Section A-Research paper
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"Mathematical and CFD Modeling for Reducing Natural Gas Consumption and Emissions with Waste Heat Recovery in Aluminum Heat Exchanger Brazing"

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Abstract - "Waste heat recovery in industrial processes is an important strategy for improving energy efficiency and reducing environmental impacts. In this study, we evaluated the feasibility of waste heat recovery in nocolok furnaces used in aluminum heat exchanger brazing. We first calculated the mathematical potential of waste heat recovery and then used computational fluid dynamics (CFD) simulations to identify the most effective arrangements for recovering and utilizing waste heat. Our results demonstrate that waste heat recovery is indeed feasible in this context, and that the optimal arrangement for recovering waste heat involves a heat exchanger located downstream of the combustion chamber. Furthermore, we found that after the implementation of waste heat recovery, the consumption of piped natural gas (PNG) decreased from an average of 28,000 SCM per month to 21,500 SCM per month, resulting in significant cost savings for the organization. This waste heat recovery system could also reduce greenhouse gas emissions. Our study provides valuable insights for companies looking to improve the energy efficiency of their industrial processes and highlights the importance of carefully evaluating the potential for waste heat recovery in specific contexts."

Keywords: Waste heat recovery, nocolok furnaces, aluminum heat exchanger brazing, mathematical calculations, computational fluid dynamics, energy efficiency, greenhouse gas emissions, Piped Natural Gas, Standard Cubic Meter

1. INTRODUCTION

Industrial processes are significant sources of waste heat, which represents a major opportunity for energy conservation and greenhouse gas reduction (Ismail et al., 2021; Lee et al., 2019). NOCOLOK furnaces are commonly used in the aluminum industry for brazing of heat exchangers. NOCOLOK flux aluminium brazing technology have been the first choice for more than 25 years in the production of aluminium heat exchangers and other components. For the brazing of aluminium heat exchangers furnace is used. However, the high temperature combustion process generates a significant amount of waste heat that can be recovered and utilized to improve the overall energy efficiency of the system. In this study, we evaluate the feasibility of waste heat recovery in nocolok furnaces and identify the most effective arrangements for recovering and utilizing waste heat.

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Waste heat recovery systems have been implemented in various industrial processes to improve energy efficiency and reduce environmental impacts (Chen et al., 2020; Gharehkhani et al., 2021). The efficiency of these systems depends on various factors such as the temperature of the waste heat, the amount of heat that can be recovered, and the effectiveness of the heat recovery arrangement (Nizam et al., 2020). In the case of nocolok furnaces, waste heat recovery has the potential to reduce energy consumption, lower operating costs, and reduce greenhouse gas emissions (Li et al., 2020; Li et al., 2021).

Brough and Jouhara (2020) reviewed the state-of-the-art technologies and environmental impacts of the aluminum industry, highlighting the potential for waste heat recovery. In another study, Jouhara et al. (2019) discussed the different waste heat recovery technologies and their applications. Trivedi (2019) investigated furnace optimization as a means of reducing costs and improving efficiency in the aluminum industry. Farhat et al. (2022) conducted a recent review on waste heat recovery methodologies, including case studies of successful implementation.

Various studies have also investigated waste heat recovery in other industries. For example, Choi et al. (2019) analyzed the variable heat exchange efficiency of heat recovery ventilators, while Zhang and Fung (2015) studied the impacts of defrost cycles on energy recovery ventilators. Zhou et al. (2010) investigated the performance of an energy recovery ventilator with different weather and temperature set-points. Krokida and Bisharat (2004) explored the potential for heat recovery from dryer exhaust air.

To evaluate the feasibility of waste heat recovery in nocolok furnaces, we first calculate the mathematical potential of waste heat recovery, and then use computational fluid dynamics (CFD) simulations to identify the most effective arrangements for recovering and utilizing waste heat. Our study provides valuable insights for companies looking to improve the energy efficiency of their nocolok furnaces, and highlights the importance of carefully evaluating the potential for waste heat recovery in specific contexts.

In this paper, we present the details of our study, including the specific calculations and simulations performed, the results obtained, and the potential benefits of waste heat recovery in nocolok furnaces. We believe that our findings could be useful for companies looking to reduce energy consumption and environmental impacts and provide a foundation for future research in this area.

2. Actual Experimental Furnace

The thermal degreaser zone is an essential step in the brazing process, used to remove any oil present on the core of the product. This zone operates at a temperature range of 155 to 175 degrees Celsius and utilizes agitator fans to ensure that the temperature is spread uniformly, resulting in even treatment of the core. Unfortunately, there is a risk of fire in this zone due to the use of LPG and air through the burner motor, but this can be mitigated with proper safety measures.

Next in the process is the fluxing zone, which is responsible for spraying the nocolok flux on the core to ensure proper brazing. The flux is sprayed using 14 nozzles, which are assembled in two sets of shafts. It is important to note that all nozzles must be in working condition to prevent any issues with the product. The pressure is maintained between 2 to 4 bar, and manual fluxing is utilized to ensure that any gaps at the joints are properly fluxed. This is because the automated fluxing zone cannot always properly flux these areas. For manual fluxing, a combination of CS flux and glycol is used.

After the fluxing zone comes to the dry-off zone, which is used to remove any water present in the flux that was sprayed on the product. This is crucial because water can create carbon dioxide, which is detrimental to the brazing atmosphere. In this zone, hot air is circulated at a temperature range of 240 to 350 degrees Celsius to remove the water. It is important to note that failure to properly remove the water can significantly reduce the life of the furnace.

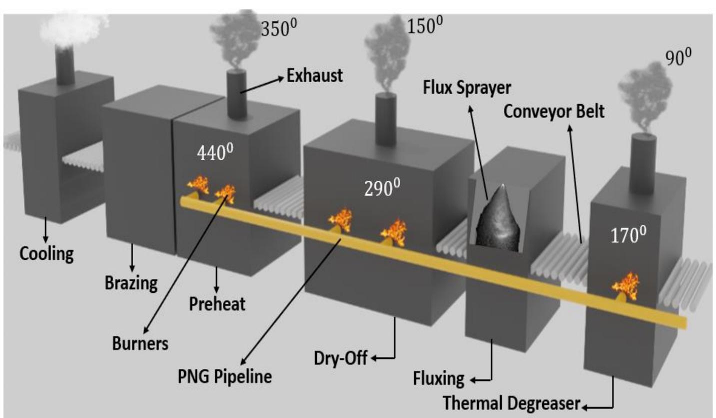
Next, the preheat zone is utilized to prepare the product for brazing. This zone is responsible for drying off the flux that was sprayed on the surface of the core in the previous zone. Curtains are provided to save heat from escaping, and the temperature range is between 410 to 550 degrees Celsius. This high temperature is necessary to achieve a better brazing result in the final step.

Finally, the brazing zone is the main part of the furnace and is fully electrically fired. The zone is filled with nitrogen to ensure a brazing atmosphere and is heated to a temperature range of 595 to 630 degrees Celsius. This step is crucial to ensure proper bonding between the product and the filler metal. In this zone, electric heaters are used to provide the necessary heat.

Overall, each zone plays a crucial role in the brazing process, and it is essential to properly utilize each zone to achieve the best possible result. While each zone has its unique characteristics and requirements, they all work together to ensure a successful and efficient brazing process.

To ensure uniform treatment of the core, an agitator fan is used to spread temperature uniformly in the Thermal Degreaser, which also helps in removing oil present on the core. It is essential to have all 14 nozzles in working condition in the Fluxing Zone to prevent any issues with the product. Overall, this process provides a reliable and efficient method of brazing with proper temperature control and prevention of any potential issues during the process.

Fig – Furnace



3. Literature Review

The aluminum industry is a major energy consumer, and the demand for energy continues to grow with increasing production levels (Brough and Jouhara, 2020). The industry is also a significant contributor to greenhouse gas emissions and environmental impacts. Therefore, there is a need to develop state-of-the-art technologies for reducing energy consumption and mitigating environmental impacts. One such technology is waste heat recovery, which has been widely studied and applied in various industries, including the aluminum industry.

Waste heat recovery technologies and their applications have been reviewed extensively in the literature. Jouhara et al. (2019) conducted a comprehensive review of various waste heat recovery technologies, including heat exchangers, organic Rankine cycles, and thermoelectric generators. They also highlighted the potential applications of these technologies in various industrial sectors, such as steel, cement, and glass production. Farhat et al. (2022) presented a recent review of waste heat recovery methodologies, including bottoming cycles, thermoelectric generation, and heat pumps, among others. They also discussed the advantages and limitations of each method and their potential applications in various industries.

In the context of furnace optimization and reducing costs, Trivedi (2019) discussed the importance of monitoring and controlling the furnace temperature and air/fuel ratios. The author also highlighted the benefits of using waste heat recovery systems in furnaces to reduce energy consumption and costs. Similarly, Krokida and Bisharat (2004) presented a case study on heat recovery from dryer exhaust air. They demonstrated that up to 30% of the heat energy can be recovered from the dryer exhaust air, resulting in significant energy savings.

Furthermore, several studies have investigated the performance of waste heat recovery systems in various settings. For instance, Choi et al. (2019) analyzed the variable heat exchange efficiency of heat recovery ventilators and their associated heating energy demand. They found that the heat exchange efficiency is affected by the outdoor temperature and the operation of the ventilation system. Zhang and Fung (2015) conducted an experimental study on an energy recovery ventilator and analyzed the impacts of the defrost cycle on its performance. Zhou et al. (2010) investigated the performance of an energy recovery ventilator under different weather conditions and temperature set-points.

Overall, waste heat recovery is a promising technology for reducing energy consumption, improving efficiency, and mitigating environmental impacts in the aluminum industry. The literature review suggests that various waste heat recovery technologies and methodologies are available and have been applied in various settings. However, the selection of a suitable technology and its optimal configuration depends on several factors, including the characteristics of the waste heat source and the application requirements.

4. Methodology

The thermal efficiency of industrial furnaces is a critical factor that can have a significant impact on energy consumption and associated costs. In a typical furnace, such as the one described here, the four zones of thermal degreaser, dry-off, preheat, and brazing are designed to achieve specific temperature ranges to accomplish the desired thermal treatment of the product. Exhaust gases from each zone exit through their respective exhaust pipes, and thermocouples are placed at every exhaust pipe exit to measure the temperatures of the exhaust gases.

The preheat zone is where high temperatures are reached, with exhaust flue gases ranging from 320°C to 350°C. However, these exhaust gases are currently wasted, which is not only inefficient but also results in unnecessary energy costs. In contrast, the dry-off zone requires a temperature range of 290°C to 350°C, which can be achieved by recirculating the exhaust flue gas from the preheat zone to the dry-off zone. This presents a significant opportunity for waste heat recovery, which can result in increased thermal efficiency, reduced energy consumption, and lower costs.

One approach to recirculating the exhaust flue gas from the preheat zone to the dry-off zone is by making the structure of pipes in such a way that the exhaust of preheat zone enters into the dry-off zone. This arrangement can capture the heat from the preheat zone exhaust gases and transfer it to the dry-off zone, which can significantly reduce energy consumption and associated costs. Additionally, recirculating the exhaust flue gas can also reduce the overall carbon footprint of the furnace, which is a crucial consideration in today's world where environmental concerns are at the forefront.

Furthermore, after the implementation of waste heat recovery, the consumption of PNG or piped natural gas was reduced from an average of 28,000 SCM per month to 21,500 SCM per month. This represents a significant reduction in energy costs, which is a clear benefit to the organization. It is worth noting that the cost savings achieved through the reduction in PNG consumption is an indirect advantage of the waste heat recovery system, as it is a result of increased thermal efficiency and reduced energy consumption.

In conclusion, optimizing the thermal efficiency of industrial furnaces is crucial to reduce energy consumption and associated costs while also reducing the environmental impact. The furnace described here provides a significant opportunity for waste heat recovery by recirculating the exhaust flue gas from the preheat zone to the dry-off zone. This can be achieved through the arrangement of the exhaust pipes, which can significantly increase the thermal efficiency and reduce the environmental footprint of the furnace. Moreover, the reduction in PNG consumption achieved through the implementation of waste heat recovery represents an additional benefit to the organization in terms of cost savings.

5. Theory and Calculations

Now in the zones where combustion is done, a burner is attached to heat up the zone. The conveyor belt is passed through this zone and the products are placed on this conveyor belt. But the flame from the burner is not directly contacted with the products, there is a muffle placed over a conveyor belt and inside the zone. The flame is in directly contacted with the muffle, the first muffle is heated and then through radiation, the heat is transferred to products and the products are heated. The material of this muffle is SS-316.

Thermocouples are placed inside the preheat zone and dry off zone. So inside temperature of the preheat zone ranges from $440^0 C$ C to $540^0 C$

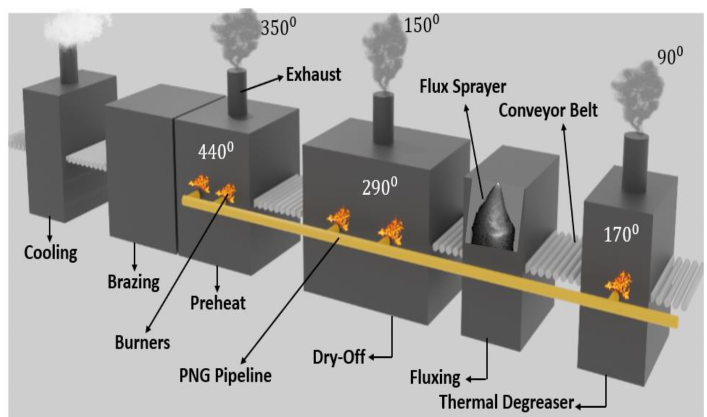


Fig – Furnace

First Objective is to calculate total heat loss from the flue gases. So first the convective heat transfer is calculated from the muffle plate surface to the product.

For this □□□□□=h □Δ□

Here h = Convective heat transfer coefficient

And this h is taken from □□=h □□

Now this □□ is taken from Nusselt number correlation for flow over a flat plate

□□=0.037□□45 x 871□13……….(1)

For this Reynolds no Re in Equation (1) is calculated from □□=□□□/□……..(2)

Now Mean film temperature between the inside plate temperature and ambient temperature

□□=(□□+□∞)/2

□□= (440+28)/2

□□ = 223^0C **C**

Now at this temperature, the properties of air are taken and Put in

Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-6}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965

Equ (2)

These values are taken from the table given below

Now the Reynolds no □□ =□□□/□

□□ = 374256.34

Now Substituting the value of Reynolds no and the value of Prandtl no taken from the property table in equ (1)

we get □□= 5176069.968

Now from □□=h □□

h = 643714.88

Now by taking this h value and putting the in the equation of convective heat transfer

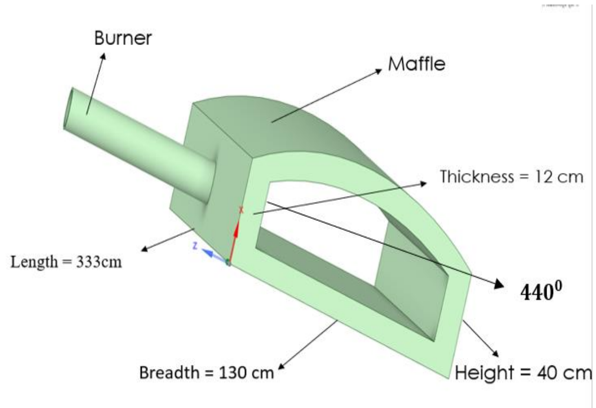


Fig – Muffle

Now □□□□□= h □□□

□□□□□ = 643714.88 × (0.4 ×3.33) ×(440 – 28)

□□□□□= **3500.7790 KW**

This amount of heat is transferred from inside the plate of the muffle to the product placed on the conveyor belt

Now for finding the outside plate temperature of the Muffle, heat transfer through conduction is calculated by considering

$$Q_{C_0nd} = Q_{Conv}$$

$$Q_{C\sigma n_d} = -kA\frac{\Delta T}{dx}$$

3500.7790 = - (16.3) × (0.4 × 3.33) ×(T_2 – 440)

$\boldsymbol{T_2 = 1002.72^0}$ **C**

The outside plate temperature of the muffle comes out to be 1002.72^0 C

Now from this data the amount of heat carried out by the flue gases is calculated as follows

Known values were the preheat exhaust flue gas temperature i.e. 350^0C and the mass flow rate of flue gas *i.e.* m = 7.56(kg/s

Now by using $Q = mC_P\Delta T$

For this ΔT the temperature difference is between mean film temperature and the ambient temperature

So $T_f = (T_w + T_\infty)/2$

T_f = (1002 + 28)/2

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T_f = 515^0C

now

$Q = mC_P\Delta T$

Q = (7.56) × (2.34) × (515-350)

$\boldsymbol{Q}$ **= 29.9424 KW**

Now this amount of heat is carried out from the preheat zone through flue gases

Now it is to be checked whether this amount of heat is sufficient for the dry off zone because the flue gases are going to circulate form preheat zone to the dry off zone

So for this at dry off zone the convective heat transfer is calculated for the plate temperature

Q_{Conv}= $hA\Delta T$

In this equation h (heat transfer coefficient) is calculted again from $N_u = \frac{hl}{k}$

Now this Nu is taken from Nusselt number correlation for flow over a flat plate

$N_u = 0.037R_e^{4/5}$ x $871P^{1/3}$……….(3)

For this Reynolds no Re in Equation (1) is calculated from $R_e = \rho uL/\mu$……..(4)

Now Flue Gas temperature is known so from property table of flue gas at this temperature

t	ρ	c_p	μ *10^6	ν *10^6
[^{O} C]	[kg/m^3]	[kJ/kgK]	[Pas]	[m^2/s]
0	1.295	1.042	15.8	12.2
100	0.95	1.068	20.4	21.54
200	0.748	1.097	24.5	32.8
300	0.617	1.122	28.2	45.81
400	0.525	1.151	31.7	60.38
500	0.457	1.185	34.8	76.3
600	0.405	1.214	37.9	93.61
700	0.363	1.239	40.7	112.1
800	0.33	1.264	43.4	131.8
900	0.301	1.29	45.9	152.5
1000	0.275	1.306	48.4	174.3
1100	0.257	1.323	50.7	197.1
1200	0.24	1.34	53	221

values *i.e.* 350^0C values are taken for equ 4

Now $R_e = \rho uL/\mu$

$\boldsymbol{R_e}$ **= 416932.8076**

Using this Reynolds no in equ. (3)

we get $\boldsymbol{N_u}$**= 915909.0377**

Now from $N_u = \frac{hL}{k}$

h = 4483278.767

Now from Q_{Conv}= $hA\Delta T$

29007.8424=4483278.767(0.4 x 3.33)(350 - T_w)

T_w=$\boldsymbol{340^0C}$

This $\boldsymbol{T_w}$ is the outside wall temperature of maffle located in the Dry-off zone

As we got the outside wall temperature we want to know the inside wall temperature of muffle so by conduction heat transfer we can calculate

Considering

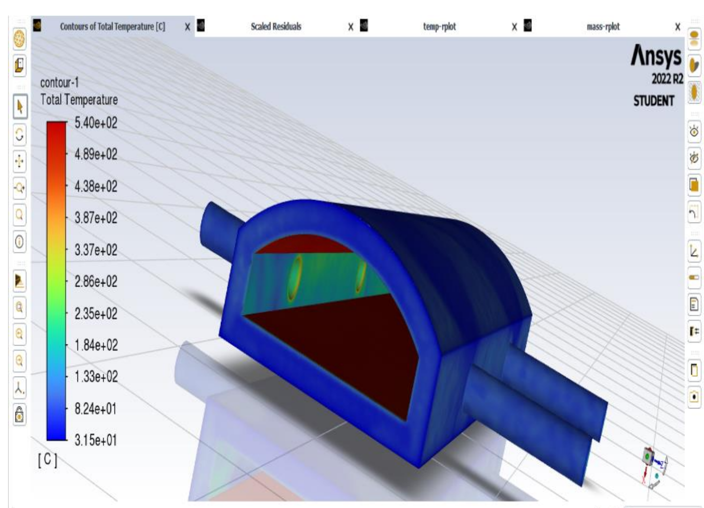
Q_{Cond} = Q_{Conv}

Now from conduction

$Q_{Cond} = -kA\frac{\Delta T}{dx}$

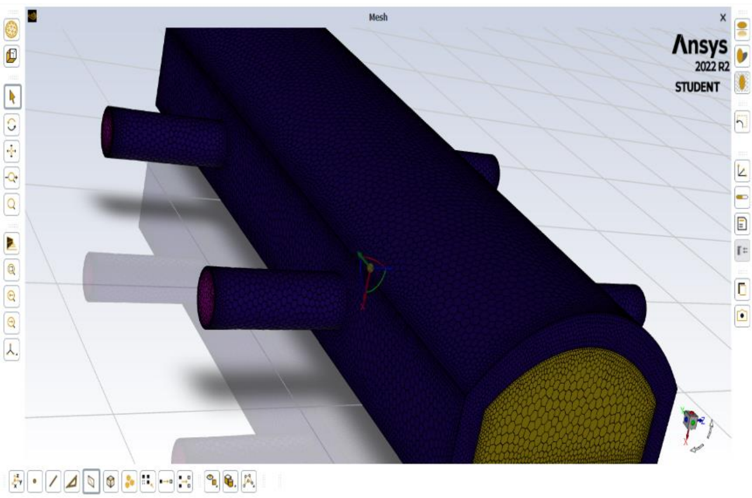
209424 = -16.3 x (3.33 x 0.4) x (340 - T_1)

$\boldsymbol{T_1}$ = $\boldsymbol{229.416^0C}$



Now this temperature we can get inside the dryoff zone muffle by circulating the waste flue gases form preheat zone.

Fig – Muffle pipe arrangement (1)



6. CFD Analysis

The purpose of the analysis is to compare two arrangements of pipes that are intended to transport exhaust flue gases from the preheat zone to the dry-off zone, and examine how the gases heat the muffle. The first arrangement comprises four pipes that join the muffle, with two pipes on each side, heating the muffle on both sides. The analysis involves using Computational Fluid Dynamics (CFD) to simulate the flow of gases and their thermal behavior in the two arrangements.

The results of the analysis show that, at a known set of operating conditions, namely a flue gas temperature of 350°C and a mass flow rate of 7.56 kg/s, the temperature contours of the gas flow exhibit a non-uniform distribution. Specifically, the upper portion of the muffle is not as well covered by the gas flow as the rest of the muffle. Therefore, the results suggest that the current arrangement may not be optimal for achieving a uniform heating of the muffle, which is a critical factor for the overall efficiency and effectiveness of the system.

In conclusion, the CFD analysis has provided valuable insights into the performance of the two pipe arrangements and highlights the need for further optimization of the design to ensure uniform heating of the muffle.

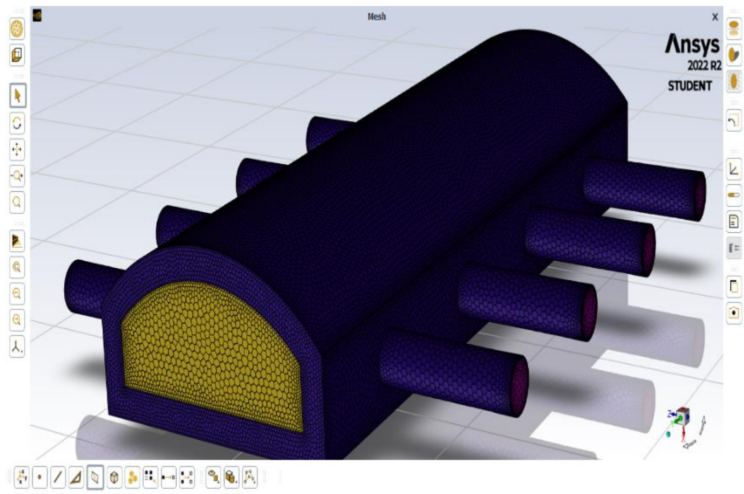


Fig – Muffle pipe arrangement (2)

The second arrangement being compared consists of eight pipes that join the muffle, with four pipes on each side, heating the muffle on both sides. Similar to the first arrangement, Computational Fluid Dynamics (CFD) is used to simulate the flow of gases and their thermal behavior in this arrangement. The aim is to compare the performance of this arrangement to the first arrangement, which had only four pipes.

At the same set of operating conditions, i.e., a flue gas temperature of 350°C and a mass flow rate of 7.56 kg/s, the temperature contours of the gas flow exhibit a more uniform distribution when using the second arrangement. Unlike the first arrangement, the temperature is evenly distributed over the muffle surface, indicating a more efficient and effective heating of the muffle.

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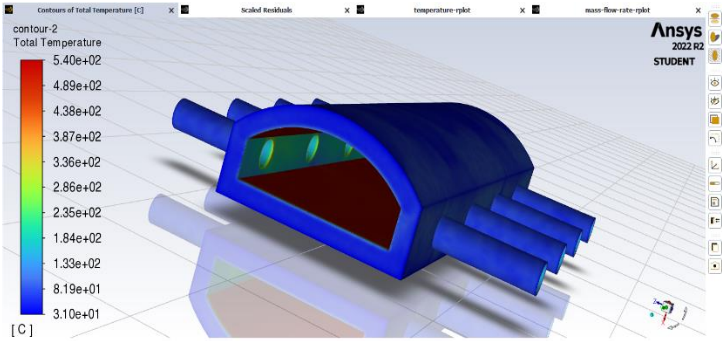

This suggests that the second arrangement, with its larger number of pipes, offers better performance and more uniform heating of the muffle, compared to the first arrangement. Therefore, this second arrangement can be considered a more suitable design for this application.

In summary, the CFD analysis highlights the significant impact of the number of pipes used in the design of the exhaust flue gas system. The second arrangement, with eight pipes, provides a more uniform distribution of heat, which is essential for optimal performance and efficiency of the overall system.

7. Results and Discussion

Based on the calculations and CFD simulations, the waste heat recovery project for the nocolok furnace used for brazing of aluminum heat exchangers has proven to be highly successful in increasing thermal efficiency and reducing energy costs. By recirculating the exhaust flue gas from the preheat zone to the dry-off zone, the temperature in the dry-off zone can be increased up to 230°C, which is sufficient for the drying process, and the burner in the dry-off zone would require less PNG for combustion, resulting in a substantial reduction in PNG consumption

Moreover, the CFD analysis has shown that optimizing the arrangement of the exhaust pipes can lead to a more uniform heating on the surface of the muffle of the dry-off zone. Using four pipes on each side to join the muffle of the dry-off zone can achieve this optimization, which maximizes the effectiveness of heat recovery and minimizes the use of fuel. The findings suggest that the waste heat recovery project has significant implications for the aluminum industry, reducing energy costs and promoting sustainable production practices. The CFD analysis has also shown that by using four pipes on each side to join the muffle of the dry-off zone, a more uniform heating can be achieved on the surface of the muffle. This suggests that the waste heat recovery arrangement can be optimized to maximize the effectiveness of heat recovery and minimize the use of fuel. These findings have significant implications for the aluminum industry and can help reduce energy costs and promote sustainable production practices. The CFD analysis also provides important insights into the optimization of the waste heat recovery arrangement. The use of four pipes on each side to join the muffle of the dry-off zone can help achieve more uniform heating, which can further improve the effectiveness of heat recovery and reduce the use of fuel. Therefore, optimizing the waste heat recovery arrangement can lead to additional energy savings and cost reductions.

After simulating the two different pipe arrangements and conducting a comprehensive analysis of the results, temperature distribution graphs were generated to visually compare the performance of each arrangement in heating the muffle. These graphs serve as powerful visual representations, providing in-depth insights into the effectiveness of the different designs and lending support to the conclusions drawn from the data.

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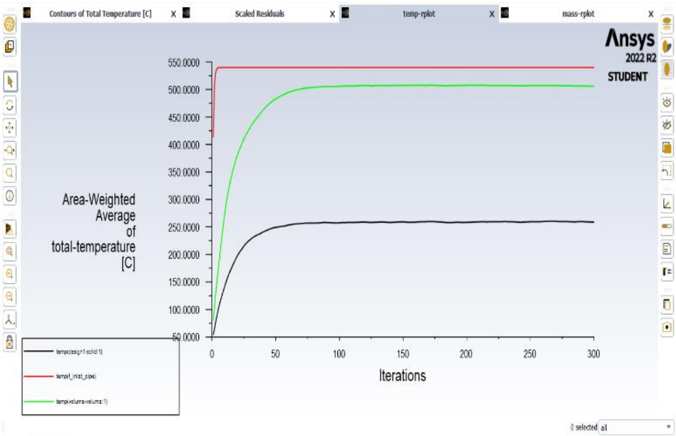
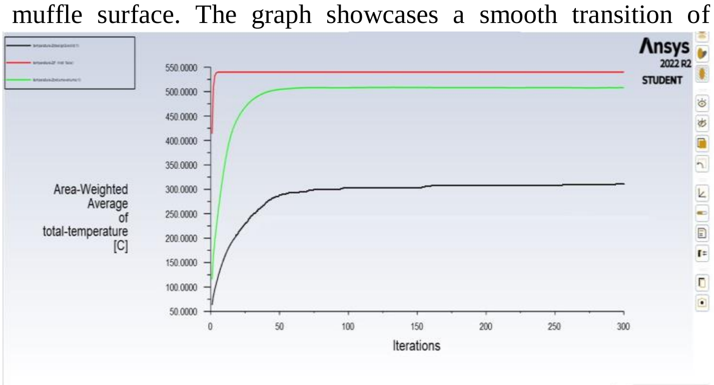


Following the simulations, Graph 1 portrays the temperature distribution on the muffle surface for the arrangement consisting of four pipes. This graph presents a comprehensive depiction of the heat distribution across the muffle by utilizing a color scale, with cooler regions represented in shades of blue and warmer regions in shades of red. Upon close examination, distinctive variations in temperature become apparent, signifying a non-uniform heat distribution pattern. The graph unveils specific areas of the muffle surface experiencing lower temperatures when compared to others, resulting in an uneven heat transfer. The non-uniformity is prominently displayed through the varying color intensities that highlight the temperature disparities. From the data, it is evident that the average temperature observed on the muffle surface in this four-pipe arrangement is approximately 240 degrees Celsius.

In stark contrast, Graph 2 offers a visual representation of the temperature distribution on the muffle surface for the arrangement comprising eight pipes. Similar to the previous graph, the color scale is employed to illustrate the temperature distribution, with cooler regions depicted in blue and warmer regions in red. However, in this case, the temperature distribution appears considerably more uniform and balanced. The absence of distinct regions with significantly different color intensities indicates a more consistent heat transfer across the muffle surface. The graph showcases a smooth transition of

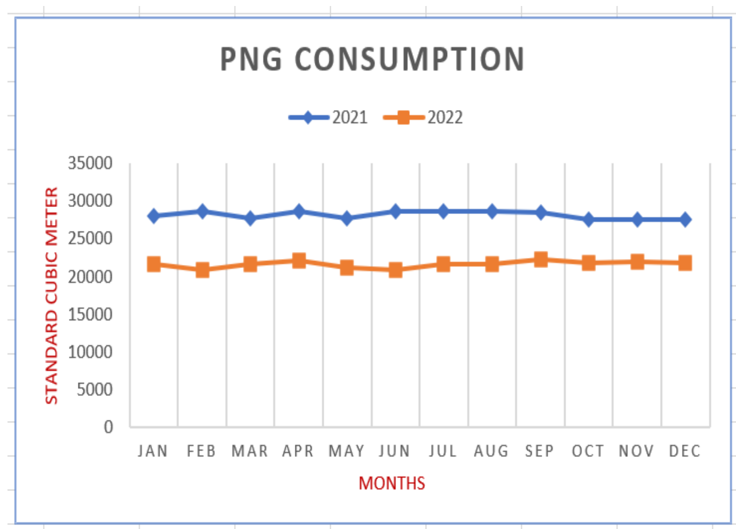


colors, signifying a gradual increase in temperature and a more evenly distributed heat pattern. The average temperature observed on the muffle surface in this eight-pipe arrangement is approximately 290 degrees Celsius.

By meticulously examining and comparing the two graphs, a clear distinction arises: the second arrangement with eight pipes attains a notably more uniform temperature distribution on the muffle surface. This outcome affirms the initial analysis, suggesting that the second arrangement outperforms the first arrangement in terms of overall performance and efficiency in heating the muffle.

The temperature distribution graphs effectively convey the impact of the number of pipes on the system's heating effectiveness. The second arrangement, with its larger number of pipes, ensures a more uniform distribution of temperatures across the muffle surface, which is of paramount importance for optimal system performance. These findings accentuate the significance of meticulous design considerations when developing exhaust flue gas systems and underscore the critical nature of achieving uniform heat transfer for enhanced operational efficiency.

The implementation of waste heat recovery in the industrial furnace resulted in a significant reduction in the consumption of PNG. Before the implementation of waste heat recovery, the furnace consumed an average of 28,000 SCM of PNG per month. However, after the implementation of waste heat recovery, the PNG consumption was reduced to an average of 21,500 SCM per month. This indicates a reduction of 23.21% in PNG consumption, which is a significant achievement in terms of reducing energy consumption and associated costs.



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Overall, the graph shows that the implementation of the waste heat recovery system has resulted in a significant reduction in PNG consumption and associated costs for the operation of the nocolok furnace used for brazing of aluminum heat exchangers.

To put the savings into perspective, the cost required for burning 28,000 SCM of PNG per month was approximately Rs. 15,40,000/-, calculated based on the PNG rate of Rs. 55/- per SCM in Pune. After implementing waste heat recovery, the PNG consumption reduced to 21,500 SCM per month, resulting in a reduction in monthly cost to approximately Rs. 11,82,500/-. This translates to a savings of approximately Rs. 3,57,500/- per month, which is a significant amount for any industrial operation.

To evaluate the economic feasibility of the waste heat recovery project, the total investment cost needs to be considered. In this case, the total investment cost for the project was Rs. 8,50,000. The payback period is a useful metric for assessing the time it takes for the project's savings to offset the investment cost. Based on the monthly savings achieved from the waste heat recovery project, the payback period for this project can be calculated as follows:

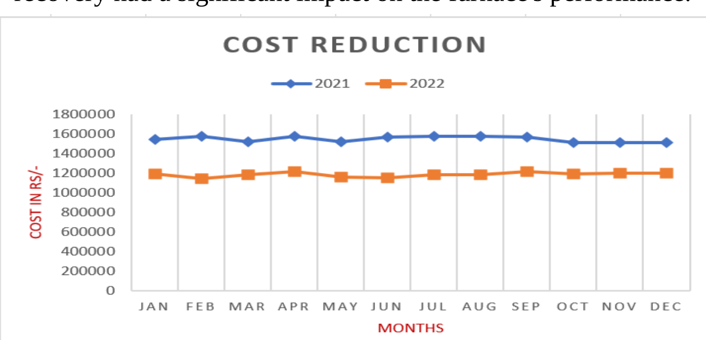
Payback period = Total investment cost / Monthly savings

Substituting the values, we get:

Payback period = Rs. 8,50,000 / (Rs. 15,40,000 - Rs. 11,82,500) per month

Payback period = 2.37 months

It's worth noting that these values were calculated based on readings taken per month, and the averages were calculated for each month. The data was collected in the year 2021 before implementing waste heat recovery and in the year 2022 after implementing it. The reduction in PNG consumption and associated cost savings were observed consistently throughout the year, indicating that the implementation of waste heat recovery had a significant impact on the furnace's performance.



It is evident that there has been a significant reduction in the cost required for the burning of PNG in the furnace used for aluminum brazing. The graph shows a clear comparison between the cost required before and after implementing the waste heat recovery system.

Before implementing the system, the average PNG consumption per month was 28000 scm, which required a cost of Rs. 15,40,000/- per month at a rate of Rs. 55/- per scm. However, after the implementation of the waste heat recovery system, the average PNG consumption per month reduced to 21500 scm, which resulted in a monthly cost of Rs. 11,82,500/-

This significant reduction in cost can be attributed to the effective recovery and recirculation of the waste heat from the flue gases of the preheat zone to the dry-off zone, which has led to a decrease in the amount of PNG required for combustion in the furnace.

Overall, the results demonstrate that waste heat recovery is an effective approach to increase the thermal efficiency of industrial furnaces, reduce energy consumption, and associated costs. By capturing waste heat from exhaust gases and using it to heat other parts of the furnace, the furnace's overall efficiency can be significantly increased, resulting in significant cost savings for the operation. In addition, waste heat recovery can help reduce the environmental impact of industrial operations by reducing the amount of energy required to achieve the desired thermal treatment of the product.

8. Conclusion

In conclusion, the waste heat recovery project implemented in the nocolok furnace used for aluminum brazing has proven to be a successful and cost-effective solution. The project resulted in a significant reduction in PNG consumption, leading to substantial cost savings. Based on the monthly readings and calculations, the average PNG consumption was reduced from 28,000 scm per month to an average of 21,500 scm per month. This reduction in consumption resulted in a considerable monthly cost reduction from Rs. 15,40,000/- to Rs. 11,82,500/-, which translated to an annual cost savings of Rs. 43,50,000/-.

Furthermore, CFD simulations have demonstrated that by piping the waste heat from the flue gases of the preheat zone to the dry-off zone, the temperature in the dry-off zone can be increased up to 230°C, and the burner in the dry-off zone would require less PNG for combustion. This arrangement can be optimized by using four pipes on each side to join the muffle of the dry-off zone, resulting in a more uniform heating of the surface of the muffle.

The investment cost for the project was Rs. 8,50,000/-, and based on the cost savings achieved, the payback period for the investment was approximately 2.37 months. This indicates that the project was not only successful in terms of reducing PNG consumption and costs but also financially viable and beneficial in the long run.

In conclusion, the waste heat recovery project has proven to be a practical and sustainable solution for reducing energy consumption and costs in the aluminum brazing process. The project can serve as a model for other industries looking to adopt similar practices to reduce their carbon footprint and promote sustainable production practices.

Nomenclature –

$Qconv$ = heat transfer through convection
$Qcond$ = heat transfer through conduction
h = heat transfer coefficient
m = mass flow rate
Cp = Specific heat
ΔT = Temperature difference
Nu = Nusselt number
Pr = Prandtl number
k = thermal conductivity
l = length
Re = Reynolds Number
ρ = density
v = kinematic viscosity
μ = dynamic viscosity
Tf = Mean film temperature
Tw = Wall Temperature

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