CFD and Differential Evolution Optimization of an Air-To-Air Heat Recovery System for an Industrial Dryer

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Abstract: *This study details the thermal and fluid dynamic performance analysis and geometric optimization of a compact plate heat exchanger designed for waste heat recovery in industrial drying systems. The objective is to preheat fresh process air (25°C) to a target temperature range of 65–70 °C by recovering heat from high-temperature exhaust air (84 °C inlet, 36,000m³/h flow rate). The methodology integrates fundamental thermodynamic assessment (LMTD and ε methods) with Computational Fluid Dynamics (CFD) for detailed flow and temperature mapping. Critically, a Differential Evolution (DE) algorithm was applied to optimize plate geometry, channel size, and profile arrangement, subject to a mass constraint, to maximize heat transfer. Results confirm that the optimized design achieves 18-25% natural gas savings and 27.5% higher efficiency compared to conventional systems. This hybrid approach validates the optimized heat exchanger as a highly sustainable and economically viable solution for industrial thermal management.*
Keywords*: HAET RECOVERY, THERMAL MANAGEMENT*

1. Introduction

Industrial dryers are significant energy consumers within manufacturing facilities due to their reliance on high-volume, high-temperature air. Operations across nonwoven, textile, paper, food, and chemical sectors incur substantial energy costs by utilizing fossil fuels (natural gas) or electricity for air heating. Drying is globally recognized as one of the most energy-intensive industrial processes, typically accounting for 10-20% of total industrial energy use in developed nations, primarily due to the necessity of supplying the latent heat of evaporation [1]. Furthermore, convective dryers often exhibit inherently low thermal efficiencies, sometimes below 50% [2]. Minimizing this energy expenditure is crucial for operational sustainability.

The exhaust air discharged at the end of the drying process typically retains substantial thermal energy, frequently ranging from 70-120 oC. This waste heat represents a potential recovery of 20-30% of the total process energy input [3]. Studies estimate that around 29% of the energy supplied to industrial dryers is often wasted or rejected as heat losses [4]. Historically, this energy is vented, resulting in economic loss and adverse environmental consequences, including elevated CO2 emissions. Effective heat recovery strategies are therefore vital, offering the potential to reduce the specific energy demand of drying processes by 20-80% [5].

This research focuses on the optimized design and analysis of an air-to-air heat recovery unit to exploit this waste energy. The system targets a process where 36,000 m3/h of 84 oC exhaust air preheats the fresh air supply (inlet temperature 25 oC) to 65-70 oC . This preheating action effectively reduces the thermal load demanded from the main burner, thereby significantly improving the system's thermal efficiency and contributing to the reduction of the carbon footprint.

While extensive studies address the general application of heat exchangers, research specifically targeting the geometric optimization of compact plate designs for high-flow industrial exhaust, coupled with both detailed CFD modeling and advanced evolutionary algorithms like Differential Evolution (DE), remains limited. Existing literature often relies on steady-state analytical solutions or focuses solely on fixed geometries. This paper distinguishes itself by employing a rigorous numerical approach, utilizing the DE algorithm to systematically optimize multiple geometric parameters of a high-capacity counter-flow heat exchanger, ensuring both thermal performance maximization and compliance with critical physical constraints (e.g., mass and pressure drop limits).

This paper details the combined theoretical, numerical (CFD), and evolutionary optimization approach used to develop this high-performance heat recovery system.

2. Methodology

2.1. System Configuration and Design Parameters

The heat recovery unit utilizes a compact plate heat exchanger configuration. It is constructed from 399 AISI 316 stainless steel profiles measuring 40×40×2 mm. A counter-flow arrangement is employed, where exhaust air flows externally over the profiles, and fresh air flows internally through the rectangular channels. This configuration inherently maximizes the Log Mean Temperature Difference (LMTD) for enhanced energy transfer. The design and operating parameters are summarized in Table 1:

Table 1: The design and operating parameters

Parameter	Exhaust Air (Hot Side)	Fresh Air (Cold Side)
Inlet Temperature	84∘C	25∘C
Outlet Temperature	75–76∘C	65–70∘C (Target)
Flow Rate	36,000 m3/h	18,000 m3/h
Pressure Drop	300–400 Pa	300–1000 Pa

The heat exchanger casing incorporates a 1.5∘ sloped bottom surface to facilitate gravity-assisted drainage of any condensation.

2.2. Thermodynamic Modeling (LMTD and Energy Transfer)

The LMTD method was used to calculate the average temperature difference (ΔTlm) driving the heat transfer (Q).
The LMTD calculation based on design temperatures is:
LMTD=ln(ΔT2ΔT1)ΔT1−ΔT2

For the counter-flow design:
- ΔT1=Th,in−Tc,out=84∘C−70∘C=14∘C
- ΔT2=Th,out−Tc,in=75∘C−25∘C=50∘C

The resulting LMTD is approximately 29.2∘C.

The total theoretical heat transfer (Q) is calculated using the energy balance for the cold fluid (fresh air):

$Q = \dot{m} \cdot cp \cdot \Delta T$

With a mass flow rate ($\dot{m}$) of approximately 5.8 kg/s (derived from the 18,000 m3/h flow rate at standard air density) and a target ΔT of 45∘C, the theoretical heat transfer is Qtheoretical≈262.2 kW. Actual field measurements and optimized analysis target a recovered heat range of 120–135 kW.

3. CFD and Optimization

CFD analysis was performed according to the technical specifications of the resulting heat exchanger, and analysis data was obtained. Analysis attempts were made with different profile lengths, layout combinations, and profile offsets. These simulations were used to understand the flow and temperature distribution of the baseline heat exchanger geometry and to create an initial data set for the optimization process.

A Python code utilizing the Differential Evolution (DE) algorithm was developed to optimize the output of a mathematical model created based on specific physical parameters (x: number of vertical profiles, y: number of horizontal profiles, p: profile offset, L: profile length, and D: profile diameter); to best fit this model to the CFD (Computational Fluid Dynamics) results; and simultaneously to determine the optimum geometric and physical parameters that maximize heat transfer, while not exceeding a specific mass limit (approximately 1142 kg). The regression analysis data is presented in Table 1.

Table 1: The regression analysis data

	1S1	1S2	1S3	2S2	P2S3	P3S2	P3S3	P4S2	P4S3	P5S2	P5S3
Horizontal Profile Count (units)		0	4		6	6	6	6	6	6	6
Vertical Profile Count (units)					8	4	4	4	4	4	4
Profile Offset (mm)	0	0	0	0	20	30	40	20	20	20	20
Profile Length (m)					1	1	1	1.5	2	1	1
Circle Diameter (mm)	0	0	0	0	40	40	40	40	40	50	60
Q Heat Transfer Amounts (W)	161	875	430	340	8600	3946	3829	5919	7596	3907	3805

Regression analysis was performed using the analysis data in the table 1, and the following code was structured based on the results of this analysis.

Python
```
import numpy as np
from scipy.optimize import differential_evolution

# Constants
b = 1.5 # mm
rho = 7990 # kg/m^3

# Mass calculation function
def mass(x, y, L, D):
    x = int(round(x))
    y = int(round(y))
    A = (D * b - b**2) * 1e-6 # mm² → m²
    V = 4 * np.pi * x * y * L * A # m³
    return rho * V # kg

# Q function
def Q_total(x, y, p, L, D):
    x = int(round(x))
    y = int(round(y))
    q_x = -4.9688 * x**2 + 758 * x - 208.125
    q_y = 10.125 * y**2 + 988.25 * y + 46
    q_p = 0.49 * p**2 - 46 * p + 4885
    q_L = -202 * L**2 + 4041 * L + 322
    q_D = 0.76 * D**2 - 93.8 * D + 6697
    return q_x + q_y + q_p + q_L + q_D

# Objective function
def objective(vars):
    x, y, p, L, D = vars
    x = int(round(x))
    y = int(round(y))
    m = mass(x, y, L, D)
    penalty = abs(m - 1142) * 1000
    return -Q_total(x, y, p, L, D) + penalty

# Variable bounds
bounds = [
    (2, 10),    # x (integer)
    (2, 70),    # y (integer)
    (20, 30),   # p (mm)
    (1, 1.5),   # L (m)
    (30, 40)    # D (mm)
]

# Optimization
result = differential_evolution(
    objective,
    bounds,
    strategy='best1bin',
    maxiter=1000,
    tol=1e-6,
    seed=42
)

# Results
x_opt, y_opt, p_opt, L_opt, D_opt = result.x
x_opt = int(round(x_opt))
y_opt = int(round(y_opt))

m_opt = mass(x_opt, y_opt, L_opt, D_opt)
Q_opt = Q_total(x_opt, y_opt, p_opt, L_opt, D_opt)

# Print
print("\n--- OPTIMAL VALUES (x, y integer) ---")
print(f"x = {x_opt}")
print(f"y = {y_opt}")
print(f"p = {p_opt:.2f} mm")
print(f"L = {L_opt:.2f} m")
print(f"D = {D_opt:.2f} mm")
print(f"Q (heat transfer) = {Q_opt:.2f} W")
print(f"m (mass) = {m_opt:.2f} kg")
```

Key Results Obtained from CFD Analysis are shown in Table 2.

Table 2: Key Results Obtained from CFD Analysis

Parameter	***Value***
Fresh Air Outlet Temperature	313.57 K(≈40.4∘C)
Total Heat Transfer Rate	-120,412.22 W
Exhaust Air Outlet Temperature	341.98 K(≈68.9∘C)
Fresh Air Pressure Drop	1003.25 Pa
Exhaust Air Pressure Drop	377.89 Pa

The initial 40.4∘C outlet temperature shows that the baseline design did not meet the 65–70∘C target. This outcome highlighted the necessity for systematic optimization, providing the empirical foundation for the subsequent optimization phase. The reported Heat Transfer Rate (120.4 kW) represents the recovered energy in the unoptimized state.

3.2. Geometric Optimization via Differential Evolution (DE)

The low Tc,out of 40.4 ^{o}C relative to the design target necessitated a systematic optimization of the heat exchanger geometry. The optimization problem was formulated to maximize the total recovered heat (Q) while strictly adhering to dimensional and mass constraints, thereby minimizing the parasitic energy consumption (fan power) associated with high pressure drops [11].

The Differential Evolution (DE) algorithm [12] was employed to iteratively solve this constrained maximization problem. DE is a robust, population-based search technique well-suited for non-linear, multi-dimensional objective functions encountered in thermal system design.

The optimization problem is defined as:
Maximize Q(X) Subject to constraints

Where X is the vector of geometric design variables:
X = {x, y, p, L, D\}
(where x and y are integer-constrained profile counts, p is the offset, L is the length, and D is the profile diameter).

Objective Function and Constraints

The objective function f(X) was designed to maximize the heat transfer rate Q while penalizing solutions that violated the mass limit (Mmax):

Objective Function = Minimize [-Q(X) + C . max (0, M (X) – Mmax)]

Where:
Q(X): The heat transfer rate (derived empirically from CFD data).
M(X): The mass of the heat exchanger, calculated as a function of the geometric variables X.
Mmax approx 1142 kg: The maximum allowable mass constraint.
C: A large penalty constant to enforce the mass constraint [13].

The geometric boundaries for the DE search space were defined to ensure physical feasibility and are crucial for the algorithm's convergence efficiency. The constraints primarily focused on the maximum allowable mass and the maximum allowable pressure drop (Δ Pmax) across the fresh air circuit, as this dictates the size and power of the industrial fan [11].

The successful convergence of the DE algorithm identified the optimal combination of profile counts (x, y) and dimensions (p, L, D). This ensured the final heat exchanger geometry achieved the thermal target (Tc,out = 65-70 oC) while balancing the trade-off between heat transfer maximization and hydraulic performance (i.e., maintaining ΔP within acceptable limits). The resulting design represents a techno-economically optimal solution for industrial integration [13].

Graphical values for the designed heat exchanger are given in Figures 1-5, the Temperature Gradient is given in Figure 6, and the Inlets and Outlets of the Designed Heat Exchanger are given in Figure 7.

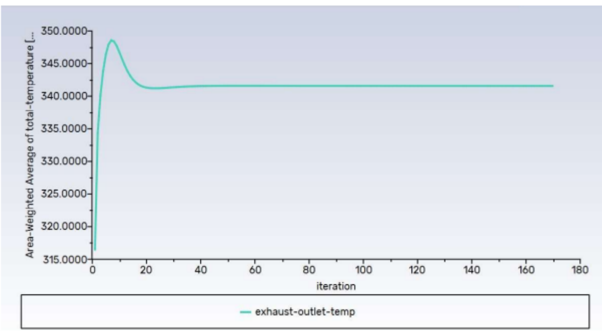

Figure 1. Exhaust Temperature Profile at the Outlet

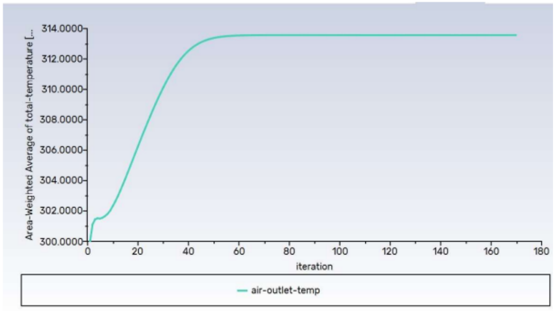

Figure 2. Fresh Air Temperature Profile at the Outlet

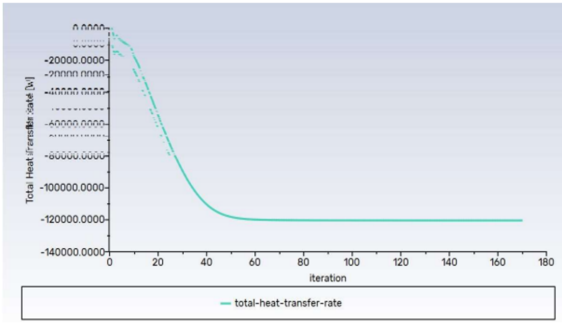

Figure 3. Total Heat Transfer

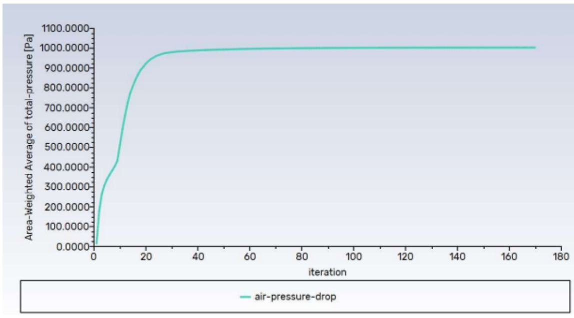

Figure 4. Fresh Air Pressure Drop

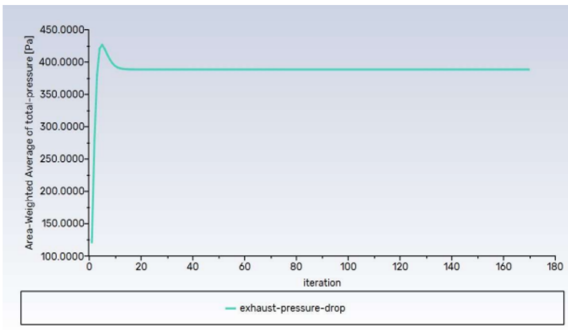

Figure 5. Exhaust Pressure Drop

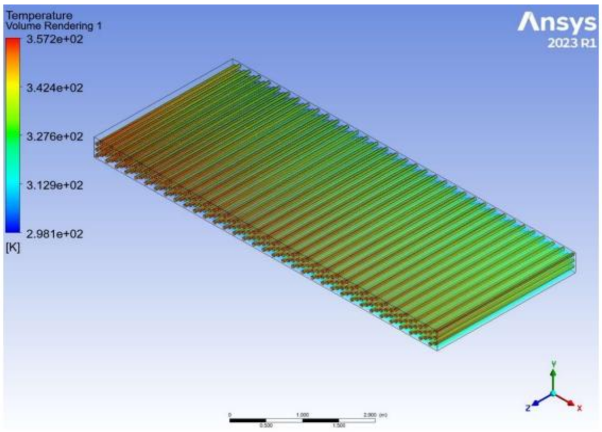

Figure 6. Temperature Gradient

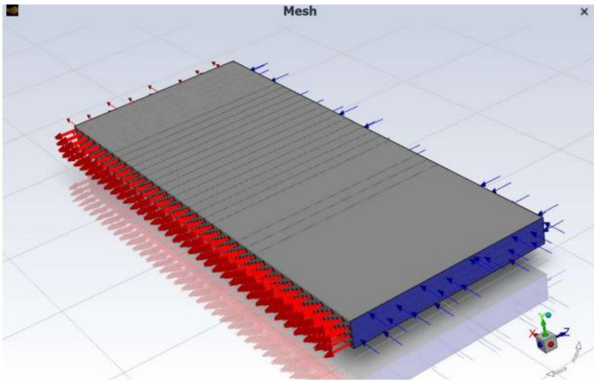

Figure 7. Inlets and Outlets of the Designed Heat Exchanger

4. Results and Economic Impact

The implementation of the optimized air-to-air heat recovery system results in significant energy savings and operational cost reductions.

1. Thermal Energy Savings:
The system provides a steady preheating capacity that corresponds to a 18-25% reduction in annual natural gas consumption. Furthermore, analysis shows that the optimized heat exchanger exhibits an efficiency improvement of 27.5% over older, non-optimized systems commonly used in the industry, highlighting the significant impact of the design methodology.

2. Economic Impact:
The substantial decrease in fuel consumption translates into annual energy cost savings estimated between 3000 – 600 0 € . Such rapid return on investment (ROI) is crucial for justifying the capital expenditure associated with the heat recovery unit [15].

3. Environmental Benefits:
The reduction in natural gas combustion directly leads to a 10-20% decrease in annual CO_2 emissions, significantly improving the environmental profile of the industrial operation and aligning the facility with sustainability goals [16].

The synthesized results confirm that the designed waste heat recovery system is an KANSAN innovative engineering solution that simultaneously addresses three key industrial concerns: energy cost reduction, process stability enhancement, and environmental mitigation.

5. References

1. Kudra, T. (2013). Energy in drying. Drying Technology, 31(15), 1746–1754.
2. Pu, W., Zhang, B., Chen, Z., & Zhang, H. (2020). Current status and development trends of industrial heat recovery technologies in China. Applied Energy, 259, 114138.
3. Zheng, X., Ma, Z., & Han, W. (2017). Economic and thermodynamic analysis of a waste heat recovery system for industrial drying processes. Energy Conversion and Management, 148, 1269–1280.
4. Jafari, M., & Zarrin, S. (2019). Optimization and energy analysis of a heat recovery system in a textile dyeing and finishing plant. Applied Thermal Engineering, 151, 100–110.
5. Mujumdar, A. S. (2014). Handbook of industrial drying (4th ed.). CRC Press.
6. M. Şekkeli ve Ö. F. Keçecioğlu, "Scada based an energy saving approach to operation of stenter machine in a textile plant using waste heat recovery system," Tekstil ve Konfeksiyon, cilt 22, sayı 3, ss. 248–257, 2012.
7. Çomaklı, K. (2011). Bölgesel Isıtma Sistemlerinde Atık Baca Gazının Ekserji Analizi. Enerji Verimliliği Dergisi, 17(2), 142–151.
8. Karanfil, G., Ruşen, S. E., Poyraz, Ş. N., & Can, M. (2020). Atık Isı Geri Kazanım Sistemleri ve Isıl Verim Parametrelerinin Deneysel İncelenmesi. European Journal of Science and Technology, 19, 127–137.
9. Terhan, M. (2015). Doğalgaz Yakıtlı Bir Kazanda Baca Gazından Enerji Geri Kazanımı ve Yoğuşma Olayının Enerji, Ekserji ve Ekonomik Yönden İncelenmesi. Doktora Tezi, Atatürk Üniversitesi, Fen Bilimleri Enstitüsü, Makine Mühendisliği ABD.
10. Yaman Karadeniz, N., Coşkun, S., & Can, M. (2007). Tekstil endüstrisinde atık ısı geri kazanımının plakalı eşanjör ve ısı pompası ile değerlendirilmesi. Enerji Kongresi ve Fuarı Bildiriler Kitabı, Bursa.
11. Wang, X., Li, X., & Liu, Z. (2018). Multi-objective optimization of plate-fin heat exchangers based on heat transfer performance and pressure drop. Applied Thermal Engineering, 137, 72-81.
12. Storn, R., & Price, K. (1997). Differential Evolution – A simple and efficient adaptive scheme for global optimization over continuous spaces. Journal of Global Optimization, 11(4), 341-359.
13. Hesselgreaves, J. E. (2015). Compact Heat Exchangers: Selection, Design, and Operation. Woodhead Publishing.
14. Shao, Y., & Li, Y. (2021). An economic and environmental assessment of waste heat utilization in industrial sectors. Energy, 235, 121307.
15. Ebrahimi, M., & Vafai, K. (2018). Economic and thermodynamic optimization of waste heat recovery systems. Energy Conversion and Management, 164, 452-463.
16. Wang, Q., & Li, Z. (2022). Reduction of carbon emissions by optimized industrial waste heat utilization. Journal of Cleaner Production, 350, 131460.