocarbons to air in a recuperator over 800^{o}C. A recuperator's key purpose is to lower fuel consumption while significantly increasing the efficiency of an industrial furnace. All of that is accomplished by pre-heating the entering atmospheric air utilizing heat contained in the exhaust gases escaping the furnace. Therefore, considering the above-discussed gaps in the literature, the objectives of the present thesis work have been decided as follows:

- To understand the furnace technology from the thermodynamic point of view.
- To propose a strategy to improve the thermal efficiency of an existing aluminium melting furnace.
- To design and develop a furnace with a recuperator to enhance thermal efficiency.
- To establish the parameters affecting the thermal efficiency of the developed furnace.

- To understand the role of optimized parameters on the furnace's thermal efficiency.

1.6 Organization of the thesis

The outline of the thesis is as follows:

1. **Chapter 1**, the discussion about the oil-fired tilting furnaces has been incorporated. Further, the importance of waste heat recovery systems has been discussed. Then, the generalized waste heat recovery procedure has been presented to cover the significance of both experimental and theory-based methods. The chapter further discusses the various waste heat recovery techniques for performance optimization and unknown parameter estimation with respect to available techniques. After that, the objectives of the present thesis have been presented.
2. **Chapter 2** reviews the evolution of oil-fired tilting furnaces have been incorporated. A brief background and motivation to carry out this research work are discussed. Moreover, a recent literature review shows various types of heat loss and limitations of oil-fired tilting furnaces analysis. An urgent need for an efficient heat recovery system for modern green foundry industries has been justified.
3. **Chapter 3** focuses on the development of an fuel-fired tilting furnace with a recuperator. The procedure begins with the crucible size of the oil-fired furnace, and the rest of the dimensions (furnace body size, stack height and hydraulic cylinder height) can be obtained accordingly. Design challenges and fabrication of helical spirals in novel recuperators have been discussed. A mechanism of data acquisition using thermocouples and flow meters at various reasonable locations within the system has been incorporated. Then discusses the testing methodology for determining thermal efficiency and specific fuel consumption of oil-fired tilting furnaces with recuperator technology. A direct comparison of oil-fired tilting furnaces with and without recuperators in the industry is reported. Incorporating a novel pre-heated primary air swirl burner improved the poor

dynamics. It provided a suitable homogeneous pre-heated air-fuel mixture to reduce NOx emission with different vane angles (15^o, 20^o, 30^o, 45^o, 60^o and 90^o).

4. In **Chapter 4**, results obtained from the study have been incorporated. The efficiency of the oil-fired furnace with and without the recuperator was found to be 11 % and 21 %, respectively. Moreover, the standalone furnace's specific fuel consumption was recorded at 0.166 kg/kWh, which was reduced to 0.138 kg/kWh after installing the designed recuperator. This means that a reduction of 10% in the specific fuel consumption could be achieved successfully with the recuperator in the furnace, which is a significant improvement. This improvement can be attributed to the availability of hot air, which pre-heats the incoming air supplied by the air blower.

   Further in this chapter, an on-site study was conducted todetermine the influence of pre-heated primary air swirling on polluting emissions (CO, HC, NOx, and CO_2) and flue gas temperature in a heavy oil-fired 250kg crucible furnace with a novel pre-heat swirl burner at different vane angles (15^o, 20^o, 30^o, 45^o, 60^o and 90^o).

5. **Chapter 5** summarized the all-relevant findings (conclusion) of this research work for a heavy oil-fired 250kg crucible furnace with a recuperator and a novel pre-heat swirl burner. Specific fuel consumption has been successfully reduced with the apllication of a recuperator, since pre-heating the primary air resulted in complete combustion and fuel savings. Because of the air and fuel pre-heating, a larger amount of metal has been melted with the same energy required. Furthermore, the environmental concerns were addressed adequately of, as the distinctive characteristics of the developed recuperator ensured excellent fuel combustion. In addition, suggestions for future scope related to a heavy oil-fired 250kg crucible furnace with a recuperator and a novel pre-heat swirl burner have been included.

Chapter 2
Literature Review

This chapter explores the history of melting furnaces regarding operating characteristics and constraints of fuel-fired furnaces. The majority of outstandingly-used waste heat recovery (WHR) methods and techniques developed to reinstate fuel-fired furnaces are discussed and examined. To complement the working of the waste heat recovery system, what kind of unique burner is required will be discussed in detail. Finally, the suggested technique, direct impact heating, is presented around its working principles, disadvantages, benefits, and past work.

2.1 Classification of Waste Heat

As quoted by S. Brückner et al.[8] “You cannot make an omelette without breaking eggs, and you cannot perform work without waste heat”. Waste heat is generated and emitted whenever items are manufactured, and equipment is run by heat, cooling fluid, or air, flue gases. Regardless of how these heat contributions are deemed lost, they usually contain considerable proportions of exergy and may be utilized to produce work using one of the various systems that recover waste temperature.

In this thesis, waste heat is defined as any type of heat (latent or sensible) which is not required by the arrangement. For instance, energy from collective power along with heating plants is not well thought-out waste heat. Waste temperature source in industry include furnaces, wastewater from drying, washing, or chilling operations, motors, refrigeration systems, and flue gases from industrial areas. When evaluating various solutions for using industrial flue gas prospective, it is crucial to determine the potential category, the hypothetical or physical potential, the technical potential or the economically feasible potential, as shown in Figure 2.1[8].

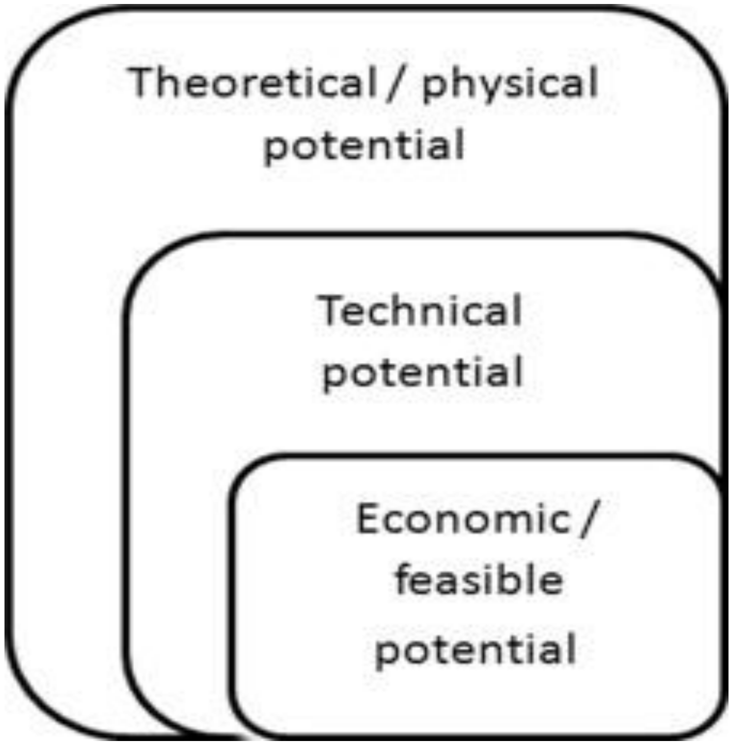


Figure 2.1 category of potential, graph based on S. Brückner et al.[8].

Byrnes et al.[31] elaborate on hypothetical potential, which simply considers practical limits: the temperature be required to be over surounding temperature, confined within a means, and so on. As a result, heat that is emitted determinant of behaviour, such as through radiation, is seldom measured. Furthermore, the opportunity of removing that heat out from transporter fluid or if it can be used is not explored. These limits characterize the technical potential. The technologies also determine the technological potential under consideration. One example of a practical limitation is the needed minimum temperature. The economic prospective, also known as the viable potential, is the single factor determining if it will be profitable to employ the technology.

A considerable quantity of surplus heat must be available in high-temperature flue gases or offshoot emissions. These gases contain corrosive elements and particles due to several processes, making them challenging to collect and reclaim as a source of energy. Blesli et al.[32] distinguish them via precision and propose three dissimilar technique for estimating waste heat prospective or heat requirement: a irregular method based on few geometric data, a medium accurate estimation based on more comprehensive literature facts and coefficients, and a high accuracy technique experimentally obtained data.

In principle, at hand are three aspects to consider when classify methods: the research size, the technique used to collect data (survey or estimation), and the method used to obtain the conclusion (top-down or bottom-up). The former is barely helpful for estimates, as assessments are always conducted from the bottom up. Figure 2.2 reviews the many ways of determining the industrialized waste heat potential.

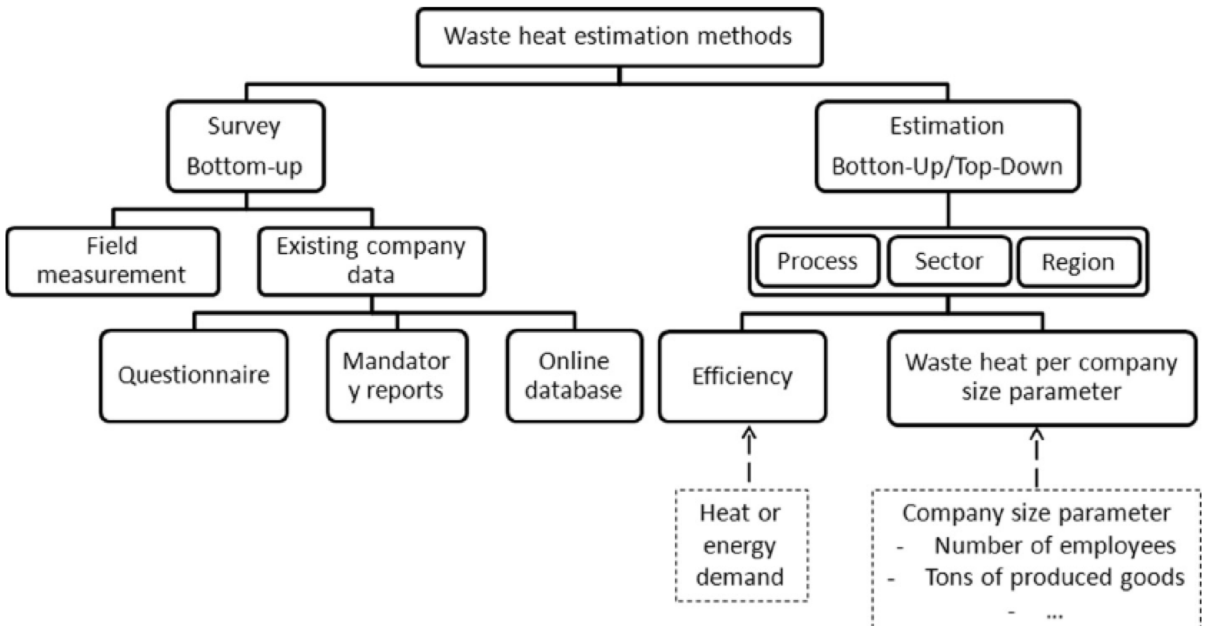


Figure 2.2 classification of different waste heat saving methods[33].

E. Woolley et al.[34] elaborate the necessity for energy efficiency improvements in manufacturing cannot be overstated. With Exports accounting for one-third of world energy consumption and the overconsumption of energy-rich hydrocarbon fuels, the future is projected to bring higher energy expenditures and both long- and short-term energy instability. It is not a favorable condition for industry, and an instantaneous reaction to this danger is essential. Manufacturers have two primary possibilities for lowering their dependence on fossil-based fuels while simultaneously minimizing environmental impact of their activities: utilize renewable resources or decrease energy usage. Renewable energy technologies are becoming more appealing as prices decrease, however they are not ideal for all places, and savings costs might still be exorbitant. Energy improvement and practice are predicated on the idea that power is never indeed consumed; it is just changed from individual form to another, so it is possible to catch it and utilize it as renewable energy, as shown in figure 2.3. This is greatest understood when examining the lifespan of energy inside a place, where power (usually flue gas) can be reclaimed closed loop or extended loop (reuse into a different approach). Consequently, recovered energy replaces a facility's requirement for a portion of its ultimate energy consumption.

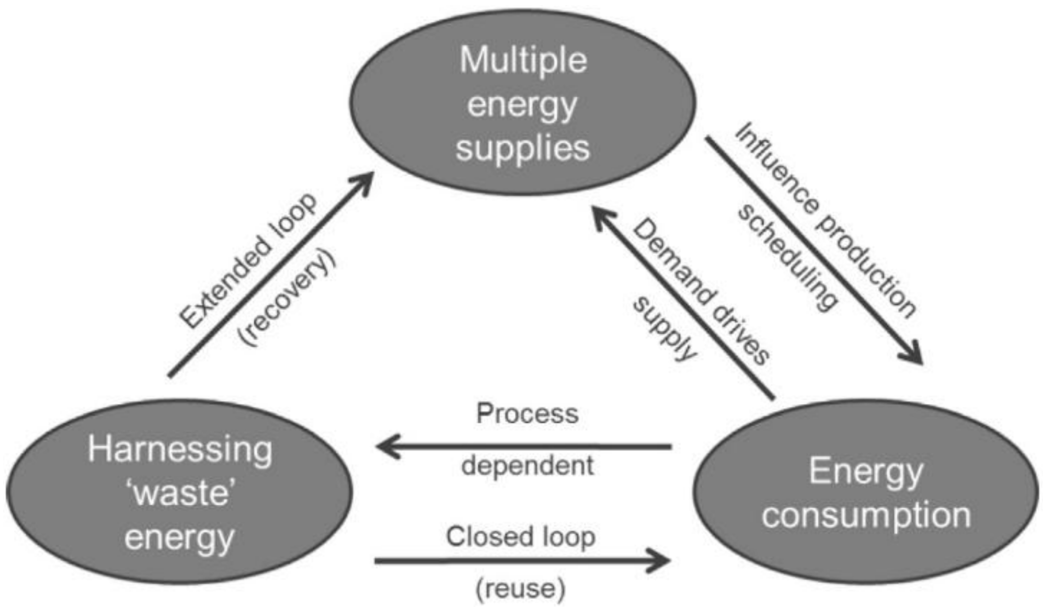


Figure 2.3 Energy life cycle at an industrial facility for waste heat recovering[34].

D. Chiaroni et al.[35] discussed energy effectiveness is sometimes eclipsed by financial competence, especially when making decisions in manufacturing settings. Actually, not all enhancements to energy efficiency are economically advantageous, but several power efficiency developments were implemented transversely a manufacturing plant, some of which be supposed to undoubtedly result in cost reserves within reasonable time frames.

2.2 Waste Heat Recovery Technologies

R. Weber et al.[36] discussed various technologies developed in industrial furnaces to increase thermal effectiveness and decrease the environmental contamination. They are as follows: optimal operation, reduced heat wastage, enhanced thermal effectiveness, and WHR from flue gases. In the case of continuous heating type furnaces, heat failure due to furnace body, waste heat, and cooling water can significantly reduce thermal efficiency. Reduced losses can assist in enhancing the thermal efficiency of the furnace. Reduced energy or hydrocarbon compounds in flue gases reduce pollution emissions and increase combustion efficiency for a clean and healthy environment.

H. Jouhara et al.[10] discussed that air preheaters are primarily used in low - to medium-temperature applications and on behalf of exhaust-to-air heat recovery. This technique is especially effective when process cross-contamination must be avoided. Exhaust from gas turbines and waste heat from furnaces, chillers, and steam boilers are two examples. Air pre-heating can be achieved using a plate or heating pipes. The flat plate type is made up of concentric cylinders that run vertically to the cold air entrance. Hot flue gas is injected into the channels between the plates, heating them and creating hot passages during which cold air is conveyed.

According to Nicholson[37], three types of air pre-heaters are regularly used along with classed as regenerators: run-around coils, rotary regenerators, and recuperator. These techniques all function on the similar principle as air heating systems, though they are designed uniquely and used for different purposes, as shown in figure 2.4.

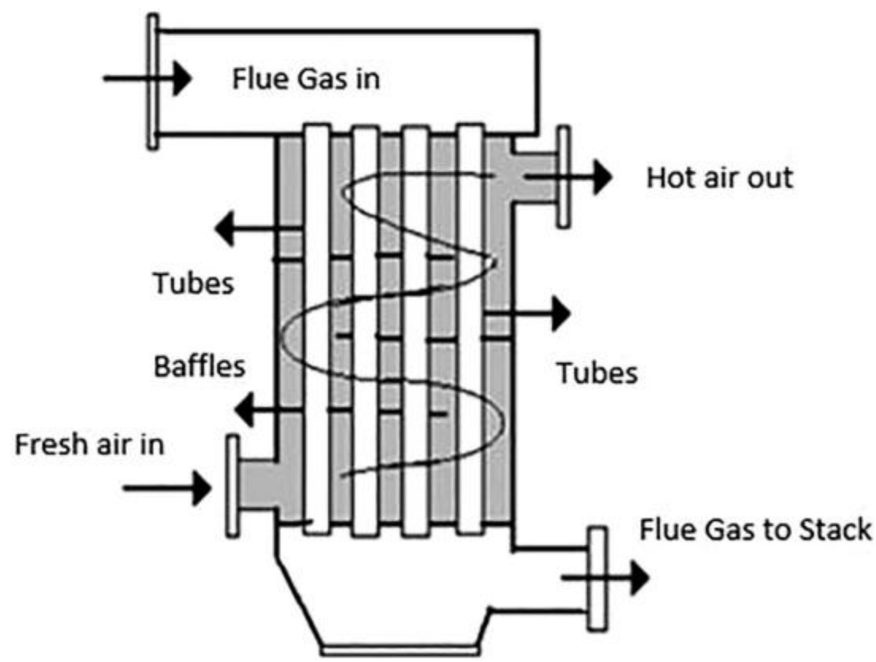


Figure 2.4 Illustration of air movement is seen in the layout of an air preheater[37].

2.2.1 Recuperators

Recuperators are heat exchanger devices that, depending on their use, are often composed of ceramic materials or metallic and are utilized to recapture waste flue gases at high to medium temperatures. The heated flue gases are routed via a network of metallic pipes otherwise ducts that convey the incoming air from the environment with this technique. As a result, the recuperation pre-heats the incoming gases, which are then returns to the arrangement. The power that is now accessible in the arrangement may thus be defined as power that does not need to be provided by the fuel, implying a reduction in energy requirement and manufacturing costs[38].

As reported by Bahman Zohuri[39] metal recuperators are employed in low to medium-temperature application, whilst ceramic recuperators are best suited for high-temperature applications. Recuperator transmits heat to the incoming gas principally by radiation, convection, or a mix of convection along with radiation, as shown in figure 2.5. A radiation type recuperator is made out of metal pipes that cover around the interior layer and allow hot flue gases to flow from beginning to end. The cold entering air is after that directed to the tubing around the heated rack, where energy is transmitted to the tube walls. The energy is transferred to the cold air through the tubes, which is subsequently given in the direction of the furnace burners.

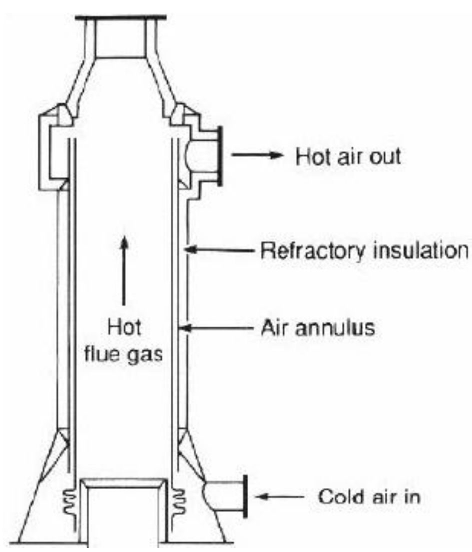


Figure 2.5 Illustration of Metallic recuperator diagram showing air movement [39]

The convective recuperator, on the other hand, heat is then transferred by circulating hot flue gases via comparably smaller diameter tubes arranged on an extensive layer. The cold air passes across the considerable frame, taking up high temperature from the waste gas-heated little hot pipes inside the rack.

D. Aquar et al. [22] discussed another option, as shown in figure 2.6, for increasing heat transfer efficacy is to use a mix of radiant and convective recuperators. Hot flue gas is pumped into an enormous layer and divided into minor diameter pipes. Ambient air is blown in to and about the frame, quantitatively improving heat transmission. Mixtures of radiation and convective designs are employed for maximal heat transfer efficacy, with the high-temperature radiation recuperator coming first, followed by the convection type. These are more costly than basic metallic radiation recuperators but are more compact.

P. Maghsoudi et al.[40] elaborate recuperators as single unit of the most efficient WHR systems for pre-heating the intake air of furnace combustors, decreasing fuel utilization and increasing the furnace total thermal efficiency. Even though using a recuperator with an efficiency of around 86% can enhance a power plant's total thermal efficiency by upto 35%, it in addition increases the total cost of plant by up to 40%.

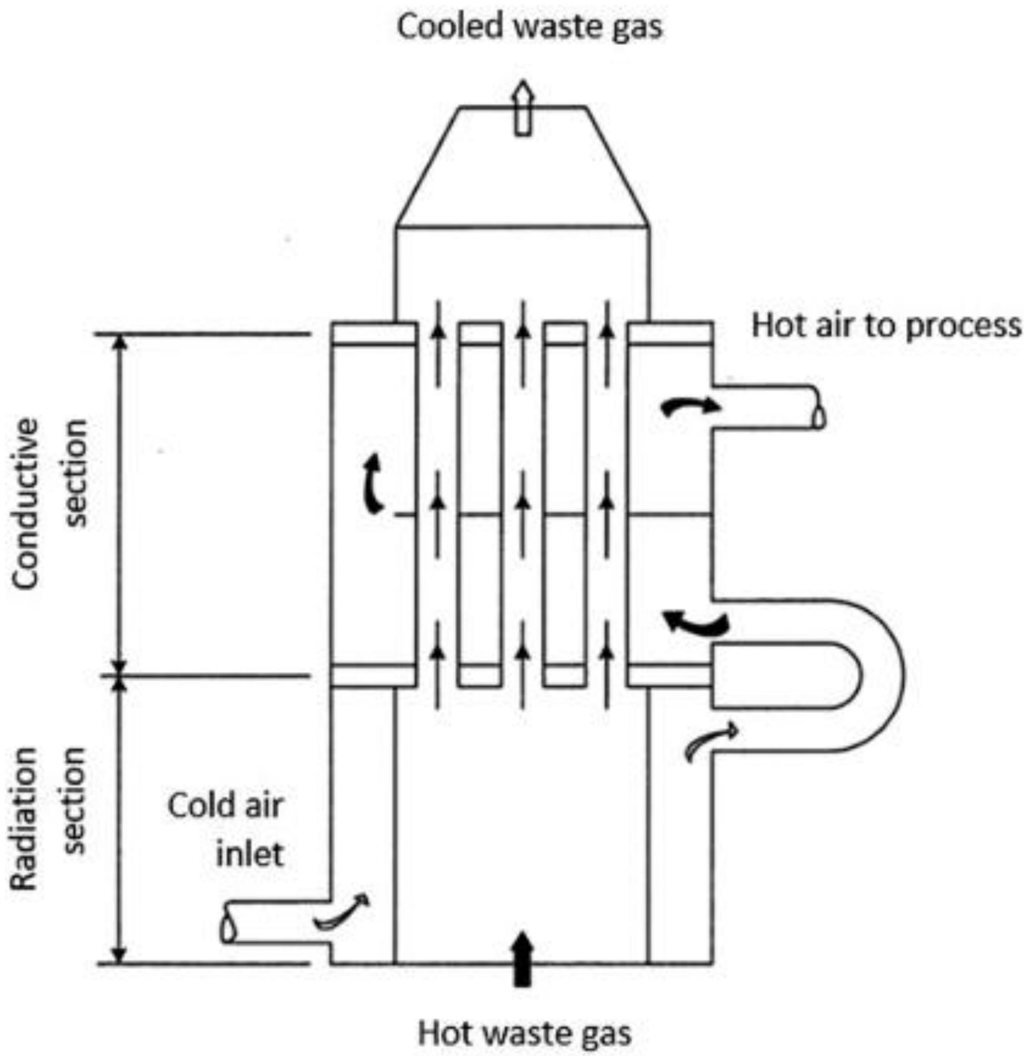


Figure 2.6 Illustration of mixed radiation and convection recuperator showing different sections[10]

In V. Karamarkovic et al.[41] study, the furnace shell (27.35% of the key energy) and flue gas (19.95%) were identified as the principal resource of heat losses in the conservation of energy of a tubular furnace using a magnesium production firm. A heatexchanger with the purpose of creates an outer channel over the carbonization region of the furnace serves to pre-heat burning air to reduce heat loss, as shown in figure 2.7. This approach is immediately usable, very lucrative, utilizes both convective as well as radiative loss of heat from the surface, and avoids overloading, which will not need air stiffness, and may be used in other furnace types with comparable surface temperature distribution. Using this technique, two opposing needs might be reconciled: one for insulating material and the other for reducing rotary furnace overheating. The offered approach can be employed in the furnace portion where the ambient temperature is the highest and exterior airflow is generally utilized to avoid overheating. The remainder of the kiln, generated by the flue gases, can be completely detached.

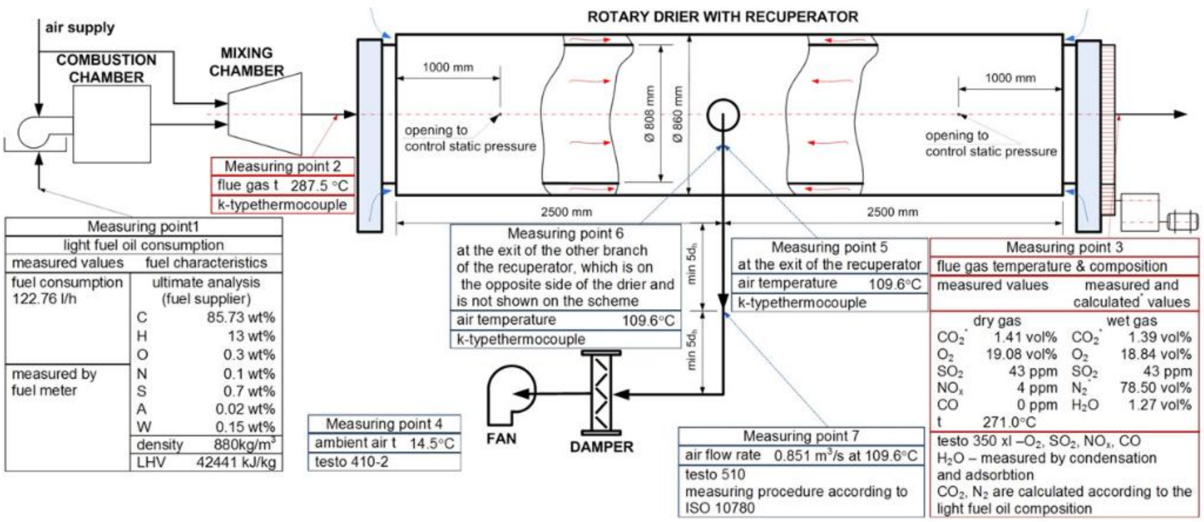


Figure 2.7 The experimental setup is depicted schematically, along with the results of the measurements[41].

A developed numerical form that allows the shape of the heat-exchanger to be created so that the convection from the furnace to the ignition air equals the heat emitted from the furnace. The exchanger significantly reduces fuel usage by 12.00% while increasing exergy and energy efficiency by 7.36% and 3.89%. To improve efficiency, the inflow and configuration of the exchangers must be set to offer the smallest possible temperature differential between the furnaces outside and the pre-heating flow, and extra air should always be maintained at the right value for the utilized fuel.

2.2.2 Regenerators

Regenerators transport thermal energy starting the hot gas channel to the cold gas channel by storing flue gas in a substance with a high temperature capability. The structure consists of a cavity that connects the hot air and cold air channels, accumulating and delivering heat force from the hot side to the cold side. For example, regenerator furnaces are made up of two ceramic chambers that exchange heat between hotside and coldside air. When hot burning gases travel during the concrete block chamber, high temperature from the hot flue gas is received, stored, and transferred to the cold side airflow[42].

The regenerative concept was initially invented and used in the construction of steam engines by the brilliant inventor William Siemens[43]. Still, it was eventually abandoned due to the heavy wear on the cylinders caused by the high temperatures. Siemens created his first investigational furnace in 1858, complete with regenerator to raise the heating air temperature and so attain greater flame temperatures. He started and developed the first workable gas-fired (propane) regenerative boiler for melting glass two years later, as shown in figure 2.8.

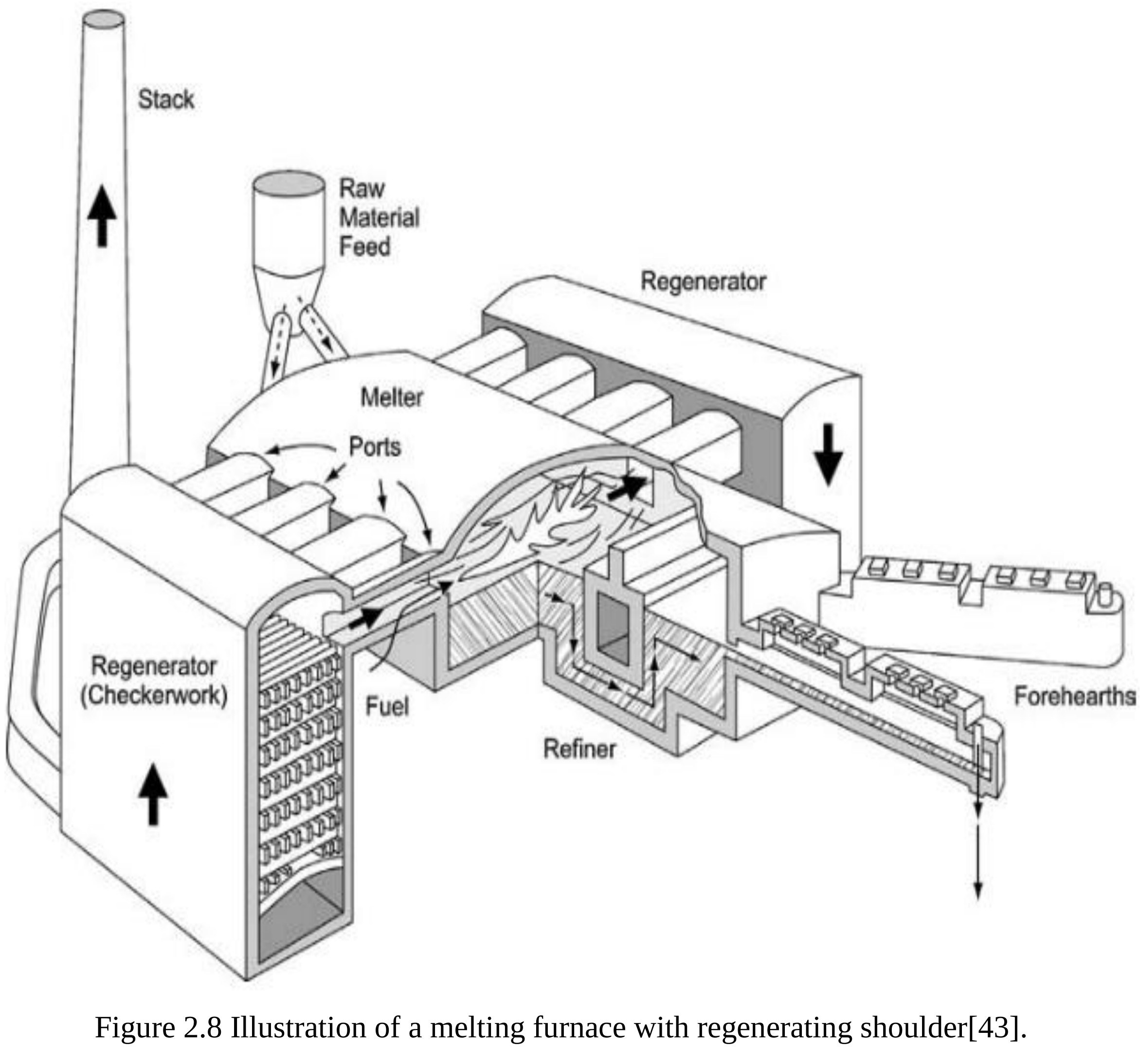


Figure 2.8 Illustration of a melting furnace with regenerating shoulder[43].

K. Tapasa et al.[44] discuss a cylinder furnace's exhaust gas that goes to the regenerator, at which heat in the combustion process is recovered to the fuel-air mixture. For case in point, if the heat of the exhaust is 1350-1450°C, the heat of the fuel-air mixture will be raised to 1100-1200°C. This increases the combustion's thermal efficiency. The cooled (400-500°C) flue gas travels to the atmosphere via the stack. The mixture is melted into glass in the mixing chamber at heat varying from 1350° C to 1550° C. The fraction of the high temperature utilized within the furnace, or the supposed "heat balance," must be recognized as a framework for structure improvement to build up the metal melting furnace efficiency discussion programme. The heat balance is also utilized to keep track of current waste heat and effectiveness in the glass-melting furnace.

Charles E. Baukal, Jr.[45] elaborates two basic strategies, which are largely determined by the higher temperature potential of the facility: the considerably smaller facility in which the burner and the regenerative attach the similar covering and the regenerator has a parallel passageway and the significantly larger entity that uses the burner has a similar composition to a standard hot air burner and yet is attached to a regenerator with the horizontally exhaust stream through the regenerative medium as shown in figure 2.9. To distinguish between the two sorts, the writers will employ terminology that one of them heard initially in Asia to explain them: "one-box" and "two-box," correspondingly.

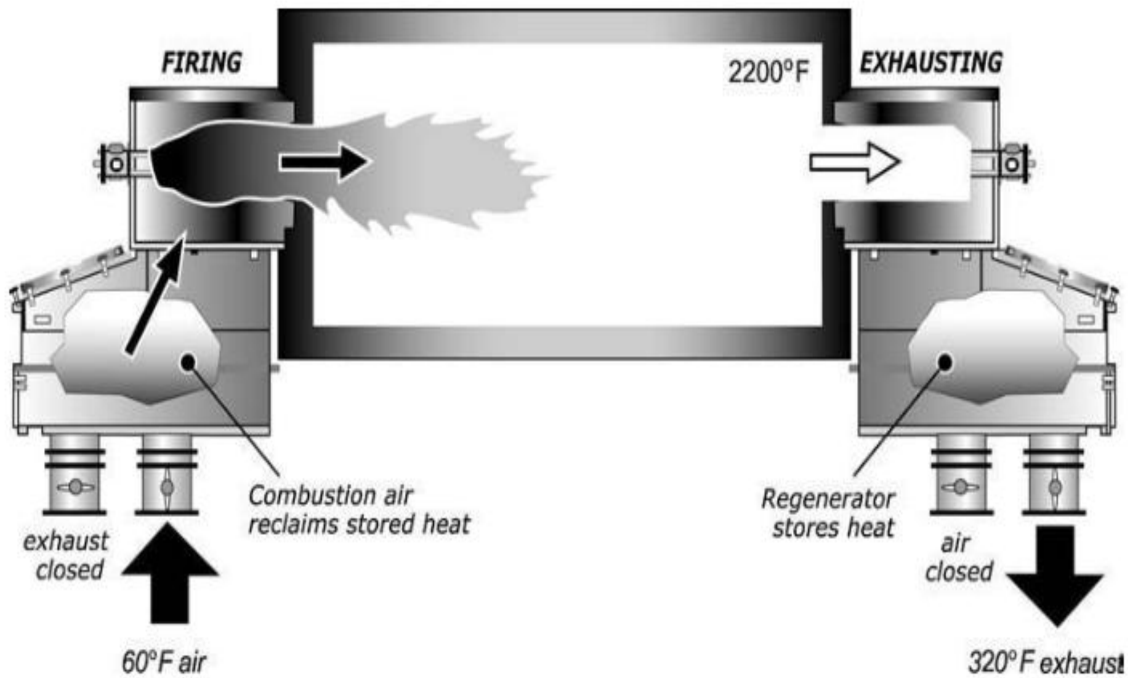


Figure 2.9 Illustration of operation of a regenerative burner for aluminum melting [45].

2.2.3 Shell-And-Tube Type Heat Exchanger

They are undoubtedly the majority widely utilized basic heat-exchanger arrangement in manufacturing operations in their numerous construction variants. The shell-and-tube type heat exchanger has relatively considerable higher heat transfer area-to-volume and weight ratios, as shown in figure 2.10. It provides this surface in a very simple shape that may be built in a variety of sizes. It is mechanically strong enough to withstand regular fabrication shop pressures, transportation, and field construction loads. and internal and external stresses experienced under normal operating circumstances[46].

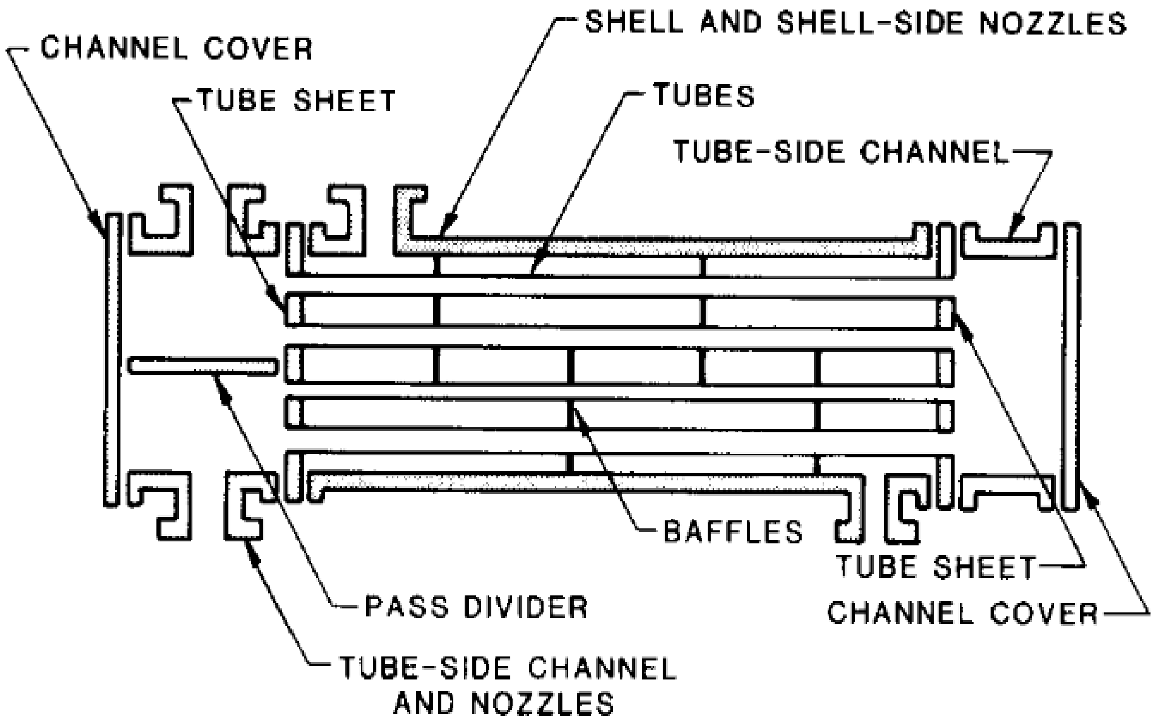


Figure 2.10 a standard (fixed-tubesheet) shell-and-tube type heat exchanger is illustrated[46].

D. Aquaro et al.[22] explain the shell-and-tube category exchanger as simple to clean, and the most prone to failure components-gaskets and tubes can be changed. This type's special construction features enable it to meet practically every imaginable function, including exceptional extremes of temperature and pressures, enormous temperature differences, vaporizing and condensed operations, and intensely polluting and corrosive fluids. Creative design approaches are accessible, as are the skills and shop facilities required for practical design and production.

Q. Wang et al.[47] explains shell-and-tube type heat exchanger is normally made out of a pair of round pipes put in a spherical tank with the pipe alignment running parallel to the shells. One fluid travels through the tubes, whilst others flow transversely them. For the reasons stated above, the conventional shell-and-tube type heat exchanger seems to have more than 45% of the contribute to the market in procedure and petroleum industry heat exchangers: its versatility in dealing with a wide range of system parameters through a variety of objects, engineering practice of approximately 110 years, demonstrated planed techniques, and installation of the system with codes and standards.

2.3 Low-Temperature Waste Heat Utilization Opportunities and Challenges

Having said that, Haddad et al.[48] proved with the purpose of there are several chances for converting flue gas in the small-temperature collection as the majority waste materials temperature falls into this group, as shown in figure 2.11. Nonetheless, the recovery process of low-temperature waste heat is further complicated than recuperating medium to high-temperature as a waste heat. The main factor on behalf of this is primarily due to issues linked with collecting waste heat. Water vapour, for example, is present in lower-temperature flue gas and is designed to cool, interact with other molecules, and precipitate harmful compounds on heat exchanger plates.

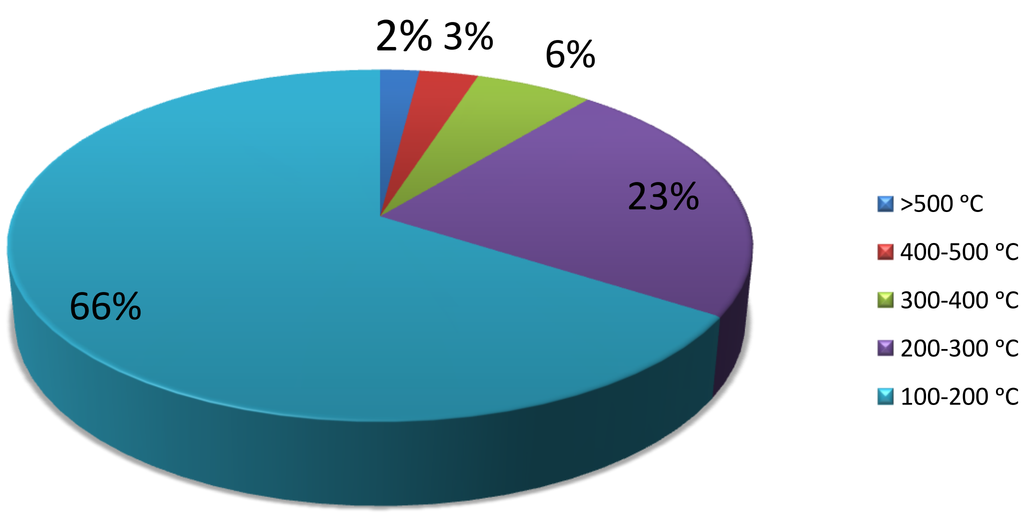


Figure 2.11 Classification of low-temperature groups with percent representation[48].

Azad et al.[49] proposed that the thickness of the pipe fluctuates along the heat-exchanger, increasing the thermal effectiveness and reducing the pressure loss. The heat-exchanger spacing is divided into segments for this purpose, such that the tube diameter in every segment is different from those of the further segmented tubes. The diameter of the pipes fluctuates anywhere beside the heat exchanger, from small to large. By enhancing the thermal effectiveness and minimizing pressure drop in the heat exchanger, the correct length for each segment reduces investment (for heated surface) and operational costs (for fluid pumping). Cooling flue gases towards dew point temperatures is a method of heat recovery low-temperature waste heat. The vapour pressure is when a wet fuel-air mixture starts to condense or become saturated and when it is cooled on a steady pressure.

E. Tian et al.[50] proposed the overall expenditure of the heat transfer device is the target utility of an engineer. The overall cost comprises the rate of the heat transfer region as well as operational costs, such as pumping expenditures incurred to compensate for rapid depressurization inside the heat exchanger. Preceding capital and operational expenses are reduced by decreasing and expanding the diameter accordingly. Reducing the heat exchanger's length reduces operating (pumping) and capital expenditures.

2.4. Fuel-Fired Industrial Melting Furnaces

With 8% of the world's soil and rocks made of aluminium, it is the third most common metal in the planet's crust. Aluminum only appears in nature in organic substances with other elements like silicon, sulphur, and oxygen. Only aluminium oxide ore can be profitably used to make pure, metallic aluminium (bauxite). Metallic aluminium is beneficial in various applications due to its various characteristics. It is nontoxic, nonmagnetic, lightweight, and robust. It reflects light and heat while transferring both. It is sturdy but manageable and maintains its strength at freezing temperatures without cracking[51]. Aluminium goods have been utilized primarily in the following industries worldwide: building (25%), transportation (23%), electrical (12%), manufacturing and equipment (11), packaging (8%) and consumer items (6%)[52].

In industrial and commercial applications, heating furnaces are insulated structures that distribute heat to loads (raw material) for various thermal processing techniques. Melting of ferrous metals necessitates exceptionally high temperatures and potentially erosive and corrosive conditions accrued[11]. Furnace technology entails thoroughly examining solid, liquid, and gaseous materials and constructing furnaces and other heat-utilization systems. The efficiency of user processes must be studied to compare the economics of different heat sources. Furnaces that use the same or different fuels can be reached, as well as the theoretical thermodynamic heat needed for the operation[53]. Various computations must be performed to arrive at practice efficiency. Thus, the accessible heat in fuels (calorific values), the rate of combustion, and the product of these two, calorific intensity, must be established to assess if enough heat of the needed passion is theoretically available in the fuel[54].

According to W. Trinks et al.[4], in fuel-fired type furnaces, the fuel type may affect furnace design, although this is not a significant issue with industry furnaces and burners, mainly where solid fuels are used, as shown in figure 2.12. Air heaters, industrial oxygen boilers, and atmosphere furnaces have similar categorization systems. Related categorization grounds include the arrangement in the furnace where ignition begins and the mechanisms for directing combustion by-products, such as internal fan ovens, high-velocity heating systems, even baffled furnaces.

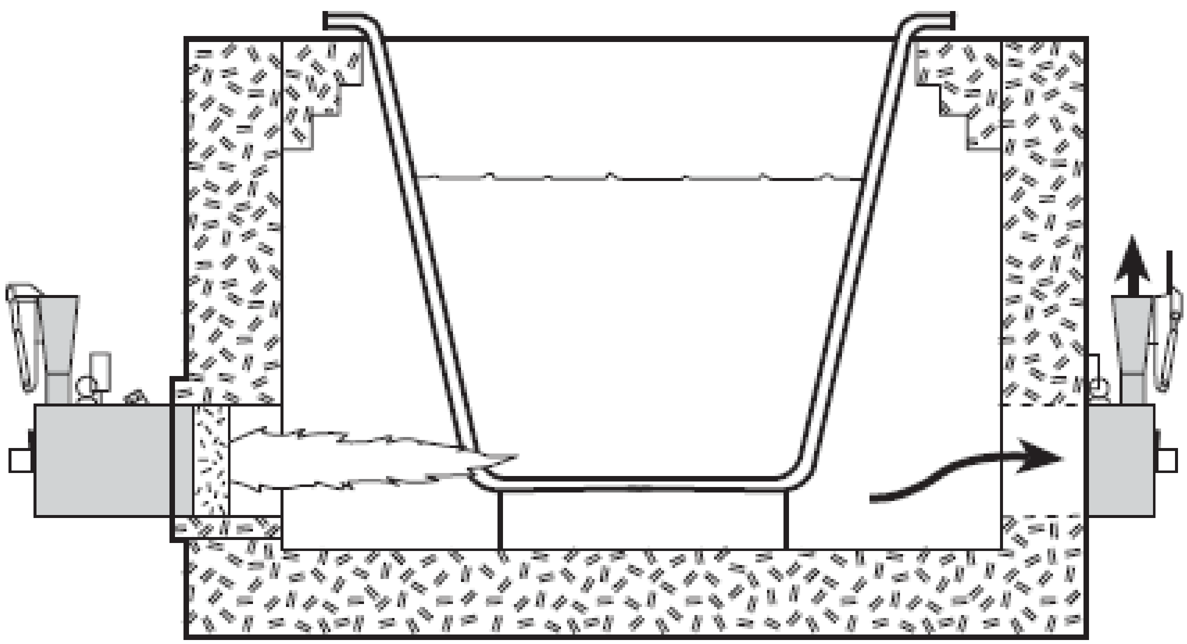


Figure 2.12 A crucible which is tangentially burned inbuilt regenerative type burners conserve fuel while providing uniform heating across the pot or crucible's periphery[4].

R. Nicholson [9] shows that exhaust gases from the crucible furnaces, ovens, fired radiators, waste incineration, heating systems, and steam turbines are the primary supply of reclaimable heat at high-temperatures. Hot byproducts from refineries, chemical processing plants, oven, and melting furnaces are other sources of superior-grade heat, as shown in figure 2.13.

In general, in the area of high-temperature WHR, the heat recovery scheme must be considered part of a systems purpose rather than installing a single piece of heat exchange equipment. This is because it is frequently essential to examine the interplay of multiple significant amounts of equipment to accomplish the desired decrease in energy use while maintaining operability.

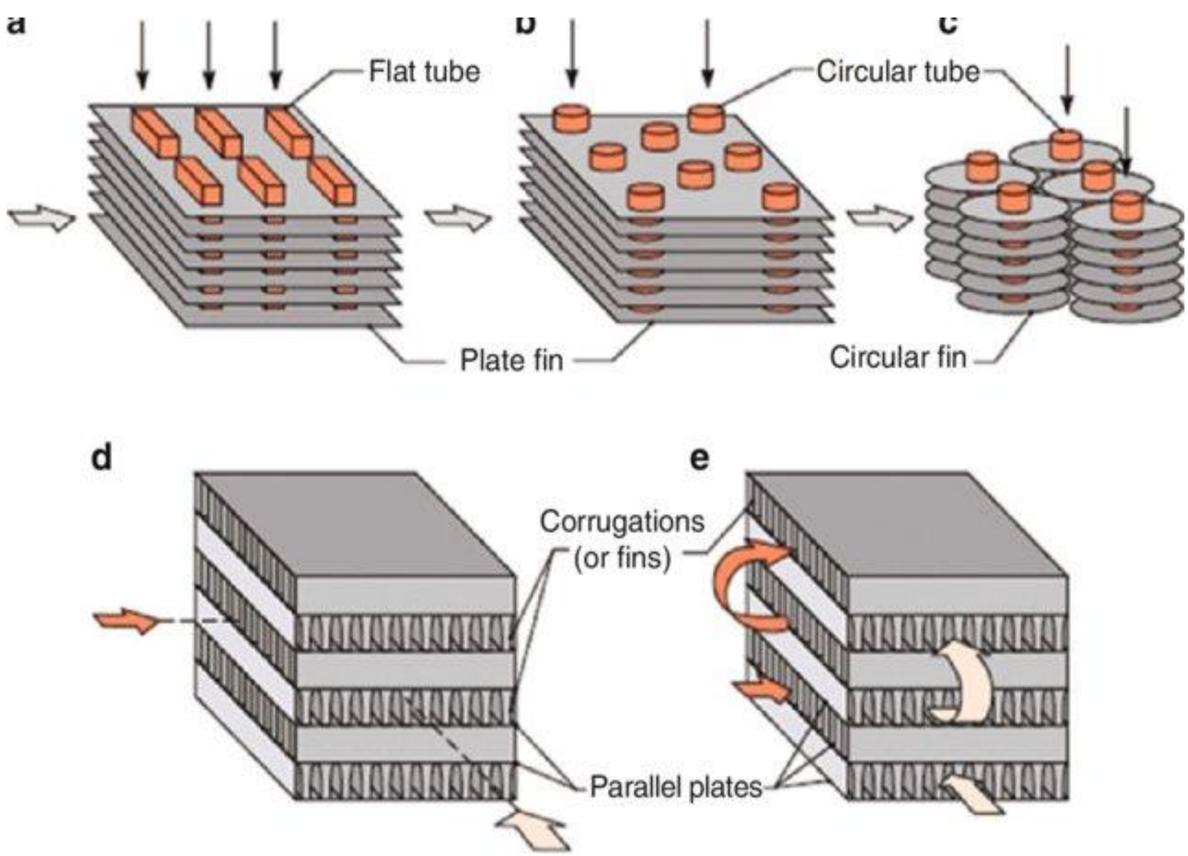


Figure 2.13 diagram of fine tube recuperator included in air pre-heat with in metallurgical industry[37].

According to N. P. Lyakishev et al. [55], the pioneering work of Japanese scientists in showing the stratified porous nature of the steelmaking interior paved the door for a real investigation of the internal gas flow. With average gas and solids residence durations of 1 second or even 5 hours, the gas travels upward via the progressively falling packed bed structure. The solid substance might be considered stationary in terms of gas dynamics. Furthermore, because the gas is driven through a relatively thick medium, the inter-phase friction factors take precedence, allowing the convective velocities, body force factors, and hydrodynamic viscosity effects to be safely ignored. As a result of this simplification, with knowledge of the physical parameters of the various zones of the furnace, such as permeability and physical properties.

Even to N. Sirilertworakul et al. [56], two critical elements are fundamental to producing castings with optimal physical and mechanical qualities at the lowest cost. One requirement is that the component is developed from the start as a casting. The other is proper alloy selection and production procedure. These needs are linked because suitable casting design depends on a prior understanding of the alloy and production process. Most general designers have limited knowledge of casting techniques and cannot design for casting without constant reference to foundry professionals or library study for necessary direction. Data is difficult to access since most of the know-how gained through years of work is not documented in technical books or software. Training programs are becoming increasingly rare, and many foundries are experiencing a loss of knowledge as qualified people depart without being replaced. A software expert system is being created to collect and secure know-how and help, suited for both supplier and customer in the design and manufacturing of castings. The knowledge base proposed in this paper puts specific knowledge in the designers' hands and, via an on-screen interface, allows structures to be built to meet specifications using the least expensive manufacturing technique.

According to Rung T Bui[57], industrial processes utilized in the material transformation from a natural form to a complete form tend to consume an increasing proportion of the overall cost compared with the price of materials. This is due mainly to the combined effect of increased process complexity and sensitivity, stricter restrictions on product performance standards, more significant labour costs, and high benefits needed from end goods to assure the industry's survival. The light metal industry is no exception. For the previous two decades, considerable efforts have been made to study, develop, and model.

2.5 Energy Saving In Industrial Furnace Systems

The foundry and metal casting industries use a lot of energy. Energy contributes approximately 10%-15% of a foundry's operational costs. Because melting might account for 50%-75% of total energy usage, it is critical to undertake efficiency and optimization initiatives. A furnace's combustion process includes both high and low-temperature operations. Low-temperature and high-temperature processes have average working temperatures in the 600-900°C and 1250-1650°C ranges, respectively[5].

"Economy" and "efficiency" in industrial furnaces refer to the heating cost/unit weight of produced, ready-for-sale output. The 'heating cost' includes not only the cost of fuel, but also the costs of running and overseeing the furnace, offsetting, operating, and restoring it, as well as the cost of creating a safeguarding atmosphere. The charges of repairing sections considered to be defective owing to inappropriate melting, as well as the costs of transferring the material into and out of the melting furnace, are included in the costs of rejected goods. As a result of the numerous elements that influence the overall expense of energy, it is possible that the really costly fuel or other thermal source of energy may be the least expensive option in some cases[4][12].

2.6 Swirl Burner System

For efficient and clean combustion, fuel atomization is crucial in heavy fuel oil burners. A fine spray of liquid fuel results in rapid fuel vaporization, improved air-fuel mixing, and complete premixed combustion. Air staging is a well-known method for lowering nitrogen oxide emissions. Air staging minimizes peak temperatures in the primary flame zone. Because rich or lean fuel areas are less valuable to nitrogen oxide creation than near-to-stoichiometric regions, it changes the composition to decrease NOx emissions. Because radiation is susceptible to the fourth power of the absolute temperature of the gases, radiant heat transmission is frequently minimized by reducing the flame temperature. Because of incomplete or poor combustion efficiency, air staging may boost CO emissions. The burner design must integrate suitable fuel and oxidizer mixing to achieve optimal combustion efficiency while limiting pollutant emissions. This is a complex undertaking since CO and NOx emissions are directional. CO levels may be low when NOx levels are high, and vice versa[58].

Villasenor et al.[59] regulated air-staging environment in a laboratory-scale furnace and achieved a 71% reduction in NOx emission. The directional injection of secondary air is the most standard operation for significantly reducing NOx emission through heavy fuel oil burners. With rich/lean fuel staged spray flame, Drennan et al.[60] observed a 25% reduction in NOx emission at the cost of increased burnout loss. Rebola et al.[61] achieve a reduction in NOx emission from 560 mg/m 3 (3% O_2) to 430 mg/m 3 (3% O_2) using air staging and 370 mg/m3 (3% O_2) by fuel gas recirculation without changing any operational conditions. Sellan et al.[62] observed a novel series of stratified and premixed gas/air flame structures using an axisymmetric swirl stabilized burner. The outer swirl enhanced the stability of the flame in the burner and hence played a significant role in mixing between streams.

Sung et al. [63] investigated the influence of swirl severity upon its internal flame recirculation region and gas vortex of air-fuel mixer flames in an experimental scenario. They employed inner SN (swirl numbers) of 0.43, 0.63, 0.89, and 1.29 and an outside SN of 1. The outcome showed that since the rapid exhaust development produced by fuel combustion in the secondary zone, the increase in temperature generated by the burning process near the entry position increased the axial velocity difference, speeding the flame flow.

Yang et al. [64] investigated a 600 MWe furnace using mathematical models and tests using traditional and contemporary combustion technologies. The approach is different in switching the swirl burner’s operation mode, reordering secondary airflow, and applying separated OFA. The study concluded that changing the swirl burner mode from clockwise-rotating to anti-clockwise-rotating reduced nitrogen oxide emissions and incomplete combustion volatile in the flue gas.

Jing et al. [65] conducted a series of studies on a significantly fuel-rich air swirl burner without OFA investigated the control of various outer-secondary air swirler vane angles and discovered that the outer-secondary air vane angle has a substantial impact on burner ignition parameters and nitrogen oxide emission at the burner output

The above results strongly propose that a conventional burner’s existing aerodynamics can be manipulated to increase combustion efficiency and lower NOx production. One of the primary goals of this research was to find the optimal point of pre-heated air-fuel jet injection into the fuel- fired furnace to obtain the lowest possible amounts of NOx and solid particles while retaining good thermal efficiency and low burnout attainment. The best injection site was found by directing the pre-heated primary and secondary air jets sequentially to several axial locations of the fuel-fired furnace. The NOx content in the exhaust gases at the chimney was then measured. The relatively inexpensive productivity of retrofitting an existing industrial-scale furnace with a novel pre-heated air-fuel burner led to the choice of this control technique.

2.7 Problem Formulation and Objectives

The overall objective is to enhance the efficiency of an oil-fired furnace for foundry. Researchers have made several attempts to design efficient recuperators for the furnaces. In general, above 800^oC, radiation is the primary mode of heat transfer from the combustion products to the air in a recuperator. The essential function of a recuperator is to reduce fuel consumption and significantly increase the industrial furnace's efficiency. This is achieved by preheating the incoming ambient air using the heat possessed by the exhaust gases going out of the furnace. Therefore, considering the above discussed gaps in the literature the objectives of the present thesis work have been decided as follows:

- To understand the furnace technology from the thermodynamic point of view.
- To propose a strategy to improve the thermal efficiency of an existing aluminum melting furnace.
- To design and develop a furnace with recuperator toward enhances thermal efficiency.
- To optimize the parameters affecting the thermal efficiency of the developed furnace.
- To understand the role of optimized parameters on the thermal efficiency of the furnace.

Chapter 3
Design and Development of Oil-Fired Tilting Furnace (OFTF) With Novel Recuperator and Burner

This chapter focuses on the development and design of an oil (Furnace oil)-fired tilting furnace with a novel recuperator and burner. Design begins with the crucible size of the oil (Furnace oil)-fired furnace (OFTF), and the rest of the dimensions (furnace body size, stack height and hydraulic cylinder height) can be obtained accordingly. Design challenges and fabrication of helical spirals in novel recuperators have been discussed. A mechanism of data acquisition using thermocouples and flow meters at various reasonable locations within the system has been incorporated.

Further in this chapter, the need and design challenges of novel hot air burners have been discussed in detail. The novelty of the burner lies in its unique design. The novel recuperator provides pre-heated primary and pre-heated secondary air for fuel combustion. The spiral spindle provides helix motion to primary pre-heated air, increasing the velocity of pre-heated air as it passes through the converging chamber. Incorporating a novel preheated primary air swirl burner improved the poor dynamics. It provided a suitable homogeneous pre-heated air-fuel mixture to reduce NOx emission with different vane angles (15^o, 20^o, 30^o, 45^o, 60^o and 90^o).

3.1 Introduction to pilot-scale industrial furnace

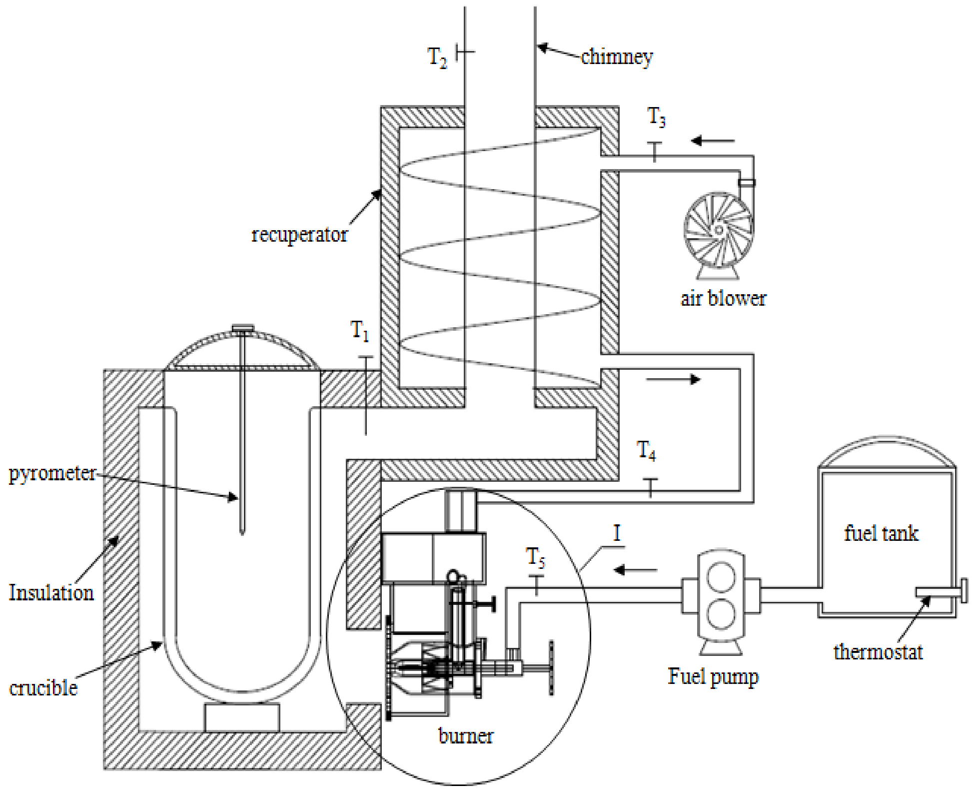
The prototype industrial furnace is a metal melting fuel-fired crucible tilting furnace with a novel recuperator with a capacity of 250 kg. Incoming air from the typical oil-fired furnace can escape into the surrounding air after melting the metal in the crucible. The designed oil furnace uses recuperator technology to pre-heat incoming both primary and secondary air, enhancing the furnace's efficiency. It's worth mentioning that although being a component of the furnace system, the recuperator is still treated as a separate device after the change.

Figure 3.1 illustrates the most straightforward schematic of a fuel-fired 250kg crucible furnace with a recuperator and new combustion system, illustrating the airflow pattern of ambient air, flue gas, and air pre-heating. The cold fire/heat of the crucible furnace takes 90 minutes, and the subsequent fire/heat takes only 45 minutes. After that, the metal is transfer into the mould, and the raw material/scrap is kept in the crucible to prepare for the subsequent heat/fire. A similar approach is used for following heat/fire. Furthermore, using a recuperator in the furnace reduced specific fuel usage by 10%.

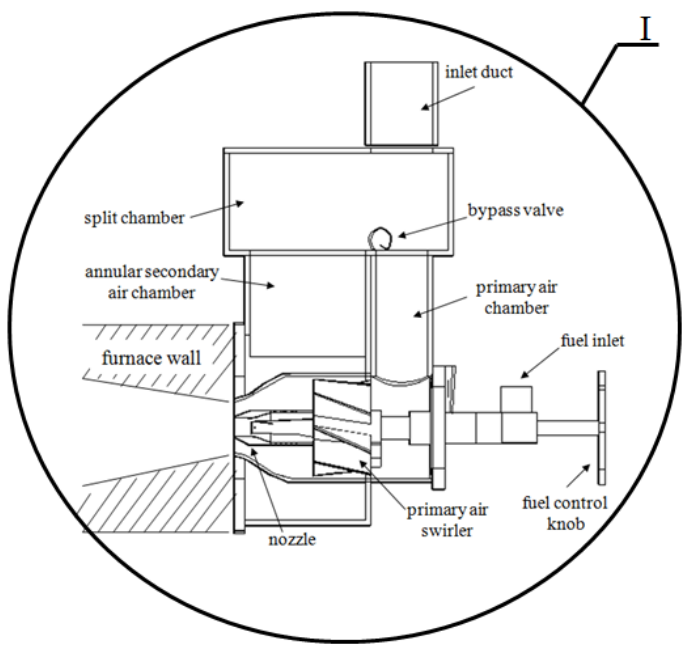
3.2 Development and design of oil-fired tilting furnace with novel recuperator

Radiation is the most important kind of heat transmission from hydrocarbons to atmosphere in a recuperator over 800oC. Another important function of a recuperator is to improve fuel efficiency and the efficacy of a manufacturing furnace. This is accomplished by pre-heating the received atmospheric air with heat from the furnace's flue gas[24].

Figure 3.2 present a simplified design of the proposed recuperator layout with two gas flows moving parallel and in the direction opposite to each other. Because of a guideway, the two channels will no longer be parallel. The said parallel gas stream inside the recuperator aids in exhaust pipe cooling, extending its life. The efficiency of heat transfer improves with opposite flows[11]. Reduced combustion air and flue loss are associated with increased fuel economy. As a result, recuperators reduce the quantity of exhaust emission and the temperature of the exhaust gases. Radiative heat from the exhaust to the inner tube shell is the recuperator's main source of heat transfer rate. In an inner tube carrying cold air, on either hand, the system of heat transmission shifts to convection[10].



(a) Sectional view of fuel fired crucible furnace



(b) pre-heat air burner

Figure 3.1 shows a simplified schematic of a fuel-fired 250kg crucible furnace with a recuperator and new combustion system, as well as the airflow pattern of the surrounding air, exhausts gases, and air preheating.

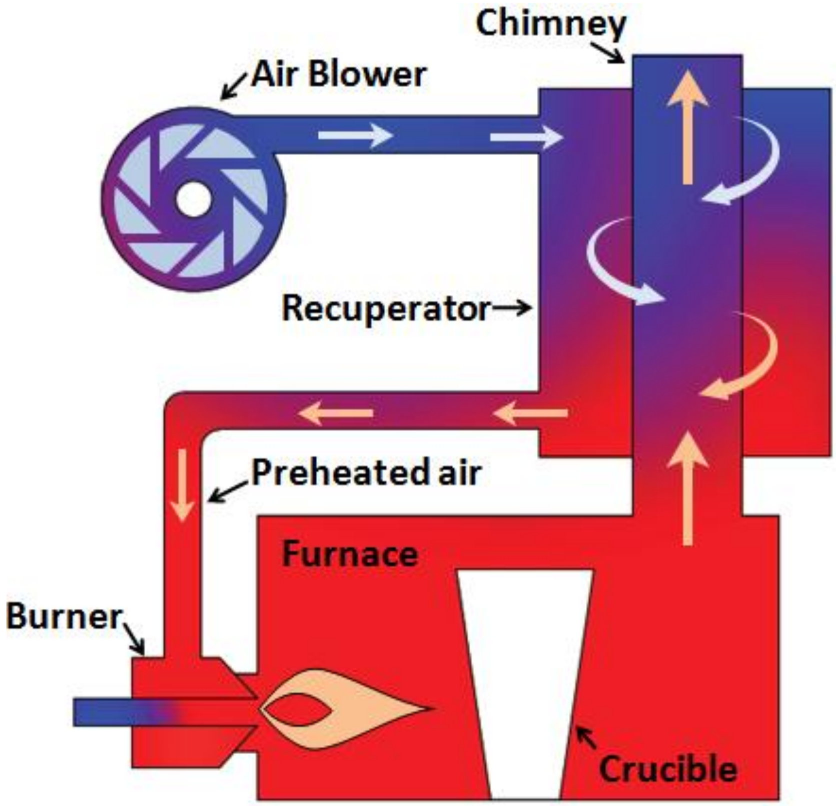


Figure 3.2 an abstracted design of the proposed recuperator system depicting the flow patterns of airflow, exhaust gases, and air pre - heating.

3.3 Framework for waste heat recovery (WHR) process

The capacity of the recuperator, design criteria and system efficiency was framed for building an optimization strategy by considering noble design, as shown in Fig. 3.3; these are used to figure out optimal flow rate, thermal performance, furnace effectiveness, volume, and budget. The proposed research developed a regulated system for collecting, assessing, and disseminating data to support industry investment in heat recovery technologies[34]. This framework was developed in response to the methodological approach offered in the research on the waste heat recovery (WHR) industry[66]. This framework is divided into four separate phases, as seen in Fig. 3.4 for heat recovery evaluation in a furnace[67].

When energy consumption per capita rise is unavoidable, if not desired, it may be lowered when Business As Usual (BAU) situation compared by implementing Demand

Side Management (DSM) programmers' and eliminating waste. Dynamic demands reduction and peak demand management in the case of electricity do not directly contribute in aggregate energy consumption reduction. Still, they avoid establishing additional transition, transmitting, and transmission lines, thereby contributing to the framework[7].

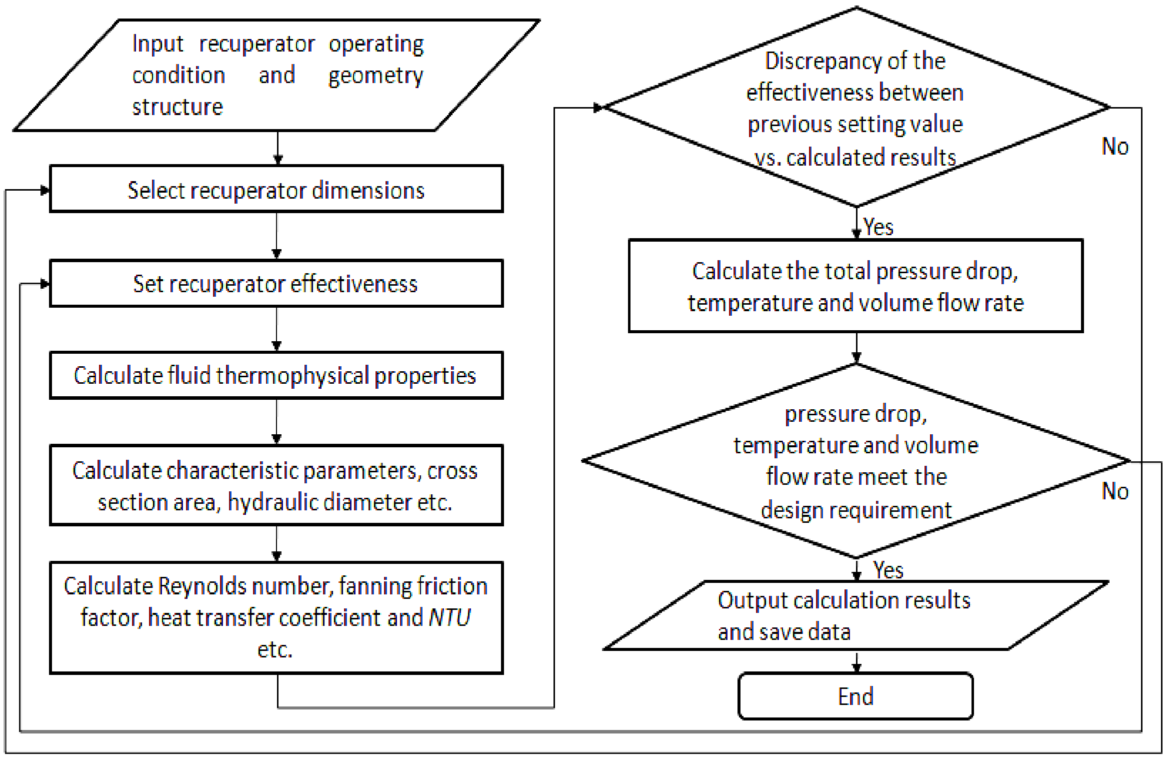


Figure 3.3 The typical flow chart of the optimization technique for calculating recuperator effectiveness[67].

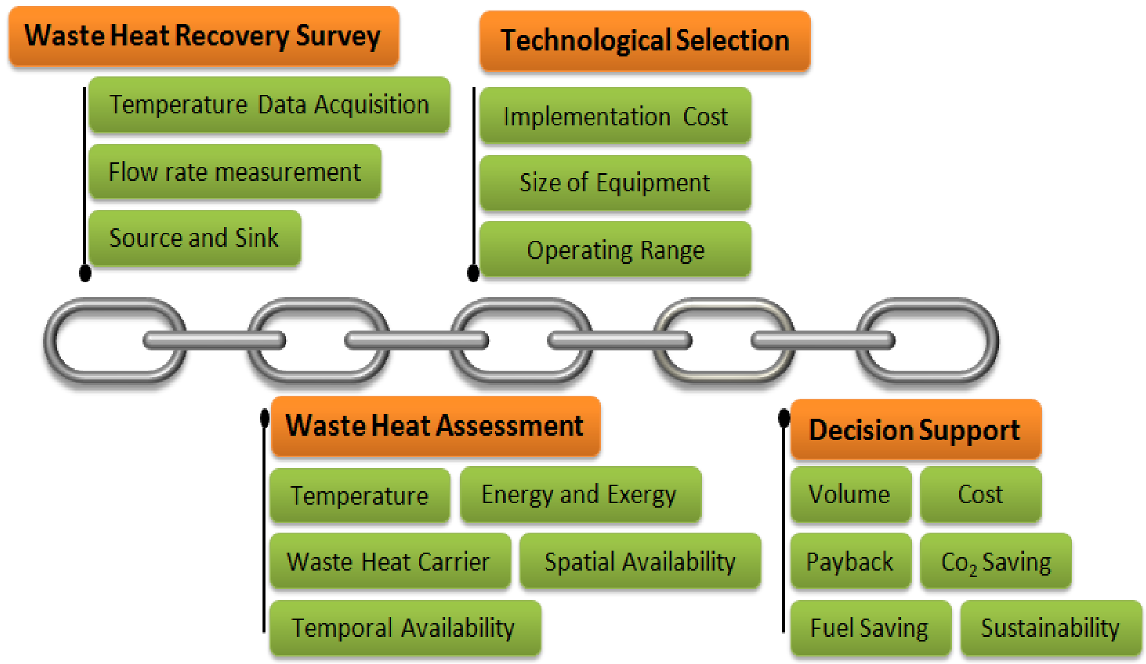


Figure 3.4 Framework for assessing Waste Heat Recovery (WHR) in a furnace[68].

3.4 Capacity Survey of waste heat recovery (WHR) Sources: Stage 1

The on-the-spot study must be performed at the main stage of the construction to establish the sources of heat and exhaust systems that will most likely be employed in energy requirements. The process, operational and product components of the greatest Waste Heat Exergy (WHE) production plants were documented (generally known by site managers)[41]. The WHE potential absorption energy was detected during the test, and the specification was entered into the database. It is assumed that the sink capability increases when sources improve their capacity to reclaim more WHE. Before choosing a new WHE protective measure, it is required to do WHE research regularly (for example, once a year). Another component of this research is to ensure the established pollution control system's availability and operating competence[69].

To account for the multiple flow variables in the furnace, such as heating the burner oil before it enters the burner, a differential pressure-flow meter was designed. The combustion temperature, on the other hand, is governed by the settings. Based on the orifice plate concept, the developed flow meter can also operate over a wide range of input temperature ranges. Fig. 3.5 illustrates a differential pressure-flow meter developed in support of an OFTF. It is worth noting that oil heating aids in atomizing oil droplets. The fluid flow and furnace outlet/inlet temperatures are regularly monitored just before determine their influence on OFTF effectiveness.

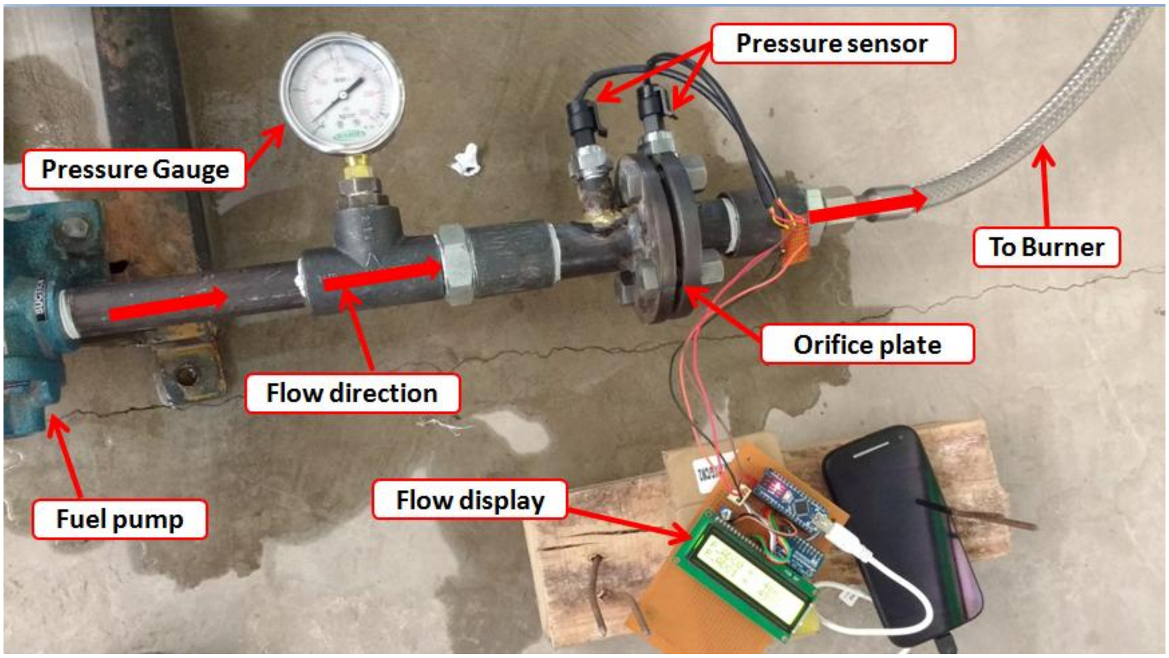


Figure 3.5 A differential pressure flow meter developed especially for OFTF.

Flow measurements were carried out using sensors and the pressure differential between lower and upper holes. The measuring process for continuous flow was governed by ISO 5167-1 and 5167-2 standards[70][71]. The flow rate of mass q_m is specified in this standard as:

$$q_m = \frac{C_d}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} d^2 \sqrt{2\Delta p \rho_1} \qquad (3.1)$$

Where Δp denotes the pressure differential amid the lower and higher pressure inlets and eq. 1 indicates the higher flow density. The changeable β sets the proportion of hole diameter d to pipe diameter D. Experimental formulations specify the discharge coefficient of C_d and the extension coefficient of, which depend on the placement of pressure valve, downstream pressure, upstream pressure, Reynolds number and adiabatic index. The C_d is typically 0.6 but practically one[72]. Modern digital data loggers are highly useful for recording the current time and temperature. The digital data logger employed in this study has 12 channels and can monitor temperatures up to 1200oC, as shown in Fig.3.6. A picture of a contemporary digital data logger placed on-site, complete with a pen drive for transferring verified data. This digital data logger saves data every 5 seconds to a pen drive and exports it to an MS Excel file.

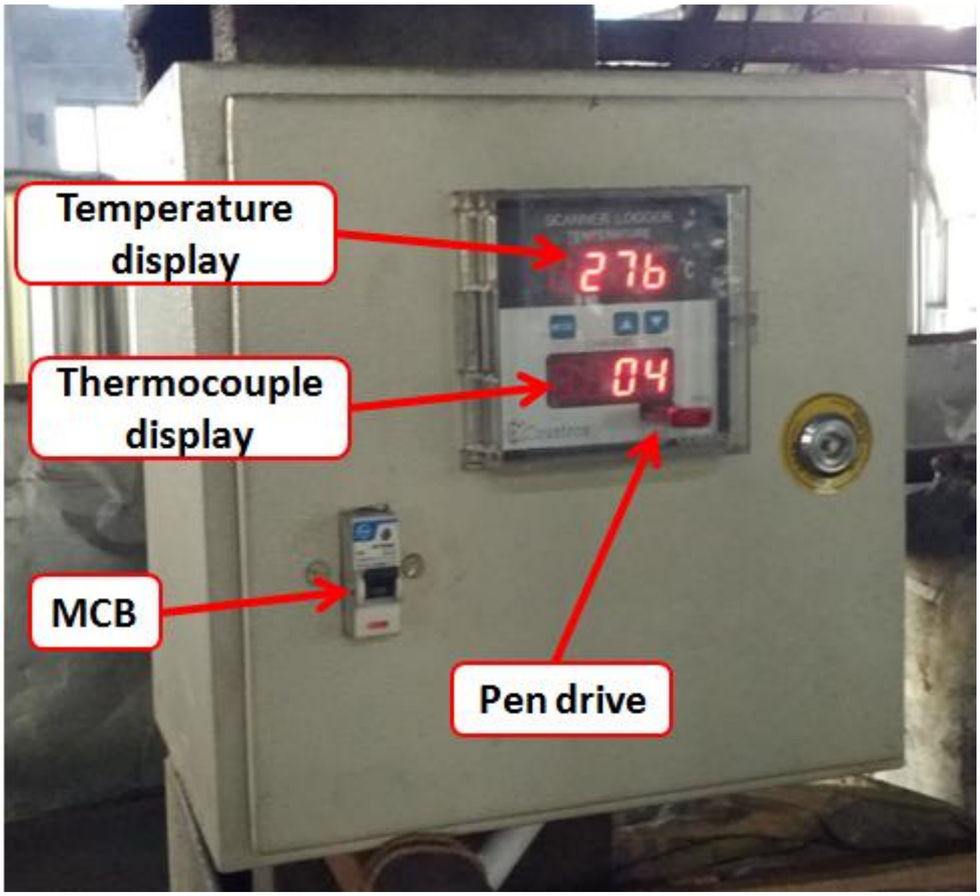


Figure 3.6 A picture of the modern electronic data logger placed on-site for data collecting. For the system's safety, the data logger is kept at a secure distance from the OFTF and disguised in a cabinet with an MCB.

3.5 Waste heat (energy) quantity and quality assessment: Stage 2

The acquired or recorded data was utilized at this crucial step to examine the source of waste heat and absorbers detected at the installation. A comprehensive qualitative and quantitative analysis of waste exergy provides a more effective comparison of exergy and potential waste heat recovery solutions[73]. The criteria for heat generated was that the higher the temperature, the enhanced the thermal gradient quality and the ease with which the WHR procedure could be optimized. As a result, knowing the highest heat captured in one performance and ensuring the resultant heating system was critical[10].

The present waste heat temperature was determined using the equation[74] given below:

$$Q = V \times \rho \times C_P \times \Delta T \tag{3.2}$$

Where Q is the temperature content (J), V is the material flow rate (m^3/s), ρ is the flue gas density (kg/m^3), C_p is the material-specific heat (J/kg/K), and T is the distinction for both the objects temperature (K) of the framework highest output temperature (T_{out}) and the initial input temperature (T_{in}). Adopting the appropriate WHR system necessitates a thorough analysis of the quantity and heat flux recovery.

The recuperator was intended to operate at maximum working temperatures of up to 1200^{o}C. A recuperator significantly reduces fuel use by pre-heating the incoming air entering the system. The large-sized and difficult-to-maintain recuperator has a construction capacity limit of 1000kg and beyond. All of the current heat exchanger restrictions were removed in this study by streamlining the design for optimum heat exchange.

In this work, the heat transport coefficient of the concentric pipe heat exchanger was improved by expanding the surface area for current recuperative burners. This construction aimed to increase heat transmission among the recuperative's concentric pipes while remaining cost-effective, compact, and with a determined pressure drop[7][75]. It is clear that exhaust gas losses be quite substantial and must not be overlooked.

The framework is robust, and numerous aspects and indicators may be used to evaluate the energy system. For an evaluation of an energy arrangement framework, four different dimensions are chosen: availability, affordability, climate suitability, and efficiency. These dimensions are separate, and selected pointer is able to classify under individual dimensions for examining the framework. The dimensions are additional subdivided into categories and sub-categories to aid comprehension.

3.6 Waste heat carrier assessments

The present technology consists of a recuperator shell installed on a frame. The shell must have an internal hollow pipe for exhaust gases linked to a bottom orifice, an orifice for air inlet, and an orifice for hot air outflow. As illustrated in Figure 3.8, the hollow innertube is built so that many turns of a guideway are welded in a helical pattern on its external surface. The key operational variables influencing recuperator effectiveness have been quantitatively examined. The operating parameters are (i) exhaust gas intake temperature and (ii) exhaust gas mass flow rate. Because of their capacity to handle high-temperature pressure and corrosion resistance, Chromium-molybdenum alloy steel is used in recuperators' inner and outer shells.

Since it is widely employed in industry, glass fiber wool one-time applied as an insulating matter. Furnace oil with a flashpoint of 339.15 K is utilized, with an air-fuel ratio of 16:1. Table 3.1 shows the assessment of the variables used to calculate the heat transfer performance. The guideways are 45^o helixes, providing tangentially velocity distribution to surrounding air entering the orifice. The overall surface area is raised by 156% with these spirals. The recuperator-equipped furnace body was mounted on a tilting frame. The size of the exhaust gas pipeline determined the number of twists. The pitch of the turns in the suggested design is considered equivalent to the diameter of the exhaust gas pipeline. The number of helix twists in a present invention is best fixed at three.

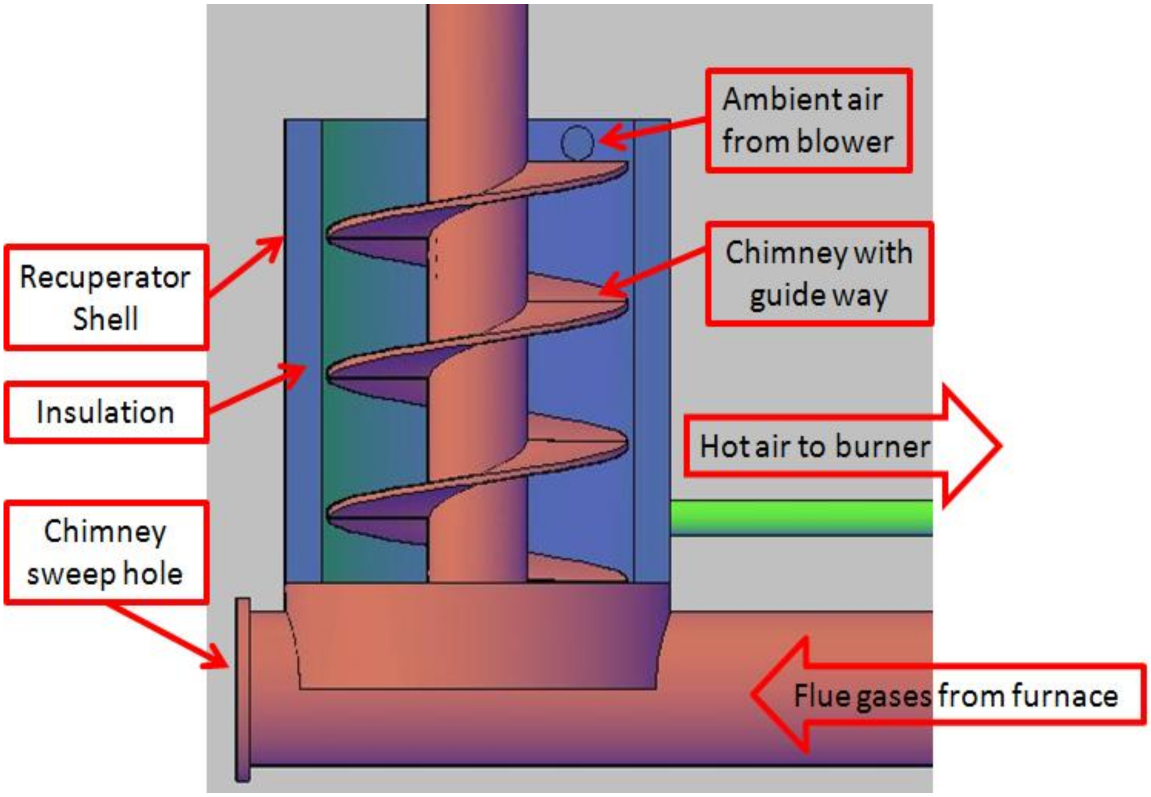


Figure 3.8 shows the developed recuperator with guideways designed for optimal heat transfer and gas movement.

Table 3.1 Parameter values utilized in the design of novel recuperator

S. No	Parameter	Value	Unit
1	Height of the recuperator	1	m
2	Diameter of chimney	0.20	m
3	Inner-radius of the inner shell	0.500	m
4	Outer-radius of the inner shell	0.502	m
5	Inner-radius of an outer shell	0.650	m
6	Outer-radius of an outer shell	0.652	m
7	Mass-flow rate of air	1.26	$kg\ s^{-1}$
8	Mass-flow rate of exhaust gas	1.36	$kg\ s^{-1}$
9	Thermal conductivity of inner and outer shell	35	$W\ m^{-1}\ K^{-1}$
10	Thermal conductivity of insulating material	0.038	$W\ m^{-1}\ K^{-1}$
11	Thickness of insulation	0.150	m
12	Ambient air temperature	303	K
13	Inlet air-temperature	303	K
14	Pre-heat air temperature	623	K

3.7 Exergy and energy investigation

Exergy is derived from a combination of thermodynamics' first and second laws. Exergy, unlike energy, is not preserved, and the primary exergy is partly lost by the unsustainability of the separate operations[76]. The product's output energy ratio toward the system's energy requirements is energy efficiency. It considers the costs of irreversibility, which damages the progression. These phrases describe how well energy is absorbed by the product[40].

$$\text{Energy efficiency}\ \eta = E_{\text{product}} / \text{E}_{\text{input}} = 1 - E_{\text{loss}} / \text{E}_{\text{input}} \tag{3.3}$$

Conversely, exergy efficiency[77]

$$\varepsilon = A_{\text{product}} / \text{A}_{\text{input}} = 1 - (A_{\text{loss}} + \text{I}_{\text{CV}}) / \text{A}_{\text{input}} \tag{3.4}$$

$E_{product}$ is the temperature delivered to the metal during the melting process. The heat produced by burning fuel is referred to as E_{input}. E_{loss} encompasses all of the energy flowing through the method. The result is exergy transmitted to melted metal. The revenue created via combustion is referred to as A_{input}. A_{loss} is a process that is concerned with the overall energy loss of the process.

3.8 Examination of spatial availability

As illustrated in Figure 3.9, the substantial rectangular frame houses the furnace arrangement, which includes a ignition chamber and a chimney. The thin rectangular shell depicts the combustion chamber, where high-temperature combustion occurs. The dashed square frame denotes the shared system's boundary, which comprises the OFTF component and the comparative environment. The suggestion environment for this investigation is T_o = 25°C (298K) and P_o = 1 atm (1.01x105 Pa). T_1 = 1380K is, the flue gas temperature; T_2 = 298K is, the ambient air flowing out of an air blower. Temperature measurements were taken using a temperature data logger from thermocouples and a pyrometer at four distinct sites in the OFTF, as shown in Fig. 3.10; two in the furnace (combustion chamber temperature = 1380K) and two at the recuperator intake, that is T_3

= 298K exit, i.e. T_4 = 623K. The temperature of the oil tank is kept at 45^{o}C (318.15k) by a single thermostat. T_1 = 1173K flue gas temperature can provide enough energy for pre-heating input combustion air T_4 = 298K. This power is produced to accomplish the burning of fuel (furnace oil). A centrifugal pump with 10 litres per hour is used to pump fuel.

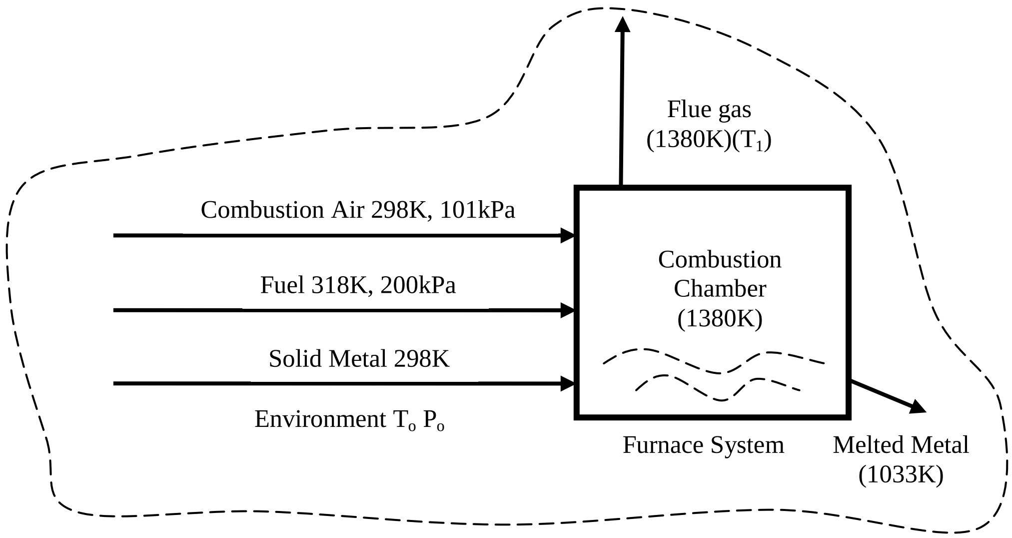


Figure 3.9 shows a system design of the OFTF unit without a recuperator, indicating the temperature situation at entry/exit points concerning the atmospheric pressure and temperature.

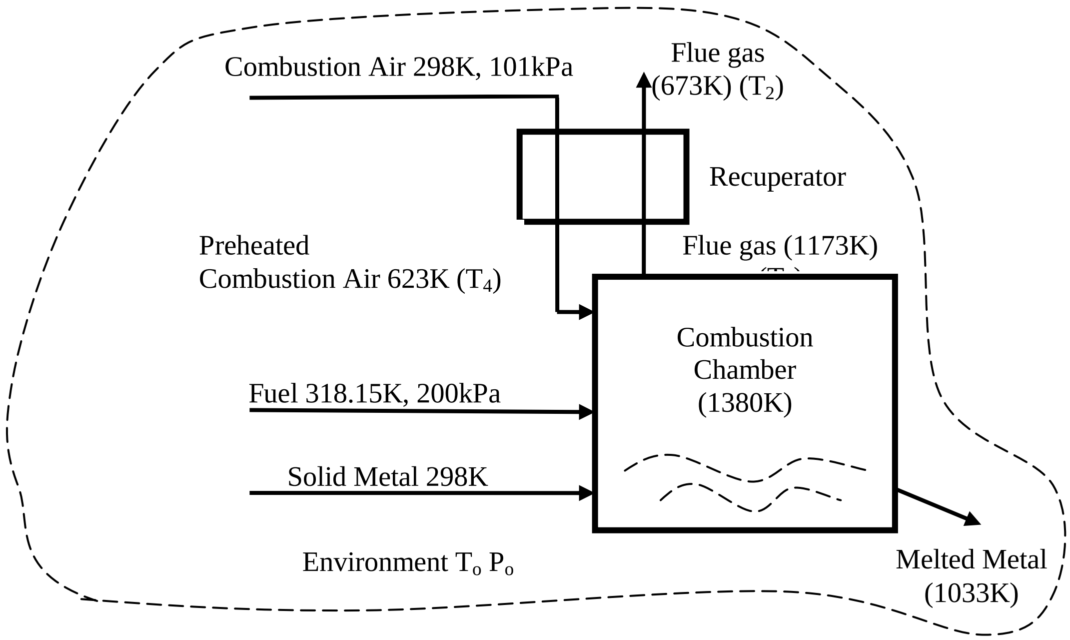


Figure 3.10 depicts the furnace unit with recuperator and temperature variations at various places with reheated air up to 623K. (350^{o}C)

3.9 Technology assessment and review: Stage 3

Qualitative and quantitative heat circulation and waste utilization estimates may be used to lower the technical data set and construct filter rules to restrict the opportunities for waste heat disposal. This procedure generates a list of possible WHR technologies for evaluating comparability to traditional evaluations[78].

Hewitt and Pugh[42] give a starter phase for selecting heat exchangers based on many parameters. During this operation, contradictory heat exchanger types are examined and eliminated from numerous essential features such as maximum and minimum pressure, thermal gradients, available size selection, process, and maintenance.

3.10 Return on investment and costing

3.10.1 The C Value approach

Heat exchangers are often priced in unit cost. Hewitt and Pugh[42] shows the computation of area (A) quickly if you know the overall coefficient of heat transfer (U), the average temperature differences (T_m) and the heat exchanger loads ($\dot{Q}$)

$$A = \frac{\dot{Q}}{U\ \Delta T_m} \tag{3.5}$$

Nonetheless, the area categorization for the various types of heat exchangers was much more extensive, and the interpretation of U was interconnected. The C value can be define as the entity price Q/T_m in the C value technique. This approach overcomes the difficulties of estimating the area and overall heat transfer effectiveness and allows for a thorough evaluation of the exchanger among the heat loads (Q) and the accessible operating temp. (T_m), which was connected to the needs assessment.

3.10.2 Assessment of $\dot{Q}/\Delta T_m$

Attempting to change the enthalpy of a particular flow yielded the heat load (Q). The mean difference in heat of temperature (T_m) for straight, single-phase heat exchangers having constant definite heat capacity is comparable to the mean logarithmic temperature difference (T_m) provided by[79]:

$$\Delta T_m = \Delta T_{LM} \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{ln\frac{(T_{h,in} - T_{c,out})}{(T_{h,out} - T_{c,in})}} \tag{3.6}$$

Where $T_{h,in}$ and $T_{h,out}$ are the hot flow inlet and outlet temperatures, and $T_{c,in}$ and $T_{c,out}$ are the cold flow inlet and outlet temperatures. If there is a major variation from the regular counter-flow procedure, the mean temperature variation must be calculated as follows:

$$\Delta T_m = F\Delta T_{LM} \tag{3.7}$$

Where F is the correction factor, its values for the suggested design were derived, and T_m and Q/T_m were determined. The heat load Q may be calculated using the heat balancing equation using the hot and cold streams:[42]

$$\dot{Q} = \dot{m}_h \cdot C_{p,h} \cdot \left(T_{h,in} - T_{h,out}\right) = \dot{m}_c \cdot C_{p,c} \cdot \left(T_{c,in} - T_{c,out}\right) \tag{3.8}$$

Where "m" represents the mass flow rate [kg/s], C_p represents the specific heat capacity [J/kg.K], and $T_{h,in}$ and $T_{h,out}$ are the hot (flue gas) and cold (ambient air) inlet and outlet temperatures, respectively. Another method for estimating Q/T_m represents to use the relationship between the *number of transmitter units* (NTU) and the *heat exchanger effectiveness* (E)[44].

Efficiency is described as the differential of the heat load Q and the highest practical heat load Q_{max}, which is the maximum heat transfer accomplished once the output temperature of one channel approaches the entrance temperature of the new channel, with the lowest value being M_{cp}, and it follows that

$$E = \frac{|T_{in} - T_{out}|_{large}}{\left(T_{h,in} - T_{c,in}\right)} \tag{3.9}$$

Where $|T_{in} - T_{out}|_{large}$ was more important than the temperature transformation on the hot and cold sides of the heat exchanger. The total number of NTU transmissions was determined as:

$$NTU = \frac{UA}{(\dot{M}c_p)_{smaller}} \tag{3.10}$$

Where M_{cp} is more minor is less than the product of flow M and specific heat capacity C_p of the circulation with lower M and C_p values. Q / T_m denote the cost component C.

$$C = exp\left\{\ln C_1 + \frac{ln(C_1/C_2)\, ln[(\dot{Q}/\Delta T_m)/(\dot{Q}/\Delta T_m)_1]}{ln[(\dot{Q}/\Delta T_m)_1/(\dot{Q}/\Delta T_m)_2]}\right\} \tag{3.11}$$

C_1 and C_2 are the C-values of the particular hot or cold relationship Q/T_1 and Q/T_2. The price of single heat exchanger represents Q/T_m, as illustrated in the numbers below in favor of clean air on the hot side and the cold side. C_1 and C_2 are recognized using logarithmic interpolation among the top and low levels of the Q/T_m values in the list, according to Y. Luo et al.[67].

The C value for $\frac{\dot{Q}}{\Delta T_m} = 1860$ is calculated by:

$$C = exp\left\{\ln C_1 + \frac{ln\,(1.822/1.45)\,ln\,[(1860)/(1000)]}{ln\,[(1000)/(5000)]}\right\} = 2.179\ £/(W/K) \qquad (3.12)$$

3.11 Decision support: Stage 4

The method was designed in a uniformly distributed and constrained range of temperature of up to 1200^{o}C, which is commensurate with the capacity to heat the metals evenly and adapt the heat to the material and processing criteria. The treated material can be put immediately in the combustion zone. The advantages are twofold: First, similar process parameters significantly improve process thermal efficiency, corresponding to a 30% decrease in the heating phase and a 40% reduction in specific fuel utilization. Second, the temperature distribution is homogeneous over the larger surface that transfers heat.

3.12. Design of the novel pre-heated air burner

The air swirled with eight vanes (blades) and various defined angles (15°, 25°, 35°, 45°, 60°, and 90°) mounted on the burner was utilized in this investigation to study the effect of input air swirling upon that ignition and exhaust parameters of the burner. Figure 3.11 displays the air swirls and a pictorial illustration of the air swirler's vane angle.

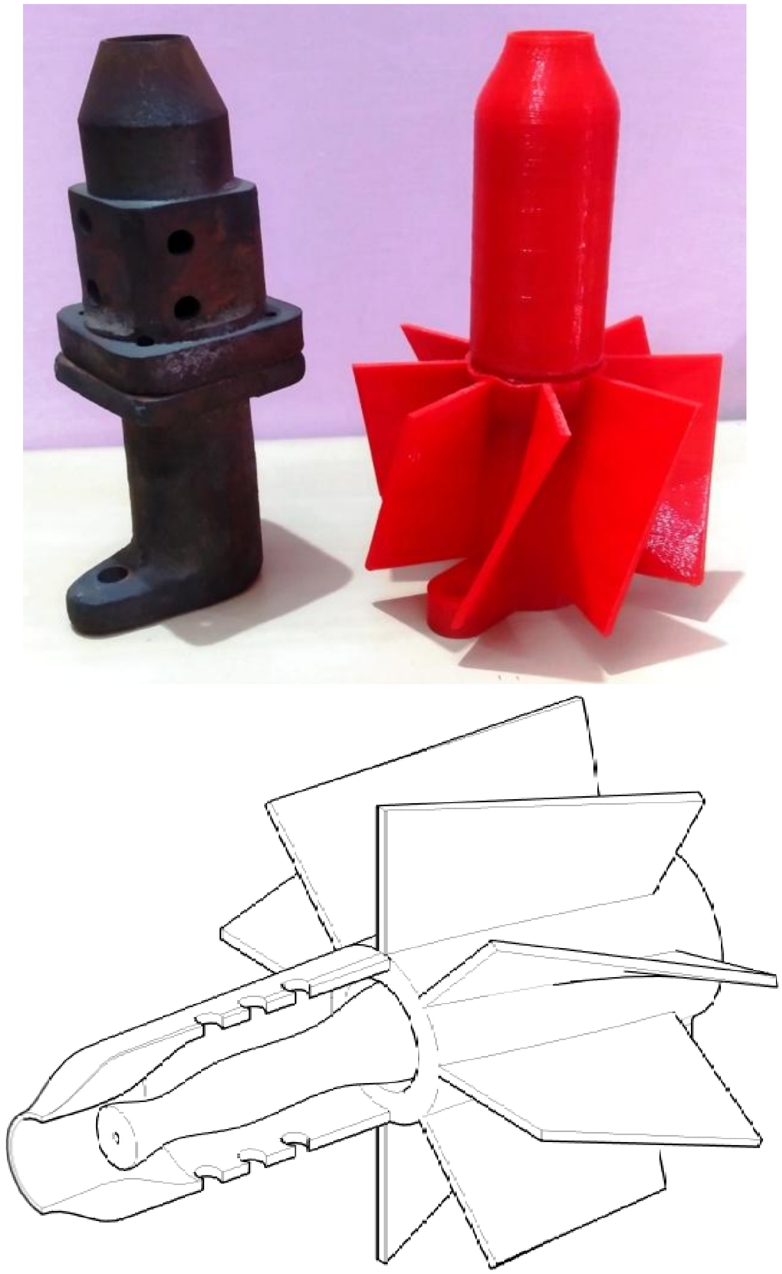


Figure 3.11 illustrates air swirl generators along with an image of the vane angle and air swirled.

The suggested new pre-heat air burner is installed in the experimental fuel-fired crucible tilting furnace. Pre-heated air enters the novel hot air burner from the primary input, as depicted in figure 3.1 (b). The splitting chamber is filled with pre-heated air. It is separated in to a concentric secondary air chamber and a primary air chamber. It contains a butterfly valve to control the amount of primary air flow and the length of the flare in the combustion chamber. To create the swirl movement of hot air in the converged enclosure, direct hot air is pushed to flow around a spiral; this offers a longer flame length than a standard burner. A sufficient supply of air for complete blending is required for optimal ignition, and the burner must be built to efficiently and effectively mix the air/fuel streams. In most combustion systems, the volume of air necessary for complete combustion is at least ten times that of the fuel. As nothing more than a result, the air's velocity is typically more prominent than the fuel alone, and it will almost certainly dominate the fuel-air mixing.

In the innovative burner, the secondary air entrance size was twice as large as the fresh air entry area to ensure precise air movement for complete combustion. Fuel enters the system through the fuel intake regulated by the gate valve lever. Energy runs parallel to the spindle, with tiny drills at one end that allow fuel to combine with warmed air in the mixing chamber. The mist of the air-fuel mixer emerges from the nozzle. The hot air assembly is installed on the body of a fuel-fired crucible tilting furnace. A bypassed nozzle is supplied for axial heated air from the split chamber to the annular secondary air chamber.

The burner's special design is what makes it unique. The improved combustion system for fuel burning can supply pre-heated main and secondary air. The spiral spindle gives primary pre-heated air helical motion and enhances the velocity of pre-heat air as it travels via a convergent chamber. Drill holes in the helix spindle enable hot direct air and coaxial fuel to combine. Drill holes on the body of the hollowed spindle allow warmed principal air to enter and mix with fuel in the mixing chamber. The primary fuel line features micro drills on the tip to aid in the homogeneous mixing of a hot air-fuel mixer.

3.13 Testing Methodology

3.13.1 In situ experimental parametric system

A recent study of nitrogen oxide emissions in industrial-size furnaces found. Heavy fuel dominates the nitrogen oxides production system in flames, contributing to around 80% of the nitrogen oxides formed in fuel-fired furnaces, with heavy oil having a N_2 content surpassing 0.6 wt. percent (as received)[80]. In terms of construction characteristics and convenience of operation, the specially developed OFTF, as illustrated in figure 3.13, can be controlled by a semi-skilled worker. The operating parameters of the heavy fuel-fired crucible furnace were carefully monitored to ensure low variation and uniform heavy fuel oil characteristics. The flashpoint of the furnace oil utilized in operation is 339.15 K, and the air to fuel ratio is 16:1 for both with and without supporting air.

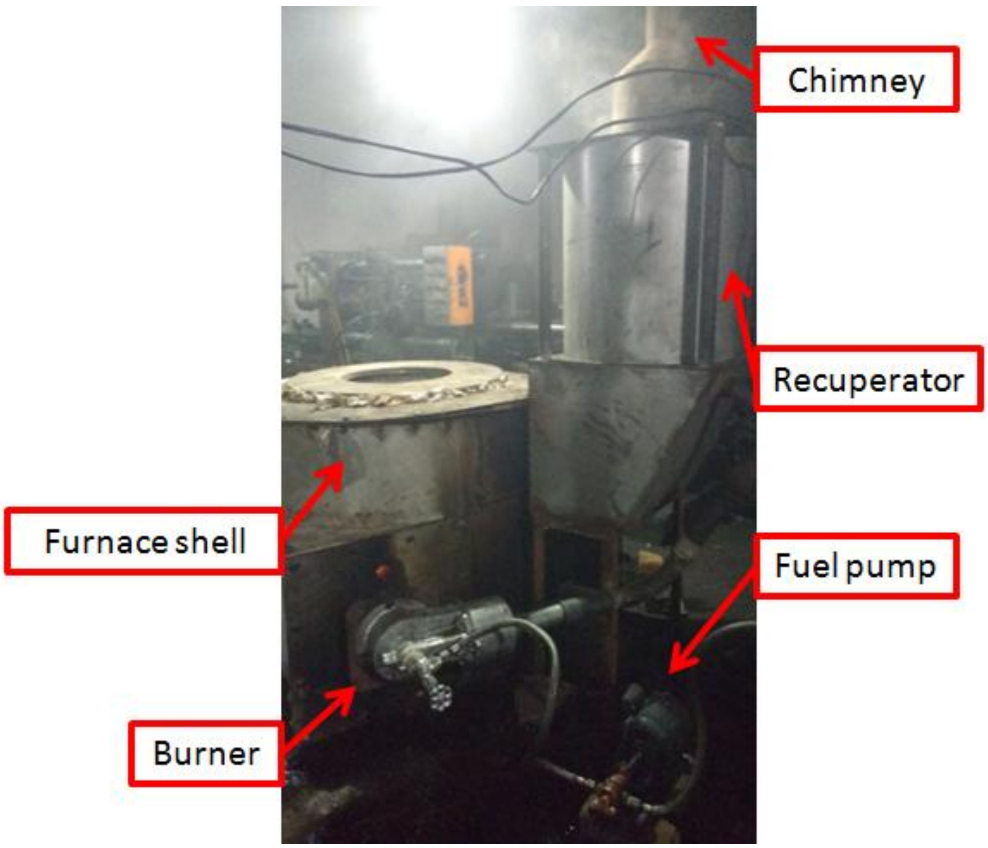


Figure 3.13 Labeled image of designed burner system for an oil-fired tilting system

Table 3.3 shows the parameters of the furnace oil utilized in the testing, and Table 3.4 shows the operating conditions of an oil-fired furnace with a novel recuperator burner. Excess air becomes necessary to compensate for impaired mixing to achieve complete combustion. In many furnaces, excess air significantly influences furnace effectiveness and is thus an essential element in furnace operation. Excess air causes heat loss in the flue gases because it must be heated to flame temperature, reducing heat transmission. Inadequate extra air leads to incomplete combustion and higher exhausts gas losses owing to carbon monoxide and unburnt particles with solid and liquid fuels. A dry gas sample's extra air can be computed as follows:

$$Excess\ air\ = \frac{100x}{(20.9-x)}\% \tag{3.13}$$

Where x is the oxygen fraction in the exhaust gas.As a consequence, 1% oxygen equals 5% surplus air, and 2.4% oxygen in a dry exhaust gases sample equals 12% excess air. To ensure the accuracy of the measurements, all data-collection devices (such as the thermocouple device and the flue gas analyzer) and the characteristics of the equipment in the digital data logger were standardized before executing the industrial-scale furnace tests. To remove any conflicting behavior, such as smoke or pollutant emission under different loads, sufficient time was provided between measurements to ensure that the heavy fuel-fueled crucible furnace remained operating regularly.

Table 3.2 Fuel characteristics used in testing and trails

Chemical properties (wt %)	
Hydrogen	11.2
Carbon	85.0
Nitrogen	0.4
Oxygen	0.0
Sulfur	3.4
Ash	0.033
Asphaltenes	5.6
Conradson carbon residue	16
Vanadium (wt ppm)	143
Nickel (wt ppm)	44
Gross calorific value (MJ/kg)	42.27
Physical properties	
Density at 290 K (kg/m^3)	991
Kinematic viscosity at 373 K (cSt)	36.66
Surface tension at 290 K (N/m)	0.0285

Table 3.3 Oil-fired furnace operational conditions

Operating Parameter	Study with Secondary air	Study without Secondary air
Excess air (%)	12	12
Heavy-fuel		
Mass flow rate (kg/h)	25	25
Temp (^oC)	65	65
Pressure (bar)	1.6	1.6
Atomizing air		
Mass flow rate (kg/h)	18.5	19.5
Temp (^oC)	350	350
Pressure (bar)	1.4	1.4
Secondary air		
Mass flow rate (kg/h)	176	-
Swirl number	1.2	-
Temp (^oC)	350	-
Velocity (m/s)	22-24	-
Furnace wall temperature (^oC)	1260	1290
Room temperature (^oC)	35	35

Wet scrubbing captures the SO_x. Because SO_x gases are particularly hygroscopic, a water spray tower erected just after the recuperator, through which exhaust air is carried, is quite successful at eliminating them in this research. This will also remove a considerable quantity of NOx from the flue gases, allowing the system to fulfil the bulk of compliance requirements. The swirl number (S_n) is considered by means of the estimations presented by Y. Sung et al.[81].

$$S_n = \frac{2}{3}\left[\frac{1-(d_i/d_o)^3}{1-(d_i/d_o)^2}\right]\tan\theta \tag{3.14}$$

Where d_i is the inner diameter of the swirl vane and d_o is the outer diameter of the swirl vane. Therefore, the swirl vane angle (θ) is the primary determinant of S_n. Swirling intensities of S_i =0.42, 0.56, 0.63, 0.75, 0.9, and 1.3 were determined at swirl vane angles of 15°, 20°, 30°, 45°, 60°, and 90°, respectively.

In this work, a 12-channel digital data logger (COUNTRONICS, India) capable of measuring temperatures up to 1200^{o}C was employed. Figure 3.6 depicts a digital data logger on-site (Prakash Alloy Udyog, India) with a pen drive for transmitting the data collected. Every 5 seconds, this digital data logger stored data on a pen drive, which was subsequently transferred as an MS Excel file. To ensure a safe and reliable operation, the digital data logger was placed at a secure distance since much of the furnace emission and concealed in a covered panel with an MCB.

All of the experimental investigations in this work were conducted under stable and steady settings, and Table 3.4 includes the gas analyzer and thermocouple characteristics. Flue gas samples were taken at the gas outlet (temperature range up to $1000^{o}C$) using a water-cooled SS probe for inspection and then investigated with a Testo 350M gas analyzer (with an error of 5% for CO, 1% for O_2, and 15 ppm for NO_x). CO_2 and HC were measured on a Testo 350M gas analyzer box using a CO_2-(IR) sensor and a CxHy sensor. The HC sensing was calibrated to detect methane ex-works.

This method was used to calculate each experimental design's nitrogen oxide and carbon monoxide emissions. Because of the lower nitrogen presence in the fuel and the higher effective flare temperature, thermal nitrogen oxides should contribute much more to total nitrogen oxide emissions than pulverized coal-fired flames. Because localized gas temperature levels strongly impact thermal NOx, the combustion constancy in the primary air-fuel combustor was selected as the key source of concern in current nitrogen oxides pollution investigations. In all cases, the NOx sample was obtained ten times in one minute and matched with the pyrometer's gas temperature measurements. These data were then averaged to minimize the hazardous cause of combustion alternations significantly. A K-type (nickel-chromium/nickel silicon) thermocouple sensor was also put at the exhaust to detect the flue gas temperature online. Verification of the various parameters established that the accuracy of these observations was within 10% on average when stable circumstances were preserved to guarantee minimum fluctuation in the air-fuel ignition state.

Table 3.4 the gas analyzer and thermocouple specifications

Variable Analyzed	Measuring range	Accuracy	Resolution	Reaction time
CO	0 to +10 Vol. %	± 0.05 Vol. %	± 0.01 Vol. %	15 s
CO_2	0 to +50 Vol. %	± 0.3 Vol. %	± 0.1 Vol. %	10 s
HC	0–21,000 ppm	± 2% reading	± 1 (ppm)	30 s
NOx	0 to +5,000 ppm	± 5% reading	± 1 (ppm)	15 s
T (Type K NiCr-Ni)	-200 to +1,200 °C	± 1 °C	± 1 °C	3 s

3. 13.2 Uncertainty analysis

Various parameters, including the types of equipment used, measuring technique, and trial environment, all influence uncertainty over investigations. The total uncertainty of such parameters was computed in this work as systematic uncertainty (Us) from sensor precision moreover operational uncertainty for random uncertainty (Ur)[82]. The total uncertainty defined by Eq. (13):

$$U_t = \sqrt{U_s^2 + U_r^2} \tag{3.15}$$

A preliminary assessment of the overall uncertainty of experimental data for heavy oil-fired fuel and air swirled with 45° vane angles is shown in Table 3.5.

Table 3.5 The total uncertainty of the performance variables measured

Variables	Average value	Systematic uncertainty	Experimental uncertainty	Total uncertainty	Unit
CO	1.88	± 0.04	± 0.051	± 0.066	(vol. %)
CO_2	8.06	± 0.5	± 0.18	± 0.51	(vol. %)
HC	35	± 1.06	± 1.67	± 2.01	ppm
NOx	32.02	± 1.55	± 1.49	± 2.1	ppm
T	611	± 2	± 1.99	± 3.89	°C

3.13.3 Oxygen enrichment of combustion air

Most applications such as industrial processes need a significant amount of energy, which is typically provided by the combustion of fossil fuels including oil or natural gas. The oxidant in the majority combustion processes is air. In lots of circumstances, such methodologies can be accelerated by utilizing an oxidant with a more significant concentration of oxygen than air. This is referred to as *oxygen-enhanced combustion* (OEC). One example of OEC is by an oxidant consisting of air mix together with pure oxygen. Another case is using high-purity oxygen as the oxidant instead of air. This is usually submit to as oxy/fuel combustion[45].

Almost major industrial heating processes traditionally employed air/fuel combustion as the primary method. In several sectors, oxygen-enhanced ignition technologies are increasingly becoming widespread. Many advantages have been proven when typical air/fuel combustion systems were converted for OEC. Higher thermal efficiency, higher processing speeds, lower flue gas amounts, and lower environmental emissions are distinct benefits. Only oxygen is required in the combustion process when air is utilized as the oxidizer. Many advantages can be gained by removing nitrogen from the oxidizer.[83].

Oxygen has traditionally been utilized to improve combustion activities in four ways: First, by adding oxygen to the incoming combustion air flow; second introducing oxygen into an air/fuel flare, third substituting combustion air with high-purity oxygen; and fourth, by delivering combustion air and oxygen to the burner separately.

Figure 3.14 depicts an air/fuel arrangement in which the air has been supplemented with oxygen. This is known as low-level oxygen enrichment or premix enrichment. This technique can be used with many standard air/fuel burners. To guarantee appropriate mixing, the oxygen is introduced into the entering combustion air intake, often through a splitter. This is usually a low-cost retrofit that can give significant benefits. The additional oxygen will often reduce and enhance combustion. Therefore, there would be some worry if too much oxygen is introduced to air/fuel burning. The jet form may have become too short. Produced at high temperatures might cause damage to the burner (burner unit). The air tubing might have to exist adjusted for safety concerns to accommodate larger quantities of oxygen. Ultimate flames required some more oxygen to accomplish the burning of the fuel. This is owing to insufficient mixing of the fuel and the air. The oxygen mole fraction within the oxidizer (air) is defined as[45]:

$$\Omega = \frac{\text{the volume flow rate of } O_2 \text{ in the oxidizer}}{\text{the total volume flow rate of the oxidizer}} \tag{3.16}$$

If air is used as the oxidizer, then Ω = 0.21. The level of oxygen enrichment is occasionally utilized. This refers to the additional oxygen volume contained in the air. For example, if = 0.35, the oxygen enrichment is 14% (ranging from 35% to 21%).

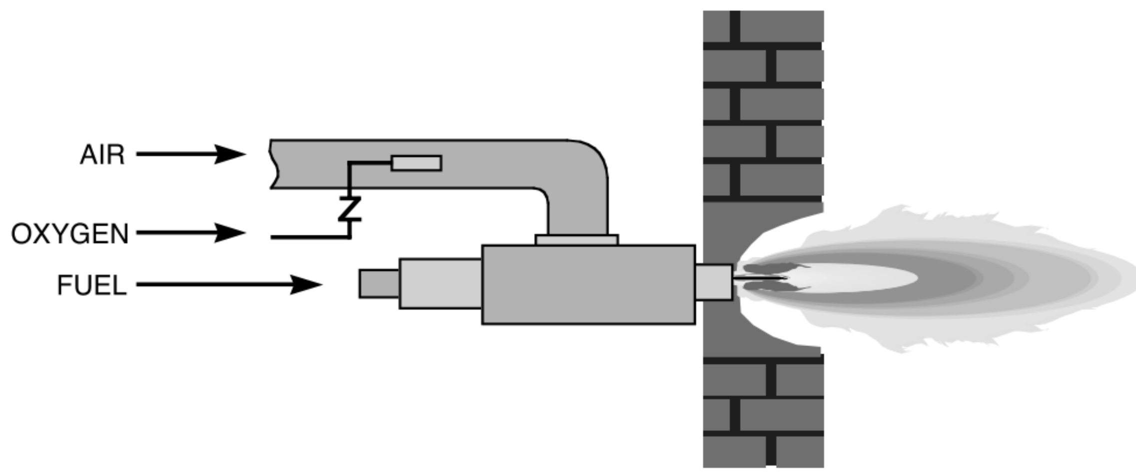


Figure 3.14 An oxygen-enrichment air/fuel burner schematic showing introduction of oxygen at center of air line

For O_2-enhanced combustion, there are currently two prevalent operating modes. The first or lower category is commonly known as low-level enrichment (Ω=0.30). This is typically employed in retrofit operations somewhere just minor changes to the existing combustion system are required. When just incremental advantages are necessary, it is employed. Across many circumstances, for example, with even relatively moderate levels of O_2 enrichment, the rate of production in a heating procedure can be greatly boosted. Most air/fuel burners be able to run reliably up to around Ω= 0.28 with no adjustments. Essentially, oxygen-enhanced combustion entails eliminating nitrogen from the air. The flue gas volume is reduced contrast to air/fuel combustion. Research is carried out by adding oxygen to combustion air, and results were obtained, which are discussed in the next section (Chapter 4). Up to 40% fuel savings have been confirmed.

Compared to the capital expenditures of extending an current unit or adding new apparatus to improve manufacturing, the extra costs of adding OEC to an existing combustion system are generally negligible. Traditionally, this has been one of the most common justifications for utilizing OEC. OEC has the benefit of being able to be employed periodically to fulfil frequent requirements for increasing output. For example, if the market for aluminium cans rises before the summer as of higher drinking, OEC can satisfy the extra burden. If prices drop over the winter, the OEC system might be rolled back or shut off until it is required yet again. If the increased manufacturing needs are inconsequential, employing OEC would be far more cost-effective than bringing additional machinery to boost output[84].

As reported, oxygen-enhanced flames contain much greater flame temperatures than typical air/fuel flames. If the temperature is not dispersed appropriately, the flame's heightened radiation output might produce refractory losses. To prevent overheating, the refractory work is done around the burner, as reported OEC burners are constructed for consistent heat distribution. Typically, the burners are housed in a refractory burner block, which is subsequently installed in the combustion process. The combustion blocks are composed of modern refractory equipment such as zirconium or alumina and are built to last for a long time with little repair work[31].

The tests in this study were carried out in the novel swirl burner, as shown in figure 3.1 (b). Air was utilized to atomize the fuel oil in a low-pressure oil burner (LPB). A 3 hp blower supplied the primary air i.e. mainly for oil atomization and secondary air i.e. for combustion. The secondary air was pumped coaxially into the novel swirl burner with the furnace oil spray. The oxygen came from liquid O_2 cylinders, evaporated by an evaporator, and mixed with the main combustion air line before valve T5, as shown in figure 3.12 (a).

The oxygen percentage in the air to the burner (vol. %) was the oxygen absorption of the feed gas. In contrast, the oxygen concentration of the oxidant (vol. %) be the volume concentration of O_2 in the overall produced oxidant in the combustion air. By steadily raising the oxygen flow rate while decreasing the air flow rate, the oxygen flow rate grew from 21% to 100%. (Air-firing to oxy-firing). The oxidant flow rate was adjusted in each experiment to match the minimal excess oxygen required. The total volume flow rate of the air supplied had to be reduced from 191.6 Nm^3/h to 46.5 Nm^3/h to raise the air's oxygen content (from air-firing to oxy-firing). The airflow rate was reduced by 76% in the oxy-firing instance (O_2 = 100%) compared to the air-firing case (O_2 = 21%). We steadily lowered and enhanced throughout the transition from air-firing to oxy-firing. The oil flow rate was kept constant, and the net flow rate of O_2 was kept practically constant at 42 Nm^3/h. While oxygen was raised, the only element in the airflow that dropped was the net frequency of N_2. In Table 3.6, oxygen concentrations while the operation is listed.

Table 3.6 Burner functioning conditions in detail

Ω (Vol. %)	21	30	45	60	75	90	100
Primary air	47.2	49.1	48.3	47.8	44.2	41.1	0.0
Secondary air	141.1	111.2	76.1	49.2	0.0	0.0	0.0
Oxygen flow rate (Vol. %)	0.0	19.5	29.3	34.8	39.1	42.9	46.3

Chapter 4
Results, Validation and Discussion

4.1 Testing and trials of the furnace with recuperator

The traditional oil-fired boiler tested in this investigation allowed the primary inlet air to exhaust into the surrounding atmosphere as waste heat before heating the raw material in the crucible. The specifically developed recuperator, as detailed in the previous chapter, was installed in the modified furnace. The recuperator utilizes this misuse heat to pre-heat the inlet air, increasing the furnace's effectiveness. Table 4.1 compares particular efficiency and fuel consumption for the proposed furnace to comparable furnaces. The data directly shows a considerable enhancement in furnace parameters, so achieving the study's objectives.

The heat vs time charts for the furnace before and following the utilization of the recuperator is shown in Figure 4.1 and 4.2, respectively. In figure 4.1, shows that the first fire (cold fire) of the furnace takes longer (90 minutes) than successive charges (45 minutes). When the charge is complete, it is transferred into the moulds. The raw material/scrap is fed into the furnace crucible to prepare the subsequently charge. For successive charges, the process is repeated. The time required for melting of raw material/scrap in the furnace not including a recuperator is depicted in Fig. 4.1. The increase in the plot indicates raw material heating. In contrast, the fall describes molten metal pouring. For every pattern indicates that molten aluminium is prepared to be poured. Four charges may be acquired in a single working day not including the recuperator. In comparison, five charges (Fig. 4.2) were produced in the same time frame after including the proposed recuperator. These findings illustrate the recuperator's utility. OFTF efficiency using and not including the recuperator found observed to be 11% and 21%, respectively. Furthermore, the noteworthy furnace's specific fuel consumption was 0.166 kg/kWh, which was lowered to 0.138 kg/kWh when the proposed recuperator was installed with the burner. This suggests that the recuperator in the furnace could successfully reduce specific fuel consumption by 10%, which is a major improvement.

Table 4.1 compares the proposed furnace to comparable oil-fired furnaces that run on furnace oil (FO)

S no.	Type of furnace	Specific fuel consumption(kg/kWh)	Efficiency
1.	Oil-fired pit furnace [85]	0.231	6.50 %
2.	Rotary furnace[85]	0.260	5.70%
3.	Oil-fired tilting furnace without a recuperator	0.166	11%
4.	Oil-fired tilting furnace with the recuperator	0.138	21%

The presence of hot air, particularly preheating the air blower's intake air, can be ascribed to this improvement. Brueckner et al.[33] the calculated cost factor (C) and total coefficient of heat transfer (U) values for various heat exchanger types, including shell and tube heat exchangers, welded plates, double tube heat exchangers, and the anticipated costs for each type are presented in Table 2.

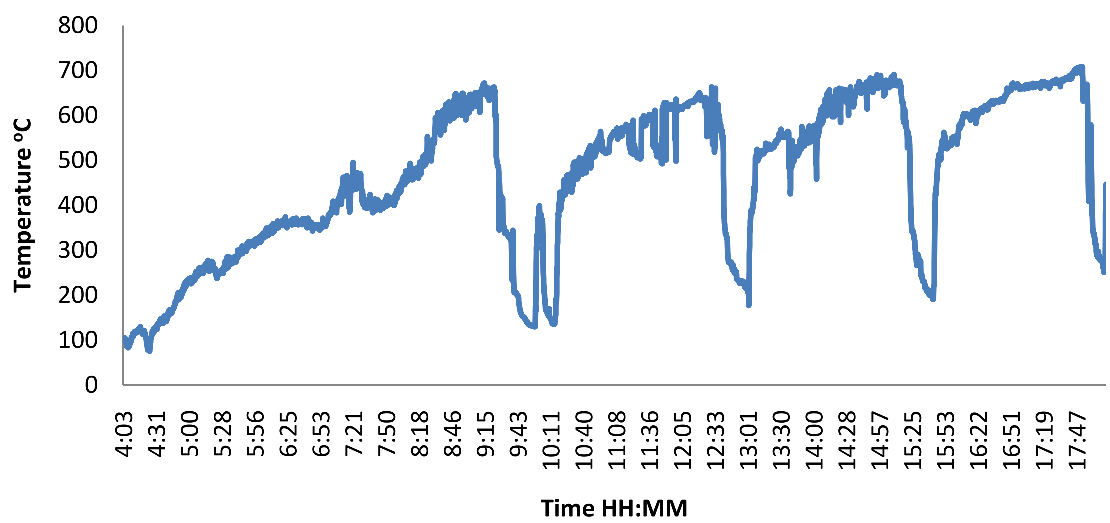


Figure 4.1 depicts the temperature change inside that furnace without a recuperator over a day

The result shows that when Q/T_m increases, so do the cost ratio of plate-and-frame exchangers to shell-and-tube exchangers. C_1 and C_2 numbers for designed recuperators are slightly higher than those for double-pipe type heat exchangers but lower than those for shell/tube and welded plates. This gives credibility to the recuperator's utility.

Following the technical details and ease of use, it is worth noting that the newly built OFTF, as illustrated in Fig. 4.3(a and b), may be operated by a semi-skilled operator in the furnace, a hydraulic system has been constructed, allowing the machinist to transfer molten metal straight into the moulds. This characteristic gives this furnace a significant advantage over the other furnaces listed in Table 4.1, which involve two or more operators to finish the pouring procedure.

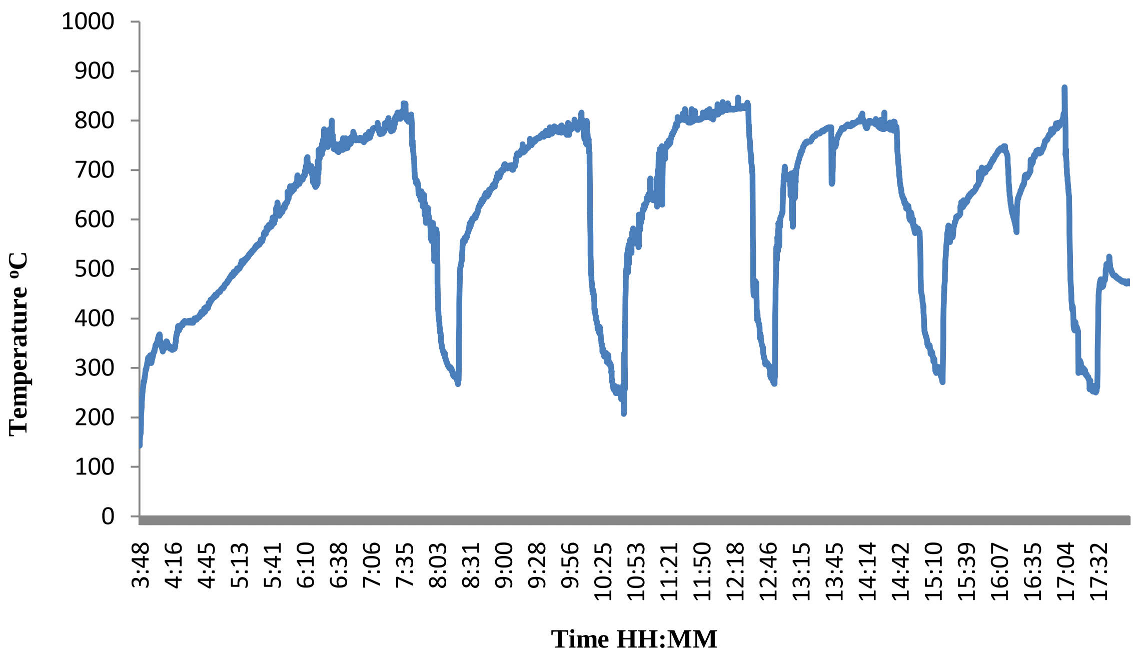


Figure 4.2 illustrates the temperature differences in the furnace following the planned recuperator's installation over a long workday.

Table 4.2 Cost factor (C) and total coefficient of heat transfer (U) values for various heat exchanger types.

Heat exchanger type	C_1 and C_2 values ($(W/K))		Interpolated C value	Costs ($)
	$Q/\Delta T_m$=l000W/K	$Q/\Delta T_m$=5000 W/K	$(W/K)	$Q/\Delta T_m$ X C
Shell-and-tube[38]	4.89	1.41	2..91	5412
Double-pipe[33]	2.8	1.0	1.74	3138
Welded plate[8]	5.6	2.54	3.26	9793
Recuperator	3.8	1.822	2.179	4053

Figure 4.4 illustrates a proposed furnace operation at Prakash Alloy Udhyog in Jagadhari, Haryana, India. It is worth noting that the capital expenditure for a pit type furnace of similar size is relatively inexpensive. Therefore, operational costs are more extensive, making it a more expensive enduring investment. Additionally, a rotary furnace of comparable capability has a greater operating expenditure than a designed furnace. Similarly, the cubic space required by an OFTF is smaller than that of a pit furnace or a rotary furnace. After initial installation, a pit furnace system had a permanent infrastructure, whereas rotary furnace movement is strenuous. On the other hand, the proposed furnace is portable and does not impose these limits.

Another significant issue with traditional furnaces is the long-term exposure of employees to harmful pollutants. This problem was solved in the designed furnace by redirecting pollutants away from the operating area.

Figure 4.3 a hydraulically tilting furnace system feeding melted aluminium into a 100kg ladle at Prakash Alloy Udhyog in Jagadhari, Haryana, India.

Finally, figure 4.4 depicts the burner input temperatures vs time plots for OFTF using and exclusive of the recuperator. The graphic shows that the burner intake temperature is atmospheric in a furnace without a recuperator (32^{o}C). Furthermore, using a recuperator, the burner inlet temperature may be boosted to over 300^{o}C, which is 268°C higher than the heat in the cold fire. This temperature increase makes the designed furnace more efficient and energy efficient. It has been demonstrated that employing the recuperator increases the furnace's thermal efficiency by 10% for every 50^{o}C reduction in exhaust gas temperature. The recuperator lowered the furnace's specific fuel usage by 10%. As a result, the designed furnace is cost-effective and has a payback time of fewer than two years.

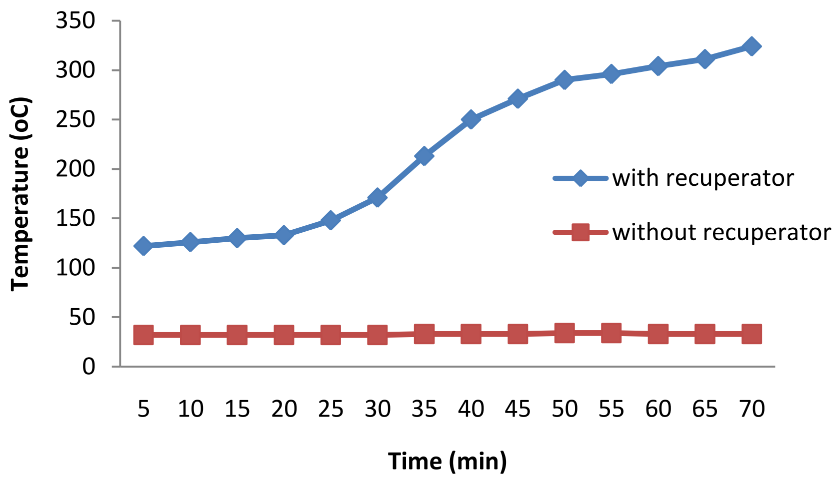


Figure 4.4 plots of burner input temperature vs time for the furnace with and without the recuperator.

4.2 Influence of air swirl vane angle on the CO emission

Figures 4.5 show the amounts of CO emission by the air swirled at various vane angles with preheated secondary air and without secondary air. According to the observations, CO emissions were initially decreased when the angle was adjusted from 15° to 25° for both with and without preheated secondary air. The air swirl vane angle of 90° caused the least change and resulted in the maximum CO emissions with and without preheated secondary air. The study revealed that air swirl vane angles of 30°, 45°, and 60° improved air swirling and fuel-air mixing; hence, CO emission is at its lowest at all of these angles. The results showed that preheated secondary air improved carbon monoxide emissions at a vane angle of 45°. This is due to the recuperator's fuel atomization in preheated air, which enhances combustion setting with air swirling and minimizes the quantity of CO[12][86].

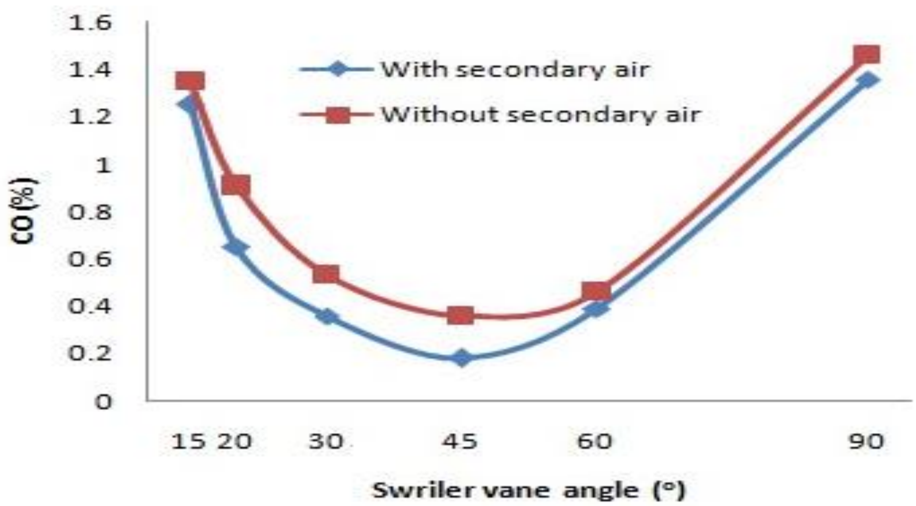


Figure 4.5 effect of various air swirl vane angles on CO emissions with preheated secondary air and without secondary air.

4. 3. Influence of air swirl vane angle on the CO_2 emission

Carbon dioxide is a non-combustible, colourless gas that is produced when carbon-containing fuels are entirely burned. As a result, CO_2 is a critical parameter for exhaust emissions. Figures 6 show the amounts of CO_2 emission by the air swirler at various vane angles with preheated secondary air and without secondary air. The results point out that adjusting the air swirl vane angle affects CO_2 emissions. The CO_2 level rise marginally when the vane angle is changed from 15° to 20° and 30°, and then decline drastically at 60° for both with and without preheated secondary air. According to the results, the smallest value of CO_2 emissions was recorded at an angle of 60°. As the angle changes from 60° to 90°, CO_2 emissions appear to increase. This has been due to a charge concentration within the combustion chamber, resulting in abrupt combustion at high temperatures and an increased carbon and oxygen reaction rate[10][87][88].

On the other end, the sum of CO_2 increases from 30° to 60°, owing to increased turbulence in the flame propagation and assists in air-fuel mixing just before ignition. The highest value of carbon dioxide emissions is associated with an air swirl vane angle of 20°. The study also exhibits that the maximum quantity of CO_2 was produced at angles of 20° and 30°, indicating that complete combustion happened, attributing to improved air swirl and air-fuel mixing[21].

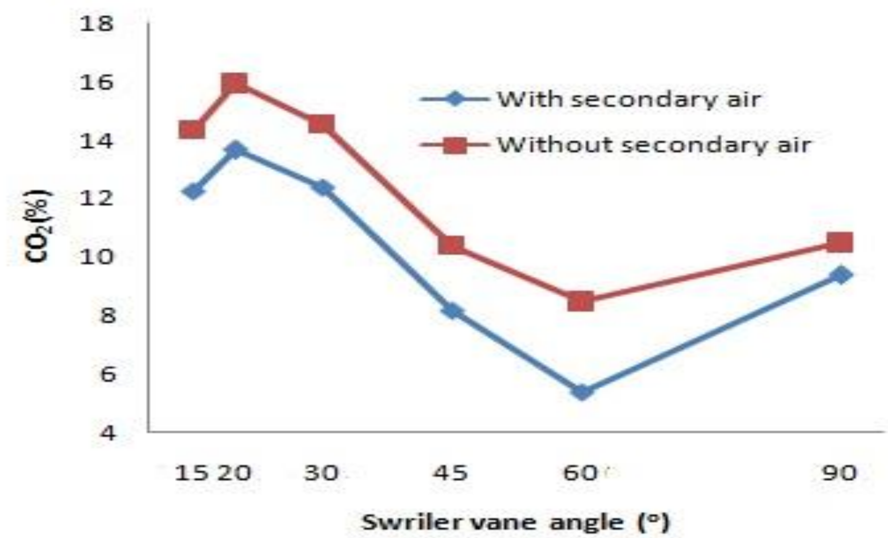


Figure 4.6 Influence of various air swirl vane angles on CO_2 emissions with preheated secondary air and without secondary air.

4.4. Influence of air swirl vane angle on the HC emission

Figures 4.7 show the deviation of hydrocarbons emission vs air swirler vane angles with and without preheated secondary air. The findings indicate that the air swirl vane angles are directly connected to HC emissions. The incomplete combustible hydrocarbons was decreased initially by varying the air swirler vane angle from 15° to 35° with and without preheated secondary air. The highest value of HC emissions was observed at vane angles of 15° and 45°. Following that, HC emissions at a 60° angle were lowered due to improved air swirl and air-fuel mixing.

According to the observations, at the vane angle of 30° produces the least quantity of hydrocarbons. Furthermore, vane angles of 15° and 45° have relatively poor outcomes for hydrocarbon emissions released by the furnace. It might also be caused by the swirl influence on the flame's stability and dimensions, as well as the extension of the recirculated mass in the primary flow region[89][81][90].

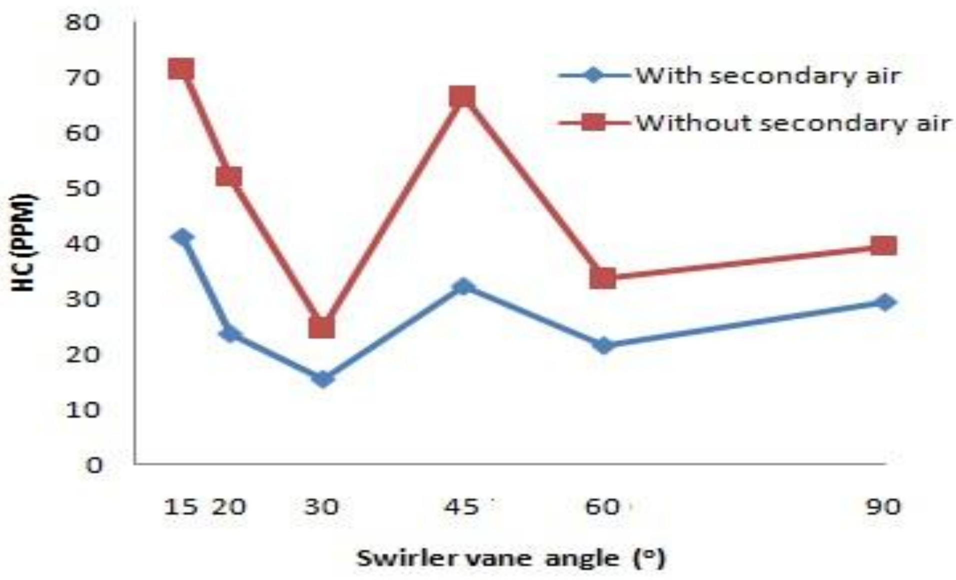


Figure 4.7 Influence of various air swirl vane angles on HC emissions with preheated secondary air and without secondary air.

4.5. Influence of air swirl vane angle on the NOx emission

Figures 4.8 demonstrate the deviation of NOx emission vs air swirler vane angles with and without preheated secondary air. Nitrogen oxide emissions were initially exceeded when the vane angle increased from 15° to 20°, then significantly decreased at the air swirl vane angle of 30°. And as per observations, nitrogen oxides are at their lowest at 45° and rise as the vane angles shift from 45° to 90° for both with and without preheated secondary air.

Furthermore, the most significant quantity of NOx occurs at a 20° angle, most possibly owing to improved air swirling and air-fuel mixing, resulting in improved temperature setting and the synthesis of thermal nitrogen oxides. It is observed that the concentration of NOx in the outlet section of the novel burner is higher at large air swirl vane angles than at smaller air swirl vane angles. Furthermore, at the most favourable vane angle of 45°, the furnace's exhaust emits the least amount of nitrogen oxides. Except for the thermal NOx process, it is well understood that nitrogen-containing organic molecules found in fossil fuels in liquid form can play a significant role in the overall NOx generated during melting[91][92].

The studies show that the secondary air distribution model with preheating of incoming air significantly impacted nitrogen oxide emission and complete combustion of heavy fuel oil. The following are the reasons: low nitrogen oxide combustion knowledge is based on calculating and delaying the air-fuel mixture in the furnace. It is predominantly focused on providing the furnace with the correct local air-to-fuel ratio. Adjusting secondary air distribution first affects air-fuel mixing, subsequently affecting NOx generation. Reducing the environment (fuel-rich) is beneficial to lowering NOx generation. Still, it decreases the burning rate of heavy oil, resulting in sizeable unburned carbon in the exhaust and carbon monoxide emissions[93].

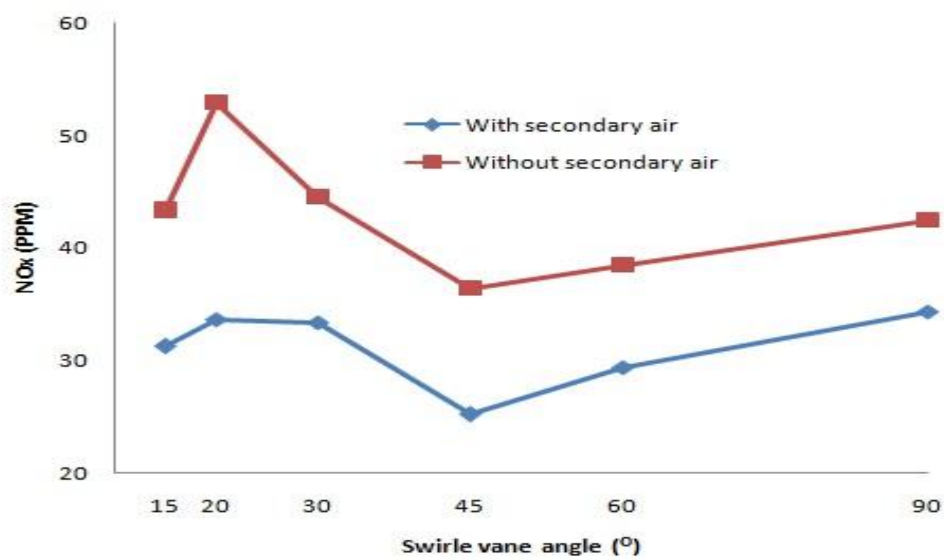


Figure 4.8 Effect of various air swirl vane angles on NOx emissions with preheated secondary air and without secondary air.

4.6. Influence of air swirl vane angle on the thermal efficiency of the crucible furnace

Figure 4.9 displays the temperature profile at six vane angles of 15^o, 20^o, 30^o, 45^o, 60^o and 90^o. It has been shown that as the swirl angle rises from 15^o to 45^o, so will the maximum furnace temperature. However, as the angle approaches 90^o, the maximum temperature drops. This behavior indicates an optimal swirl angle of 45^o for the vane. The air-fuel mixing rate reaches its maximum at the optimal angle of 45^o. It results in complete combustion and the maximum flame temperature. Air-fuel impact time (the duration that air-fuel are in contact) and air-fuel contact area influence the mixing process. A hollow-cone nozzle injects liquid droplets into the heavy fuel burner, and air flows around the conical layer of heavy fuel for homogeneous air–fuel mixing. The significant axial component of the input air velocity reduces the contact area and duration between the air and the heavy fuel jet when there is a slight air swirl angle of about 15^o. However, at angles more significant than the optimal angle (such as 90^o), the substantial angular component of the input air velocity, comparable to effective centrifugal force, steers the air travelling toward the furnace insulation lining, limiting the air-fuel jet contact area. However, in an ideal scenario, the combined effect of contact area and duration optimizes both the input air and the mixing rate of the fuel jet at 45^o. The greatest possible flame temperature and maximum heat transfer component from the furnace, i.e. a minimum exhaust gas temperature, are required for effective combustion. The combustion efficiency of the burner was defined as Eq. (4.1) to take these requirements into account.

$$\eta = \frac{h_{\text{fuel (LHV)}} + h_{air} - h_{\text{fuel gas (inlet)}}}{h_{\text{fuel (LHV)}}} \tag{4.1}$$

Where $h_{fuel(LHV)}$ is the lesser heating rate of the fuel, h_{air} is the enthalpy of the preheated combustion air, and $h_{flue\ gas\ (inlet)}$ is the enthalpy of the exhaust at the inlet of the recuperator. Figure 4.9 illustrates the combustion efficiency at various vane angles, including 15^o, 20^o, 30^o, 45^o, 60^o and 90^o. According to Fig. 4.10, as the air swirl vane angle rises, the combustion efficiency increases as far as it reaches a maximum (45^o), at which point it begins to decline. It demonstrates that the vanes have an optimal air swirl vane angle of 45^o. Radiation heat transmission is the most critical heat transfer mechanism at high flame temperatures. Temperature and the emissivity coefficient of the furnace crucible influence radiation heat transfer. The dominant radiative species of combustion by-products are carbon dioxide, water vapour, and soot particles[94][13][59].

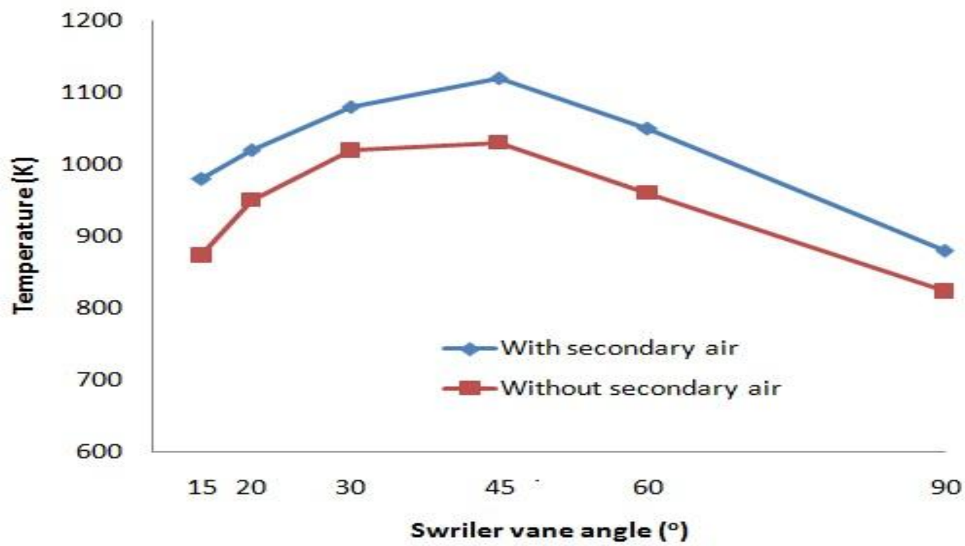


Figure 4.9 Influence of various air swirl vane angles on the temperature of the furnace with preheated secondary air and without secondary air.

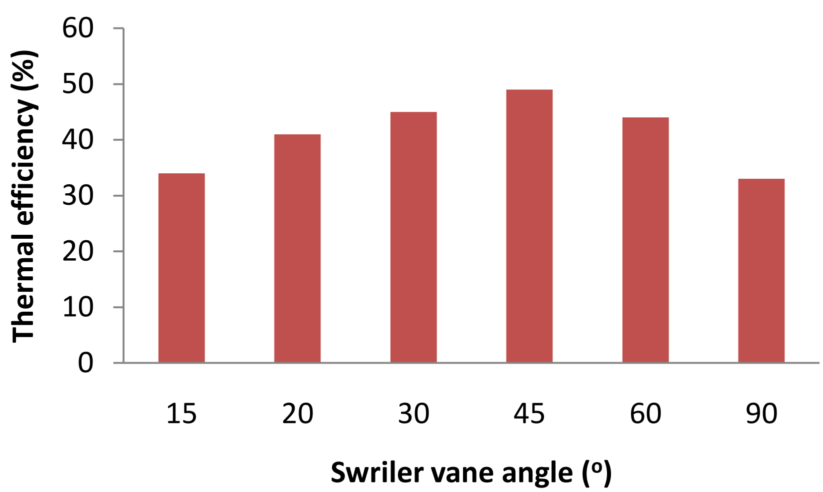


Figure 4.10 Effect of various air swirler vane angles on furnace thermal efficiency with preheated secondary air and without secondary air.

4.7 Oxygen enrichment

Figures 4.11 show the results of the flue gas composition analysis. Each experiment case was calibrated to satisfy the minimum excess O_2 necessary for complete fuel efficiency; hence carbon monoxide was all the time kept at a low value; nevertheless, carbon monoxide level rose when oxygen was more prominent than 60% in operation. The outstanding oxygen remained constant until the oxygen intensity reached around 60%; the residual oxygen grew somewhat in these cases. We started replacing the atomizing air when oxygen got roughly 55%. Reduced oxygen in the atomizing air may aid in producing CO. If the CO level had to be reduced to a minimum, more surplus oxygen was needed.

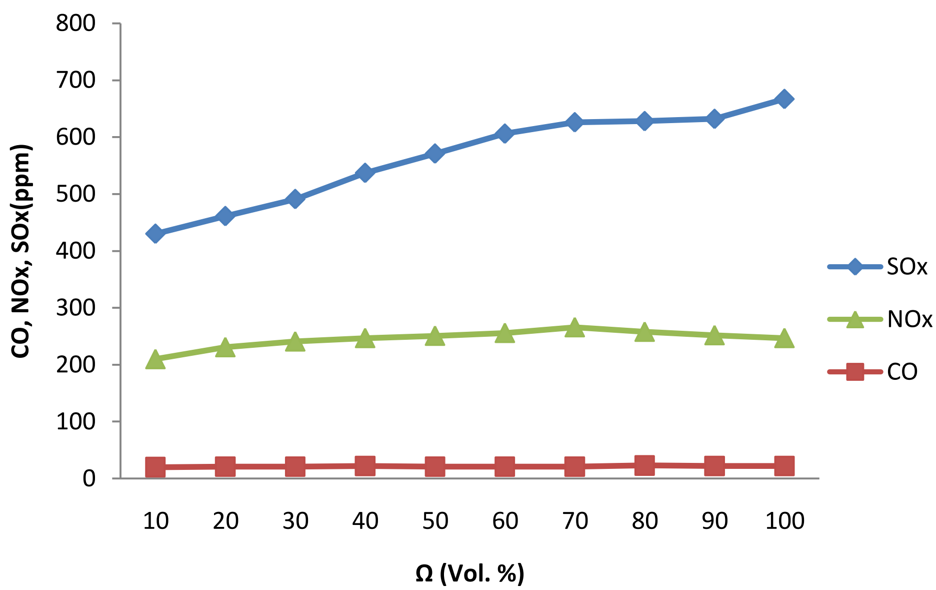


Figure 4.11 Effect of oxygen enrichment during monitoring of emission spices SOx, NOx and CO in operation.

The level of nitrogen oxide emission grew with oxygen due to a rise in combustion zone temperature, favoring thermo-nitrogen oxide production. The sulfur dioxide emission level rose considerably with oxygen; also, the sulfur dioxide concentration in the exhaust gas was more significant in the process than in the oxygen enrichment function. This may be due to less air leaking into the furnace during the oxygen enrichment procedure. Furthermore, because sulfur dioxide generation is directly related to the fuel's sulfur concentration, the operation's emission level was limited to roughly 350 ppm. The attention of nitrogen oxide and sulfur dioxide in the exhaust gases grew as oxygen increased, improving the efficiency of flue gas treatment. The absorption of CO_2 in the exhaust gas grew when oxygen was added. The concentration of CO_2 increased from 13% to 34.4% and 14.7% to 61.1% in the operations at some point in the shift from air-firing to oxy-firing. Because the swirling portion was still operating, the O_2 content in the oxidant was thinned by the entering air; the outcome were substantially lower than the predicted value.

4.8 CO/CO₂ ratio analysis

The CO/CO_2 ratio is considered CO divided by CO_2 in the flue gas. It indicates how excellent a flue gas testing the device is reading and how clean the furnace is running. To satisfy the need of clean combustion of fuel and efficient, it is required to be aware of and accept the combustion character of fuel and then precisely anticipate the combustion characteristics, which serves as the foundation for oil-fired tilting melting furnace design and optimization.

Furnace-oil (FO) combustion is a simple process, but it isn't easy. Mainly, C and O are involved in furnace-oil combustion regarding chemical components; sometimes, H is also considered[95]. Moreover, many things affect the furnace-oil combustion process, including changes in pore structure, the most important of which are chemical reactions, the deactivation phenomenon at high temperatures, oxygen diffusion processes, and the catalyzed or inhibitory effect of smoke, all of which have been extensively studied[96]. Between all elements, there is not much question that the substance reaction is the foundation of furnace-oil combustion, with the following movements implicated[97]:

$$C + O_2 \rightarrow CO_2 \quad \Delta H_1 = - 395.4 \text{ kJ/mol} \tag{4.2}$$

$$C + 1/2O_2 \rightarrow CO \quad \Delta H_2 = - 109.9 \text{ kJ/mol} \tag{4.3}$$

$$C + CO_2 \rightarrow 2CO \quad \Delta H_3 = 175.6 \text{ kJ/mol} \tag{4.4}$$

$$2CO + O_2 \rightarrow 2CO_2 \quad \Delta H_4 = - 572.1 \text{ kJ/mol} \tag{4.5}$$

Between such processes, reaction (4.4) is commonly referred to as furnace-oil gasification, and it can largely be neglected below 900°C. Many outstanding investigations have been conducted on the chemical reaction system of C and O_2. The broad view of this reaction mechanism is that oxygen is first attributed to the presence of furnace-oil elements, then interacts with free-site carbon can form complexes such as C(O) or C(O_2), and subsequently departs from the furnace- oil particle surfaces as CO or CO_2. The most common method for studying the chemical reactivity of furnace-oil combustion is to quantify it many obvious physical quantities, such as combustion rate, CO/CO_2 ratio, and particle temperature, in order to collect key thermodynamic properties such as pre-exponential determinant and activation energy of every phase of the reaction. As a result, the CO/CO_2 ratio of FO burning is essential in understanding the chemical reaction process and estimating the combustion time. But, due to the influence of reaction (4.5), the fast transformation of CO/CO_2 on the surface of furnace-oil particles or in the boundary layer makes it impossible to correctly determine the quantity of CO to CO_2 generated by the heterogeneous reaction. Consequently, it is still controversial if the result of furnace-oil combustion is solely CO or both CO_2 and CO, as well as the particular CO/CO_2 ratio. Because the secondary reaction cannot be prevented, it doesn't remain easy to honestly evaluate the primary CO to CO_2 ratio of FO combustion, regardless of the analytical approach. Moreover, as previously stated, one of the immediate impacts of the CO/CO_2 ratio relates to the calorific value and, as a result, the heat of the FO particles. It is also practicable to analyze the CO/CO_2 ratio of FO combustion again from the standpoint of temperature release.

The CO/CO_2 ratio (%) of FO burning is illustrated in figure 4.12. The monitoring of CO and CO_2 at six vane angles of 15^o, 20^o, 30^o, 45^o, 60^o and 90^o and graphing the ratio shows that combustion efficiency fluctuates with oxygen enrichment. According to the observations, CO/CO_2 ratio (%) were initially decreased when the angle was adjusted from 15° to 25° for both with and without oxygen enrichment. The air swirl vane angle of 90° caused the slightest change and resulted in the maximum CO/CO_2 ratio (%) with and without oxygen enrichment. The study revealed that air swirl vane angles of 30°, 45°, and 60° improved air swirling and fuel-air mixing; hence, CO/CO_2 ratio (%) is at its lowest at all of these angles. The results showed that using preheated secondary air and oxygen enrichment did not significantly affect the vane angle of 45°. This is due to the recuperator's fuel atomization in preheated air with oxygen enrichment, which enhances the combustion setting with air swirling and minimizes the quantity of CO/CO_2 ratio (%).

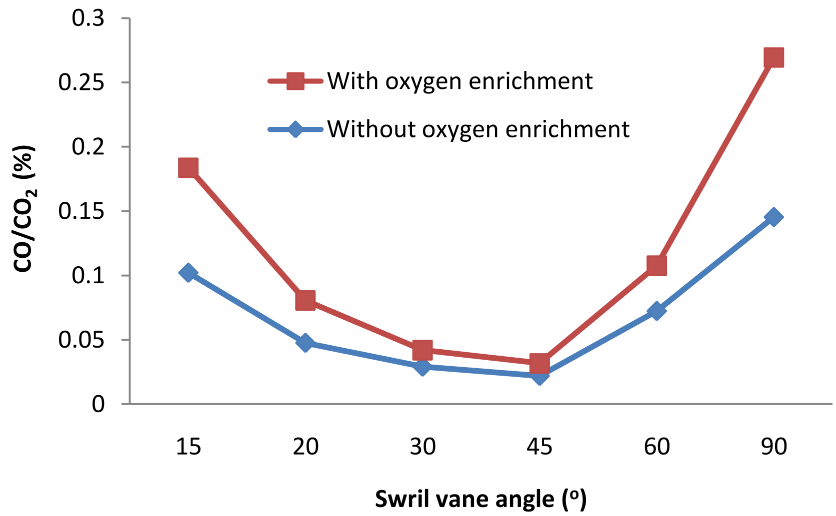


Figure 4.12 Influence of various air swirl vane angles on CO/CO2 ratio (%) with and without oxygen enrichment.

Chapter 5
Conclusions and Future Scope

5.1 Conclusions

Using the proposed recuperator design, the heat energy, which would waste in the environment, was used efficiently to obtain maximum fuel combustion. Applying hot air to the burner resulted in a considerable improvement in the consumption of fuel. Moreover, the proposed recuperator reduced the furnace exergy loss and enhanced thermal efficiency by 50%. The scientific research might fulfil the technological objective of minimizing the consumption of fuel without threatening the furnace's functionality. Air preheating could indeed successfully lowered specific fuel consumption through a novel recuperator since preheating the primary air resulted in efficient combustion and significant fuel savings. Because of the air and fuel preheating, a larger volume of metal may be melted with the same amount of input energy. Furthermore, the environmental considerations were adequately bothered since the developed recuperator's unique features resulted in efficient fuel combustion.

On-site testing and trials were conducted to determine the influence of preheated primary air swirling on polluting emissions and flue gas temperature in a heavy oil-fired 250kg crucible furnace with a novel preheat swirl burner at different vane angles (15^o, 20^o, 30^o, 45^o, 60^o and 90^o). Based on the findings, the following conclusion and recommendation may be drawn:

1. Changes in CO, HC, NOx, and CO_2 emissions can be influenced by varying the air swirl vane angle in the novel burner.
2. Air swirl vane angles of 45° produce the lowest CO, HC, and NOx emissions, whereas swirl air vane angles of 60° produce low CO_2. It is due to the homogenous mixing of fuel particles with incoming preheated air at vane angles of 45°.
3. For all the parameters tested in the furnace, HC and CO emissions were less than 20 ppm, which is 10% lesser than the permissible limit in the emission by-products.

4. Preheated primary air reduced nitrogen oxide emissions more effectively, while fuel atomization with preheated outer secondary air-fuel mixture reduced particle emissions more effectively. As a result, combining both approaches allow the user to reduce both nitrogen oxides and particle emissions from heavy fuel oil burning.
5. Fuel atomization combining pre-heated air and heavy fuel oil particles is an effective way to reduce nitrogen oxides and particle emissions at the same time. Preheating helps to gain latent heat and increase the volume of premixed air-fuel particles.
6. An air swirl vane angle of 45° is better than other air swirl vane angles to produce lower various pollutant emissions. This happens only when air-fuel particles are homogeneously mixed in the premix chamber.
7. The air swirl combination is critical in the arrangement of the combustion flame, and the outer air swirl is more significant in mixing air fuel, improving the flame's stability. With an increased stratification ratio, the impact becomes more prominent and gives additional resilience to flame stability.
8. An advantageous system of preheated secondary air quickly enhances the temperature distribution. Intense mixing and a prolonged dwell time in the reducing combustion zone were critical to lowering nitrogen oxide emissions. The multi-layer and staggered arrangement of pre-heated secondary air drastically reduced nitrogen oxide emissions by 25 PPM or less. It is due to the homogenous mixing of fuel particles with incoming preheated air at vane angles of 45°.
9. The current study also revealed significant improvement during aerodynamic variations within air-fuel mixing. Differences in primary and secondary preheated air velocity impact and flame shapes caused it.
10. The recuperator's fuel atomization in preheated air with oxygen enrichment enhances the combustion setting with air swirling and minimizes the CO/CO_2 ratio (%).

5.2 Future scope

In the present work, an oil-fired tilting furnace has been systematically designed and fabricated using recuperator technology to achieve near-perfect fuel combustion. The following points may be considered in future studies:

1. Efforts can be made to make the oil-fired tilting furnace suitable for the ferrous melting application.
2. A device can be designed as a technology development activity to monitor the furnace's performance with a recuperator in real time.
3. Automation of air-fuel mixing of fuel blending with bio-fuel and bio-gas may be investigated.
4. Melting application may be investigated with pallet firing from agricultural waste like paddy straw.
5. Experimentation can be carried forward by incorporating different types of oxygen enrichment techniques.
6. To reduce heat losses through the wall of the furnace, the role of interlocking refectory bricks work can be investigated.

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