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Optimal Design and Performance Analysis of a Gas-Gas Heat Exchanger for Harvesting Waste Heat

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Keywords:
Gas-gas Heat Exchanger; Waste Heat Recovery; Experimental Investigations; MATLAB Algorithm.

Abstract
This study reports the design of an optimized heat exchanger capable of efficiently extracting and transferring waste heat from flue gas to air. An experimental setup was constructed to recover waste heat from the exhaust steam of a boiler, using this heat to warm compressed air. Thermocouples recorded the temperatures at the inlet and outlet of both the hot and cold fluids. A MATLAB code is developed to compare the experimental results. According to our code, the cold fluid outlet temperature ranged from 71.5°C to 76°C, while the experimental setup showed temperatures ranging from 66°C to 71.5°C at air mass flow rates of 0.1564, 0.1346, and 0.1794 kg/s. The deviation may arise from the inaccuracies of the flow rate and the temperature measurement devices as well as the constraints in correlations which calculate heat transfer coefficient and friction factor in pressure drop. Future work may focus on minimizing the deviations and propose an improved design of heat exchanger.

1. Introduction

With the continuous rise in fuel prices and increasing concerns about global warming, engineering industries face the challenge of reducing greenhouse gas emissions and enhancing efficiency of thermodynamic devices. Waste heat recovery systems have become a pivotal focus in industrial research to decrease fuel consumption, mitigate harmful emissions, and enhance production efficiency. The term "industrial waste heat" describes the energy produced during industrial processes that is currently wasted or released into the environment. Gas-gas heat exchangers can recover waste heat from exhaust gases in power plants, industrial facilities, and even vehicles. By transferring heat from hot exhaust gases to incoming air or another gas stream, gas-gas heat exchangers improve energy efficiency and reduce fuel consumption. These exchangers are also used in chemical reactors to control temperature and pressure, heating or cooling the reactants or products to optimize chemical reactions. In processes like steelmaking, gas-gas heat exchangers preheat combustion air, reducing the energy required for melting and refining metals. A comprehensive review of the available literature is presented in Table 1.

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Table 1: A literature review of heat exchangers for waste heat recovery

Authors and Year	Purpose	Methodology	Result/Outcome
Koehler *et al.* 1997	The aim is to develop and evaluate an exhaust- gas-powered absorption refrigeration system for truck refrigeration.	The condenser and absorber's two-phase binary flow was developed and validated. Additionally, an estimation of the available heat in the exhaust gases has been made using real truck driving cycles.	Analysis reveals that the unoptimized prototype can be improved by more than 25%, with a COP of almost 27%.
Horuz 1999	Explores the application of vapor absorption refrigeration (VAR) systems in automobiles, emphasizing the utilization of waste heat from the exhaust gases of the main propulsion unit as the energy source.	Experimental research is being done on the application of vapor absorption refrigeration (VAR) systems in automobiles that use waste heat from the primary engine unit's exhaust emissions as their energy source.	Results demonstrated that the experimental diesel engine could run the 23.2 kW VAR system on the 110 kW exhaust gas heat capacity.
Yang *et al.* 2002	Investigates the feasibility of using heat pipe heat exchangers to warm vehicle exhaust gas and develop a calculation method for this purpose.	The electrochemical reaction between the pipe's shell and water vapor, which has the potential to produce hydrogen gas and lower the heat pipe's vacuum level, was stopped using the bluing procedure.	When the engine was idle, it showed how effective it is to heat using exhaust gas. The heat exchanger's capacity to transfer heat increased with the temperature of the gas.
Crane & Jackson 2003	A cross-flow heat exchanger's air cooling should be optimized while taking into account the power losses caused	Cross-flow correlations for air-side heat transfer in thermoelectric-less heat exchangers were verified by the use of an iterative Newton-Raphson approach to	The ideal configuration of the cross-flow heat exchanger yielded net power densities exceeding 40 W/l when employing

	by an air fan and a fluid pump.	solve non-linear steady-state temperature equations.	Bi2Te3 thermoelectric.
Wang *et al.* 2014	To investigate the efficacy and thermodynamic analysis of a low-pressure economizer (LPE)-based waste heat recovery system for a coal-fired power plant (CFPP).	The variation of the first law efficiency after the installation of LPE was investigated, taking into account the heat recovered by LPE and the extraction efficiency.	Operational metrics for a 350 MW CFPP with an LPE system showed variations in thermal performance at 100 THA (turbine heat acceptance) load.
Sonthalia *et al.* 2015	Analyze the effects of engine load, speed, and air-to-fuel ratio on the thermoelectric output and coefficient of performance (COP) of the VAR system.	The output from the engine drove the pump of the vapor absorption refrigeration system. The simulation was performed using MATLAB-Simulink.	The simulation's results showed that the air fuel equivalency ratio, engine load, and speed all affected the vapor absorption refrigeration system's coefficient of performance (COP).

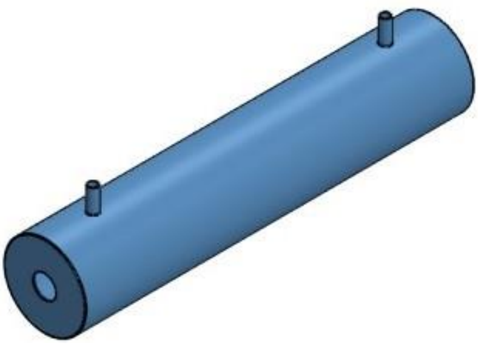
The literature review shows that waste heat recovery exchangers have significant potential in industries. This study aims to develop a simple tube-shell heat exchanger for recovering waste heat from a boiler. A validated MATLAB code for a heat exchanger was written and compared against experimental results available in the literature. The code helps design the geometry and other boundary conditions of the heat exchanger. Based on these results, a heat exchanger was fabricated and compared against the numerical results.

2. Materials and Methods

Shell-and-tube heat exchangers are highly versatile and can handle a wide range of fluid temperatures, pressures, and flow rates. Table 1 lists the parameters for the finned counter-flow heat exchanger. Figures 1 and 2 depict various design parameters of the heat exchanger. Figure 2 shows the exploded view of the fabricated heat exchanger. According to the design, the heat exchanger was fabricated and fitted in the boiler exhaust manifold. Mild steel was selected for constructing the heat exchanger due to its cost-effectiveness. Mild steel is a common material choice for the shell and tubes of heat exchangers, particularly in applications where cost considerations are important. Counter-flow heat exchangers are designed to maximize the temperature difference between the hot and cold fluids, thus enhancing heat transfer efficiency.

Table 2: Dimensions of heat exchanger

Parameters	Symbol	Dimension	Unit
Shell Length	L	0.604	m
Shell Inside diameter	D_i	0.124	m
Shell Outside diameter	D_o	0.127	m
Shell Hydraulic Diameter	Dhc	0.0965	m
Tube Length	L_t	0.700	m
Tube Inside Diameter	D_i	0.0295	m
Tube Outside Diameter	D_O	0.03	m
Tube Hydraulic Diameter	Dh	0.0295	m
Length of Fin	L	0.58	m
Number of Fin	n	15	-
Gap between Fins	θ	22.5	°
Thickness of Fin	t	0.003	m
Width of Fin	w	0.030	m



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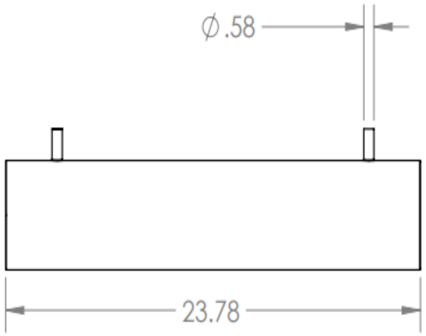

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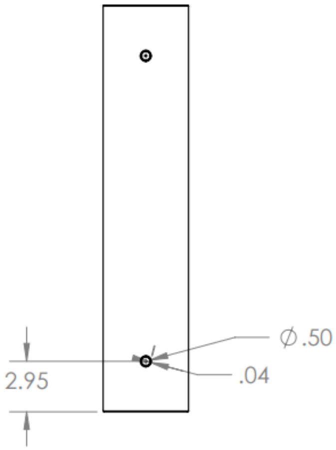

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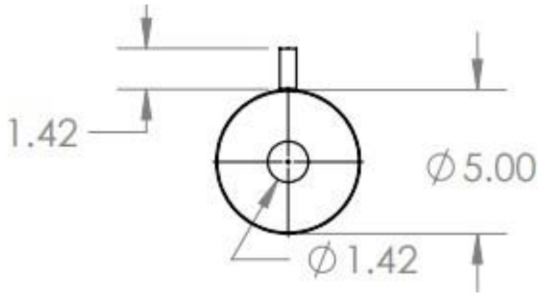
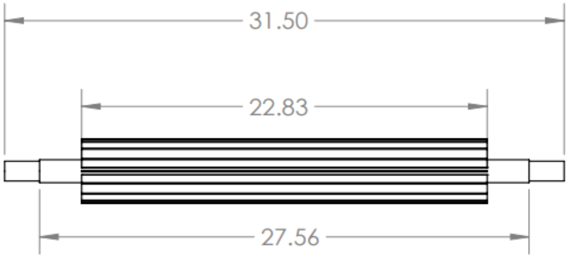


(d)

(e)

Figure 1: Schematic diagram of 2-Dimensional, 3-Dimensional and fabricated heat exchanger shell, (a) Isometric view (b) Front view (c) Top view (d) Side view (e) fabricated view. (All dimensions are in inches)

(a)



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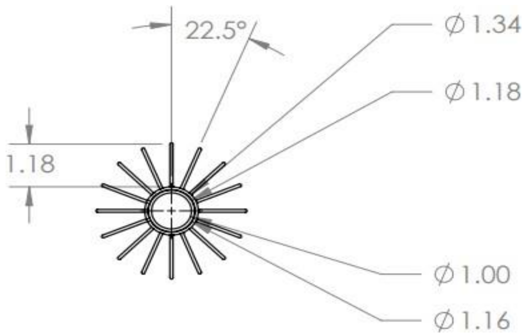

(c)

Figure 2: Schematic diagram of diagram of 2-Dimensional, 3-Dimensional finned tube (a) Isometric view (b) Front view (c) Side view (All dimensions are in inches).

The heat exchanger's surface area plays a crucial role in heat transfer since it can raise the overall heat transfer coefficient (Alnaimat, 2003) and heat transfer rate. Heat exchanger fins are becoming more efficient and effective in terms of performance metrics because of their MOC's higher thermal conductivity. Hence, the heat exchanger was built with enlarged surfaces in the form of finned tubes. After being designed in SolidWorks, the heat exchanger was manufactured and installed into the boiler's steam exhaust manifold.

2.1 Experimental Setup

Shell and tube heat exchanger (Figure 1e) is the main component of the experimental setup. Figure 3 shows a schematic diagram of the experimental setup. Exhaust steam of the boiler flows inside the tubes, while compressed ambient air around the outside of the tubes within the shell. Steam enters the heat exchanger through an inlet connection, carrying thermal energy at a higher temperature. Inside the heat exchanger, steam flows through the tubes, transferring heat to the tube walls and fins. This heat is then conducted through the tube walls to air on the shell side. After transferring heat to the tube walls, steam exits the heat exchanger at a lower temperature through an outlet connection. The cold fluid (air) enters the heat exchanger shell through an inlet connection, provided by an air compressor. This fluid is at room temperature and absorbs heat from steam. After absorbing heat, the now-warmed cold fluid exits the heat exchanger through an outlet connection.

Temperature sensors were installed at the heat exchanger's inlets (steam) and outlets (air) to measure the respective temperatures of the steam and air. Proper sensor placement was ensured to obtain accurate readings. The sensors were connected to a data acquisition system, following the manufacturer's guidelines for wiring and connections to ensure precision. Arduino software was installed on a laptop to monitor and record temperature data from the sensors. The software displayed real-time temperature readings, facilitating accurate data collection.

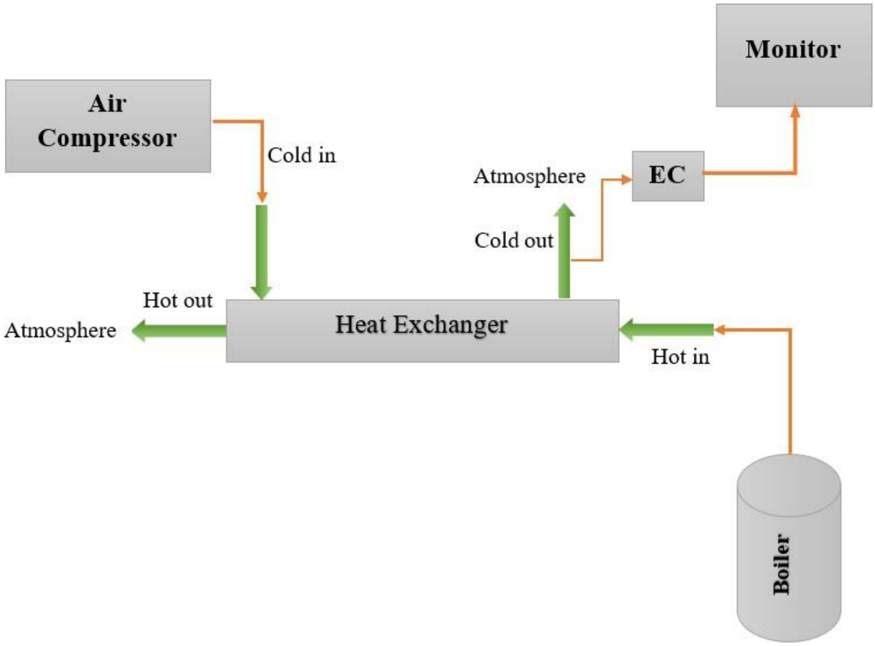

Figure 3: A schematic diagram of experimental setup.

Three experiments were conducted to test the heat exchanger, with approximately 60 minutes between each test. In each experiment, the steam flow rate was kept constant while varying the airflow rate. Each test lasted approximately 15 minutes. During the first test, we collected three output temperature readings of the cold fluid once the temperature stabilized, typically after 8 minutes, resulting in 7-8 data points. We then selected the three highest output temperatures and calculated their average for the first experiment. This procedure was repeated for the subsequent experiments.

2.1.1 Error Analysis

Errors and uncertainties are inevitable in any research undertaking including primary experimental measurements and performance computations. These can happen when choosing an instrument, calibrating it, organizing tests, and gathering data. The mass flow rate and temperature error measurements were found to be ±2.13% and ±4.96%, respectively, using the proper calculating techniques.

2.2 Numerical Design and Analysis

2.2.1 Total Heat Transfer Area of the Heat Exchanger

The convective heat transfer area needs to be determined in order to calculate the heat transfer rate and other important thermal characteristics. Fins were added to the cold fluid (air) side of the experiment in order to promote boundary layer separation and improve heat transfer. The following formula is used to determine the total surface area of heat transfer:

$$As = Auf + Af \quad (1)$$

Here, As, Af and Auf represent the total heat transfer surface area, finned area, unfinned area, respectively.

$$Auf = \pi d_o L - nt \quad (2)$$

Here do, L, n, t are present the tube outside diameter, length of tube, number of fin, and thickness of the fins, respectively.

$$Af = n(2L_f h) + Lft \quad (3)$$

Where $Lf\ and\ h$ represent the length of fin and height of fins, respectively.

Table 3: Surface Area of Finned heat exchanger

Description	Symbols	Dimensions	Unit
Finned Area	A_f	0.5481	m^2
Un finned Area	Auf	0.0224	m^2
Total surface Area	A_s	0.5705	m^2

2.2.2 Counter flow heat exchanger design parameters

Table 3 lists the properties of the working fluids utilized in the heat exchanger, including the air and the boiler's steam. A mild steel heat exchanger with a thermal conductivity value of 44 $W/(m \cdot K)$ was used.

Table 4: Properties of hot and cold fluids.

Input Parameter	**Symbols**	**Hot Fluid (Steam)**	**Symbols**	**Cold Fluid (Air)**	**Units**
Inlet Temperature	Thi	140	Tci	32	$°C$

Outlet Temperature	Tho	113	Tco	72	$°C$
Thermal Conductivity	K_h	0.035	K_c	0.0273	$W/m \cdot k$
Specific Heat Capacity	Cph	1996	Cpc	1047.66	$J/(kg \cdot k)$
Viscosity	μ_h	0.000028	μ_c	0.000021	$(N \cdot s)/m^2$
Density	ρ_h	11.61	ρ_c	2.4	kg/m^3
Mass Flow Rate	m_h	0.0259	m_c	0.002	Kg/s

2.2.3 Convection Heat Transfer Coefficient of Heat Exchanger

The convective heat transfer coefficient of a heat exchanger accounts the rate of heat transfer between the heat exchanger surface and the fluid passing over it. This coefficient is influenced by various factors, including the fluid's properties, flow conditions, and the heat exchanger's geometry. Table 4 lists the key parameters essential for determining the heat transfer coefficient. Several factors were considered, and data were calculated to determine the heat transfer coefficients for the inner and outer pipes of a typical heat exchanger. Using the Reynolds number, Prandtl number, friction factor, and Nusselt number, we can find the heat transfer coefficient. An important parameter in this context is the fluid's mass flow rate, which varies depending on the heat exchanger's design and objectives. To calculate the velocity of the cold and hot fluids, the mass flow rate ($\dot{m}$) is needed, given by:

$$\dot{m} = \rho AV \tag{4}$$

Here A and V represent the hydraulic area of fluid flow and velocity of fluid. Velocity is also required to calculate Reynolds number, Prandtl number, friction factor and Nusselt number. Reynolds number was calculated using the following equation

$$Re = \frac{\rho V D_h}{\mu}. \tag{5}$$

Here, $D_h and$ µ present the fluid flow hydraulic diameter and viscosity of the fluid, respectively.

$Re < 2000$ (laminar flow): characterized by smooth, orderly motion with minimal mixing, often described as "streamline" flow.

$2000 < Re < 4000$ (Transitional Flow): the flow can be unstable, transitioning between laminar and turbulent states, with unpredictable behavior.

Re>4000 (Turbulent Flow): characterized by chaotic, swirling motion and mixing, exhibiting eddies, vortices, and enhanced mixing.

The Prandtl Number (Pr) is a dimensionless number used in heat transfer to characterize the relative importance of momentum diffusivity to thermal diffusivity in a fluid. It is defined as:

$$Pr = \frac{c_p \mu}{k}. \quad (6)$$

Here, $Cp \ and \ k$ present the specific heat capacity and thermal conductivity of hot and cold fluid, respectively. The friction factor (f), a dimensionless number, measures the resistance of flow in a tube or conduit. While it is generally used to compute pressure drop in fluid flow (especially in tubes), it can indirectly affect the computation of the heat transfer coefficient (h). The friction factor is defined as (Kumar 2019):

$$f = \frac{64}{Re} \qquad \text{when } Re < 2000 \quad (7)$$

$$f = \frac{0.316}{Re^{0.25}} \qquad \text{when } Re > 2000 \quad (8)$$

The Nusselt number provides information about how effectively heat is transferred from the surface to the fluid and is particularly important in applications involving convection, such as in heat exchangers.

$$Nu = 3.66 + \frac{0.65\frac{D_h}{L}RePr}{1+0.04\left(\frac{D_h}{L}RePr\right)^{0.667}}. \qquad \text{when } Re < 2000 \quad (9)$$

The Dittus-Boelter equation is applicable to fully developed, steady-state, turbulent flow of an incompressible fluid inside a circular pipe or tube.

$$Nu = 0.023Re^{0.8}Pr^{0.5} \qquad \text{when } Re > 2000 \quad (10)$$

The heat transfer coefficient (h) measures how effectively heat is transferred from a solid surface to a fluid. The Nusselt number (Nu) is used to relate the heat transfer coefficient (h).

$$Nu = \frac{hD_h}{k} \quad (11)$$

From equation (11), the convective heat transfer coefficient can be readily obtained using the Nusselt Number. This relationship provides a straightforward and efficient method for calculating the convective heat transfer coefficient., $h = \frac{Nu.k}{Dh}$.

Table 5: Heat transfer calculation parameters for heat exchanger.

Parameter	Symbols	Inner pipe Hot fluid (Steam)	Symbols	Outer Pipe Cold fluid (Air)	Units
Velocity of fluid	V_h	4.0082	V_c	0.1700	m/s
Fluid flow area	A_h	0.00053	A_c	0.0064	$m2$
Hydraulic diameter	Dhh	0.295	Dhc	0.0900	m
Reynolds Number	Re_h	4902.8	Re_c	1330.8	-
Prandtl Number	Pr_h	2.3782	Pr_c	0.8051	-
Friction Factor	f_h	0.0252	f_c	0.0481	-
Nusselt Number	Nu_h	105.3385	Nu_c	8.4259	-
Heat Transfer coefficient	H_h	83.9137	H_c	2.5559	$W/m^2 \cdot k$

2.2.4 Overall Heat Transfer coefficient

The overall heat transfer coefficient (U) measures the rate at which heat is transferred through a pipe wall comprising multiple layers or materials. It is a critical parameter in the design of heat exchangers. The overall heat transfer coefficient, measured in W/m^2·K accounts for both conduction and convection heat transfer processes. In our study, the determined value of the overall heat transfer coefficient was 2.47.

$$\frac{1}{UA} = R_{total} = \frac{1}{h_h A_h} + \frac{R_{fi}}{A_i} + \frac{ln\frac{d_o}{d_i}}{2\pi Lk} + \frac{R_{fi}}{A_i} + \frac{1}{h_c A_o}. \quad (12)$$

Here, h, d, k and L represent the heat transfer coefficient, tube diameter, tube thermal conductivity, and tube length, respectively. The subscripts i and o represent tube inside and outside diameters. Heat exchanger analysis and design, a dimensionless metric called the Number of Transfer Units (NTU) is used to understand the performance and efficiency of a heat exchanger.

$$NTU = \frac{UA_s}{C_{min}} \quad (13)$$

Where, NTU is the Number of Transfer Units, U is the overall heat transfer coefficient ($w/m2 \cdot k$), As is the heat exchanger's effective heat transfer surface area (m^2), and $Cmin$ is the minimum heat capacity rate among the two fluid streams (J/K). The minimal heat capacity ($Cmin$) to the maximum heat capacity ($Cmax$) is represented by the thermodynamic parameter known as the heat capacity ratio (Cr).

Heat capacity ratio, $C_r = \frac{C_{min}}{C_{max}}$. (14)

2.2.5 Effectiveness of the Heat Exchanger

The effectiveness of a heat exchanger indicates how efficiently it transfers heat from one fluid to another. This is a critical factor in evaluating a heat exchanger's performance. The formula for calculating the effectiveness of a heat exchanger depends on the type and configuration of the heat exchanger. There are two commonly used methods for calculating the effectiveness: one for parallel flow heat exchangers and another for counterflow heat exchangers. For our experiment, we used counter flow heat exchanger.

Effectiveness, $\varepsilon = \frac{1-e^{-NTU(1-c_r)}}{1-c_r e^{-NTU(1-c_r)}}$. (15)

Where ϵ is the effectiveness of the heat exchanger, Cr is the heat capacity rate ratio, and NTU is the Number of Transfer Units. By substituting the values into equation (15), we calculated the heat exchanger effectiveness to be 52.53%.

The maximum rate of heat transfer (Qmax) and the actual heat transfer rate (Q_{act}) in a finned tube heat exchanger can be determined using the following equation:

$$Q_{max} = C_{min}(T_{hi} - T_{ci}). \quad (16a)$$

$$Qact = \varepsilon \times Qmax \quad (16b)$$

Here, Q_{max} is the maximum possible heat transfer rate, C_{min} is the minimum heat capacity rate between the two fluids, T_{hi} is the inlet temperature of the hot fluid, and T_{ci} is the inlet temperature of the cold fluid. Knowing the initial temperature of the cold fluid, the output temperature of the cold fluid (Tco) can be calculated as follows:

$$T_{co} = T_i + \frac{Q_{act}}{C_c}. \quad (17)$$

2.2.6 Flowchart of MATLAB program

A gas-gas heat exchanger design program has been developed in MATLAB. Heat transfer processes can be precisely modeled using MATLAB, leading to more accurate heat exchanger designs. The program allows for the easy variation and optimization of design parameters such as shape, materials, and flow rates. Figure 4 demonstrates the algorithm of the MATLAB code. Various parameters, including Reynolds number, Prandtl number, Nusselt number, and friction factor, were calculated from input variables. The fin area and tube area were also calculated. Subsequently, the heat capacities of the hot and cold fluids were determined, and the maximum heat transfer rate was calculated using the minimum heat capacity value. The effectiveness of the heat exchanger was then multiplied by the maximum heat transfer rate to obtain the actual heat transfer rate.

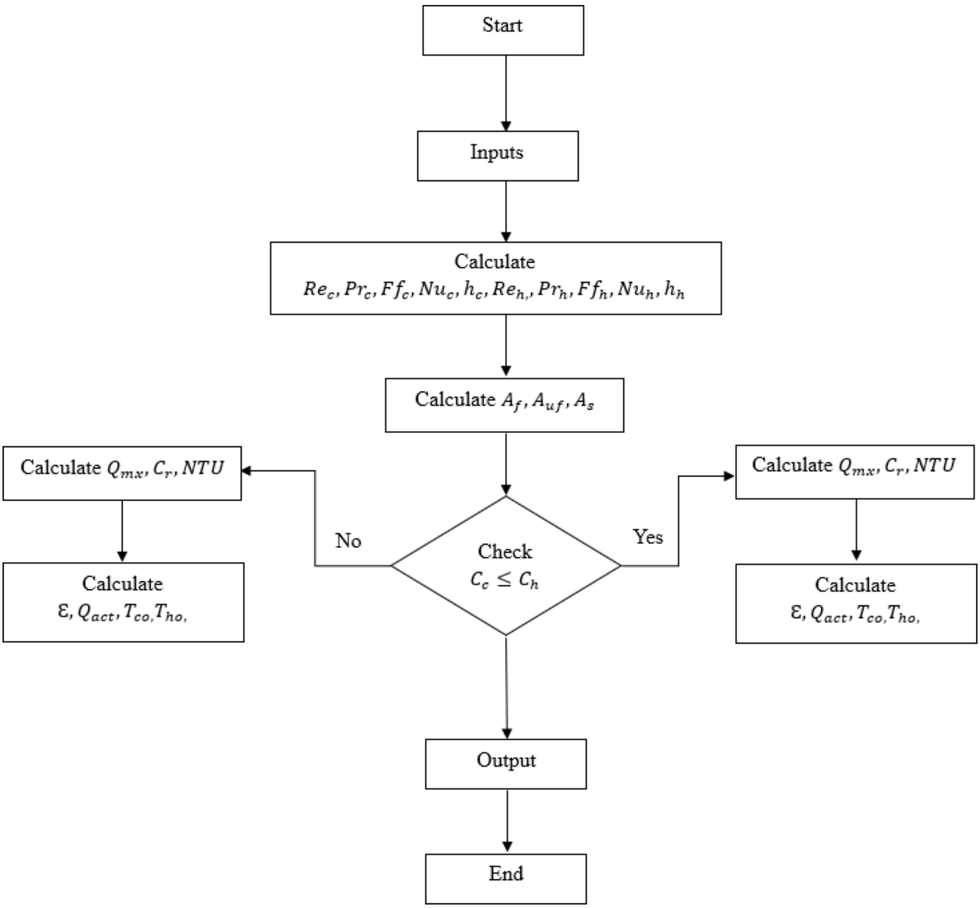

Figure 4: Flowchart of MATLAB program.

3. Results and Discussion

The air outlet temperature as a function of time for an air flow rate of 0.0026 kg/s is illustrated in Figure 5. The X-axis represents time, while the Y-axis represents temperature. Initially, the air outlet temperature was 31°C. After 7 minutes, it stabilized at 69°C. This temperature-time curve demonstrates the increase in air temperature over time during the test. Similar patterns were observed for air flow rates of 0.0023 kg/s and 0.002 kg/s, with the outlet temperature negatively correlated with the air flow rate. Specifically, the highest outlet temperature of 72°C was recorded for the lowest air flow rate of 0.002 kg/s. These results indicate that lower air flow rates allow for greater heat absorption, resulting in higher outlet temperatures. This relationship is crucial for optimizing the efficiency of heat exchangers in various industrial applications.

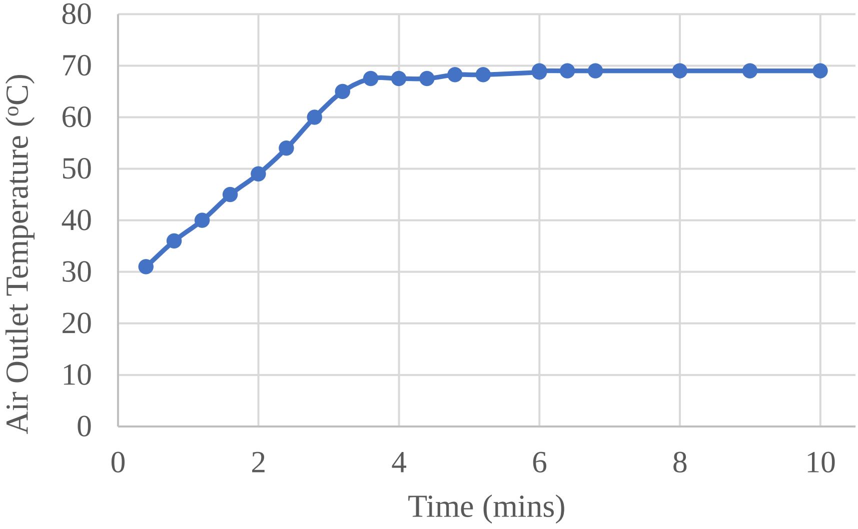

Figure 5: Cold Fluid Outlet Temperature Rises with Temperature.

Figure 6 shows cold fluid outlet temperature for three different flow rates of air such as 0.0026, 0.0023, and 0.002 kg/s. Then the temperature and pressure were recorded. The data has been collected when the temperature becomes stable.

Figure 7 shows that the numerical simulation results are higher than the experimental results. Numerical simulations rely on mathematical models and assumptions regarding fluid behavior, heat transfer, and other physical phenomena. Discrepancies arise when these assumptions do not precisely reflect the complexities of real-world heat exchanger systems. Moreover, experimental measurements are subject to uncertainties due to factors such as measurement errors, apparatus accuracy, and specific conditions of the experimental setup.

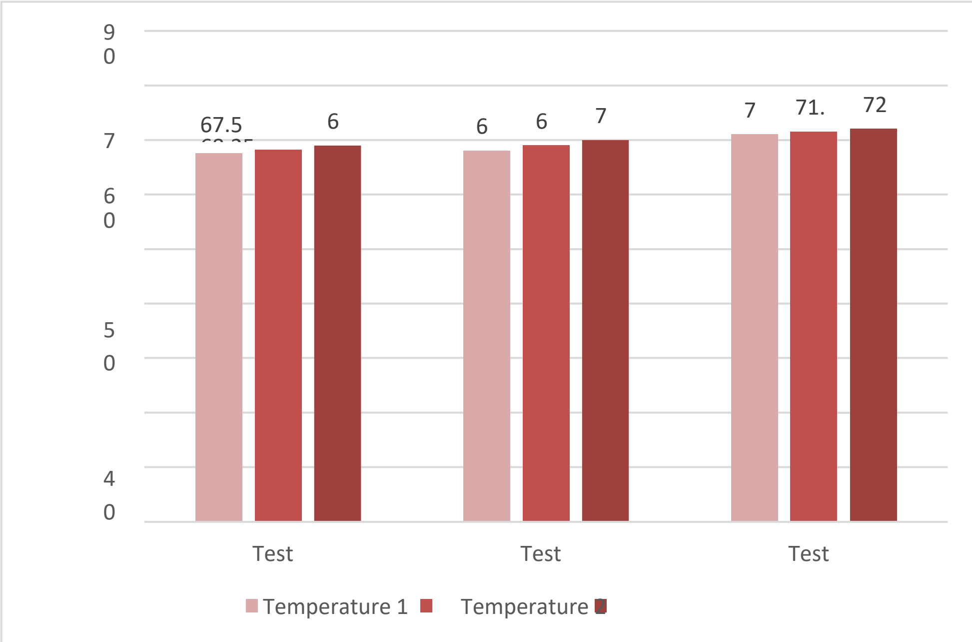

Figure 6: Experimental Result of Cold Fluid Outlet Temperature

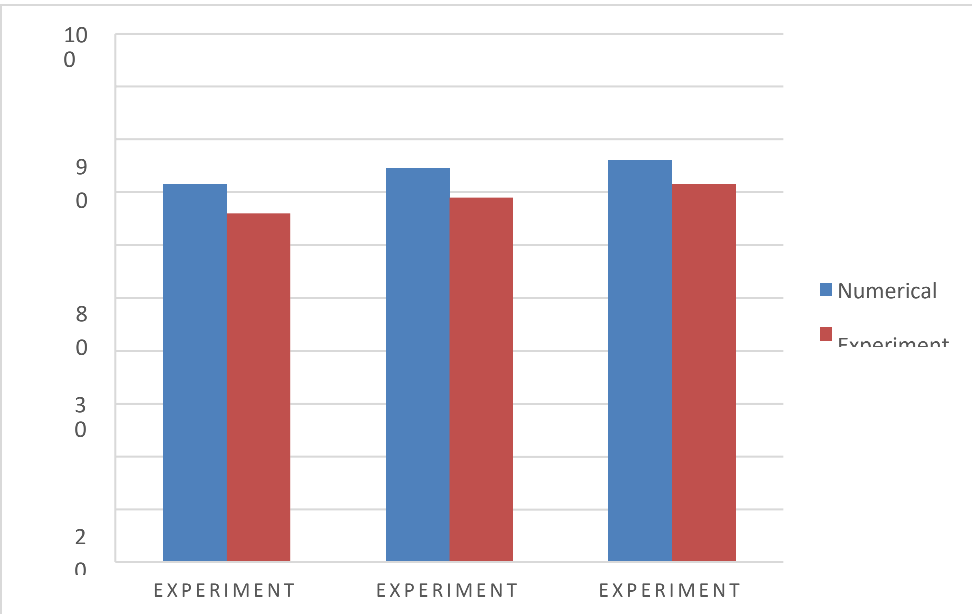

Figure 7: Comparison between experimental and numerical cold fluid out temperature

These uncertainties can significantly impact the experimental outcomes, leading to differences when compared with numerical simulations. Understanding these variations is crucial for refining both numerical models and experimental techniques to achieve more accurate and reliable results in heat exchanger analysis. Therefore, future works will be directed to analyze and reduce the uncertainties, and eventually improve the validation results.

4. Conclusion

In conclusion, integrating a gas-gas heat exchanger with a boiler system for waste heat recovery offers an effective and sustainable solution for energy recovery. By harnessing waste heat in this manner, industrial processes can significantly reduce their environmental impact. Gas-gas heat exchangers play a crucial role in various industrial applications. Our research highlights several key findings:

The development of efficient heat exchangers is essential due to the increasing heat load per unit area and the need for low-temperature waste heat recovery. Numerical simulations indicated that the cold fluid output temperature ranged from 72°C to 77°C, whereas experimental results showed a range of 66°C to 72°C at different air mass flow rates of 0.1564, 0.1346, and 0.1794 kg/s. To enhance our research, further experiments could be conducted under varying conditions. This includes altering the flow rates of the hot and cold fluids, adjusting the heat exchanger's design, or experimenting with different configurations. These steps would provide deeper insights and potentially improve the efficiency and effectiveness of the heat exchanger system.

Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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