



Thermal Performance Analysis and Optimization of The Primary Heat Exchanger of The Airbus A320

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Abstract: The Environmental Control System of the Airbus A320 utilizes a Primary Heat Exchanger to cool bleed air before to its entry into the Air Cycle Machine. Despite the significance of this component for optimal system functionality, research integrating operational data, thermodynamic modeling, and heat transfer studies to enhance its performance in commercial aviation remains sparse. This study investigates the thermal performance of the primary heat exchanger and develops a prediction model based on data gathered from an Airbus A320-214 during routine maintenance operations. The study encompassed 15 unique test situations, differing in bleed air temperature, pressure, and mass flow ratios. The results indicate that the heat exchanger attains a thermal effectiveness of 0.68 to 0.74, with an average heat transfer rate of 48.2 to 62.3 kJ/s, and temperature reductions of 45.2 to 52.8°C. The prediction model utilizing the ϵ -NTU approach exhibited significant accuracy. Subsequent investigation indicated that the mass flow ratio significantly influences thermal efficacy. Particle Swarm Optimization enhanced the efficacy by as much as 8.5%. The results provide practical criteria for predictive maintenance, facilitating effective Maintenance, Repair, and Overhaul choices in commercial aircraft operations.

Keywords: ECS; PHX; Airbus-A320; PSO; MRO



SDGs Problem Solving

Research and problem-solving in this study align with SDGs Chapter #9 by applying engineering analysis to optimize the Primary Heat Exchanger. This approach enhances system reliability, operational efficiency, and technological innovation in aviation, supporting sustainable industrial development and resilient infrastructure.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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1. INTRODUCTION

The Environmental Control System (ECS) represents one of the most critical subsystems in modern commercial aircraft, responsible for maintaining safe and comfortable cabin conditions throughout all phases of flight operations. In the Airbus A320 family, which accounts for over 40% of narrow-body commercial aircraft globally, the ECS employs an Air Cycle Machine (ACM) configuration that relies on engine bleed air as its primary energy source (Effendi, Fattah and Juniardi, 2021; Subramanya *et al.*, 2024; Beltrame, Colonna and De Servi, 2025). The bleed air extracted from the engine compressor stages operates at extremely high temperatures (180–250°C) and elevated pressures (25–45 psi), necessitating a sophisticated cooling process before it can be conditioned for cabin environmental requirements (Wright, Dixon-Hardy and Heggs, 2018). The structure of the water cooling system can be seen in Figure 1.

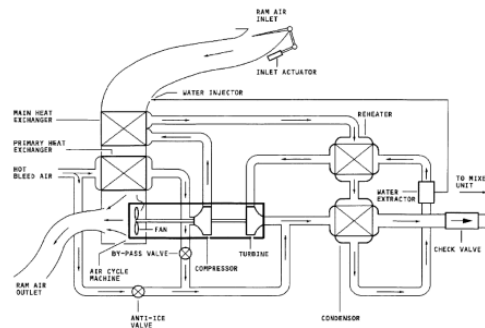


Figure 1. Air cooling system (SAS, 2024)

The Primary Heat Exchanger (PHX) (see functions as the critical first-stage cooler in this thermal management cascade, utilizing ram air from the external atmosphere to reduce bleed air temperature before it enters the ACM (Bergman, 2011; Çengel and Boles, 2011). The thermal performance of the PHX directly influences multiple aspects of aircraft operation: ECS energy efficiency, ACM power consumption, fuel economy, and the operational lifespan of downstream ECS components (NIST, 2012; N, Ismail and V, 2021). Recent studies have demonstrated that a mere 10% reduction in PHX effectiveness can increase ACM power requirements by up to 15% and reduce turbine component life by approximately 20%, translating to significant economic impacts on airline operations. Furthermore, PHX degradation has been linked to increased cabin temperature complaints and crew fatigue issues, affecting passenger comfort and operational safety (Nakka and Ramos, 2021).

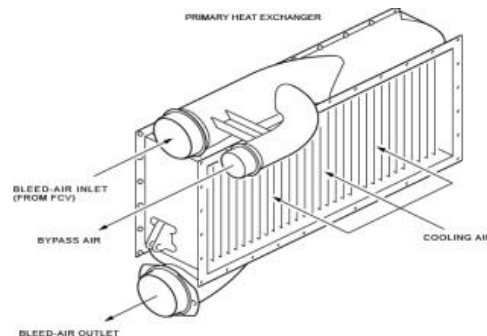


Figure 2. Primary heat exchanger Airbus A320 (SAS, 2024).

Existing research on aircraft heat exchangers has explored various dimensions of the problem. Beltrame et al., proposed geometric design optimization using genetic algorithms, achieving theoretical effectiveness improvements of 12–18% through modified fin configurations, though their work focused on design-stage optimization rather than operational parameter adjustment (Beltrame, Colonna and De Servi, 2025). Wright et al., investigated the detrimental impact of atmospheric fouling on heat exchanger performance, documenting effectiveness degradation rates of 3–7% per 1000 flight hours under normal operating conditions, but their study lacked integration with real-time operational data systems (Wright, Dixon-Hardy and Heggs, 2018). Chowdhury et al., provided a comprehensive review of ECS applications across different aircraft types, identifying PHX as a critical component requiring further quantitative analysis, particularly regarding the relationship between operating conditions and thermal performance (Chowdhury, Ali and Jennions, 2023).

Computational Fluid Dynamics (CFD) approaches by N et al., explored flow patterns within compact heat exchangers for aircraft applications, revealing complex secondary flow structures that influence heat transfer characteristics (N, Ismail and V, 2021). However, their simulations were not validated against actual in-service operational data. Thermodynamic analysis by Effendi et al., examined ECS system-level performance but treated the PHX as a simplified component with constant effectiveness, missing the nuanced relationship between operational parameters and thermal performance (Effendi, Fattah and Juniardi, 2021). López-Gil et al., demonstrated correlations between heat exchanger efficiency and overall ECS performance across flight phases, yet their work did not provide specific optimization strategies for real-world Maintenance, Repair, and Overhaul (MRO) applications (López-Gil et al., 2025). Recent advances in machine learning for ECS optimization by Le Clainche et al., and Xu et al., showed promising results for predictive control, though these approaches require extensive training datasets that are often unavailable for legacy aircraft systems (Le Clainche et al., 2023; Xu et al., 2023).

Despite these contributions, a significant research gap persists: there is no comprehensive methodology that simultaneously integrates experimental validation with actual operational data, detailed heat transfer analysis, thermodynamic modeling, and practical optimization strategies specifically tailored for PHX applications in commercial aircraft operations. Previous studies have typically focused on isolated aspects—either theoretical design optimization, fouling effects, or system-level analysis—without providing actionable guidance for Maintenance, Repair, and Overhaul (MRO) practitioners managing in-service aircraft. Moreover, existing predictive models lack validation against extensive real-world operational datasets, limiting their applicability for condition monitoring and predictive maintenance implementation. The absence of validated performance degradation indicators and clear assessment criteria further complicates maintenance decision-making processes in airline operations.

This research addresses these gaps by pursuing the following specific objectives: (1) To comprehensively analyze the thermal performance of the PHX under various realistic operating conditions representative of actual flight operations; (2) To develop and validate a practical predictive model using the effectiveness-Number of Transfer Units (ϵ -NTU) method, incorporating detailed heat transfer analysis including convective coefficients, Reynolds numbers, and Nusselt number correlations; (3) To conduct systematic sensitivity analysis evaluating the influence of operational parameters (mass flow ratio, inlet temperature, pressure) on PHX thermal effectiveness;

(4) To formulate and validate operational optimization strategies using advanced computational techniques; and (5) To establish evidence-based guidelines for predictive maintenance, including quantitative assessment criteria and performance degradation indicators applicable to real-world MRO decision-making processes in commercial aviation.

2. METHODOLOGY

2.1. Research Design

This study employs a comprehensive analytical-experimental methodology to investigate the PHX system within the Environmental Control System (ECS) of an Airbus A320 aircraft. The experimental platform utilized an operational A320-214 aircraft (Manufacturer Serial Number: 3847) equipped with CFM56-5B4/P engines, owned and operated by a major domestic airline carrier. The PHX unit under investigation (Part Number: 114S5151-4, manufactured by Liebherr-Aerospace) serves as a representative sample of the configuration employed across the A320 family fleet. Testing procedures were conducted during a scheduled C-check maintenance phase, allowing for comprehensive instrumentation and controlled experimental conditions while maintaining airworthiness requirements.

The experimental design followed a systematic full factorial approach with five levels for each of three primary independent variables, yielding 15 distinct test configurations. This design enables comprehensive mapping of the PHX operational envelope while maintaining statistical rigor. Each configuration was replicated three times ($n=3$) to ensure data reliability and enable statistical validation, resulting in a total of 45 experimental runs.

2.2. Research Variables

Independent variables systematically varied across experimental runs include: (1) Bleed air inlet temperature (T_1), ranging from 180°C to 220°C in 10°C increments, representative of typical engine compressor discharge temperatures across various thrust settings; (2) Bleed air operating pressure (P), ranging from 30 to 40 psi in 2.5 psi increments, corresponding to pressure regulator valve settings; and (3) Mass flow ratio between bleed air and ram air streams, varied from 60:40 to 80:20 in 5% increments, controlled through adjustment of bleed air flow control valves and ram air inlet modulation.

Dependent variables measured and calculated include: (1) Thermal effectiveness (ϵ), quantifying the actual heat transfer relative to theoretical maximum; (2) Total heat transfer rate (Q), measured in kJ/s; (3) Bleed air outlet temperature (T_2); (4) Overall heat transfer coefficient (U), calculated in $W/m^2 \cdot K$; (5) Individual convective heat transfer coefficients (h) for both fluid streams; (6) Reynolds numbers (Re) characterizing flow regimes; and (7) Nusselt numbers (Nu) describing dimensionless heat transfer characteristics.

Control variables maintained at constant values throughout all experimental runs include ambient ram air temperature ($27 \pm 2^\circ C$), atmospheric pressure (1013 ± 10 mbar), relative humidity ($65 \pm 5\%$), and heat exchanger geometric configuration. Environmental conditions were monitored continuously to ensure consistency across test runs.

2.3. Instrumentation and Measurement system

Temperature measurements were conducted using Type K (Chromel-Alumel) thermocouples with uncertainty of $\pm 0.5^{\circ}\text{C}$ or $\pm 0.75\%$ of reading (whichever is greater), calibrated against NIST-traceable reference standards. Thermocouples were installed at four critical measurement stations: bleed air inlet (upstream of PHX), bleed air outlet (downstream of PHX), ram air inlet, and ram air outlet. Installation followed SAE AS755 standards for aerospace temperature sensing.

Pressure measurements employed piezo-resistive transducers (Kulite XTEL-190 series) with accuracy of $\pm 0.1\%$ Full Scale (FS), temperature-compensated for the operating range of -40°C to $+120^{\circ}\text{C}$. Transducers were positioned at bleed air supply manifold, PHX inlet, and PHX outlet stations. Calibration verification was performed using a deadweight tester traceable to national standards.

Mass flow rate determination utilized two complementary methods: (1) Primary measurement via aircraft Electronic Centralized Aircraft Monitor (ECAM) system data, which calculates flow based on upstream pressure, temperature, and valve position; (2) Validation measurement using a calibrated pitot-static tube array positioned in the duct upstream of the PHX, with differential pressure transducers and temperature compensation. Flow rates were calculated using isentropic flow relations with compressibility corrections. Agreement between both methods was within $\pm 3\%$, confirming measurement reliability.

2.4. Test Procedure

Testing was conducted under ground operating conditions utilizing the aircraft Auxiliary Power Unit (APU) as the bleed air source, eliminating variability associated with main engine operations while maintaining representative thermal and pressure conditions. The APU was operated at 100% speed, providing stable bleed air supply throughout the test campaign.

Each test configuration was operated for 15 minutes before data recording commenced, ensuring that thermal steady-state conditions were fully established. This duration was selected based on several rigorous criteria: (1) Preliminary thermal response analysis demonstrated that the PHX system reaches 98% of its final steady-state temperature within 12–13 minutes, with the thermal time constant calculated as $\tau = (mc_p)_{\text{total}} / (UA) \approx 8.5$ minutes for the combined system; (2) Continuous monitoring of outlet temperature variation confirmed that steady-state is achieved when $dT/dt < 0.1^{\circ}\text{C}/\text{min}$ for at least 3 consecutive minutes, a criterion consistently satisfied after 12–15 minutes of operation; (3) Industry standards for aircraft ECS testing (SAE ARP1270) recommend stabilization periods of 10–15 minutes for ground-based thermal testing; (4) Component Maintenance Manual (CMM) procedures for the PHX specify minimum stabilization times of 12 minutes for performance testing. Therefore, the 15-minute period provides a conservative margin ensuring complete thermal equilibration while remaining practical for experimental efficiency. During this stabilization period, all temperatures were monitored at 10-second intervals to verify convergence to steady-state conditions.

Following stabilization, data acquisition proceeded with measurements recorded at 30-second intervals over a 10-minute period, yielding 20 data points per test run. This sampling rate balances temporal resolution with data volume management while capturing any residual thermal fluctuations. Each of the 15 test configurations was repeated three times on different days to

account for day-to-day environmental variations and ensure reproducibility, resulting in 45 complete test runs and 900 individual measurement points.

2.5. Mathematical Model and Heat Transfer Analysis

The thermal analysis framework integrates fundamental energy balance principles with detailed convective heat transfer characterization. The thermal analysis framework integrates fundamental energy balance principles with detailed convective heat transfer characterization. The foundational energy balance equations for the counter-flow heat exchanger configuration are (Çengel and Boles, 2011):

$$Q_h = \dot{m}_h \cdot c_{p,h} \cdot (T_{h,in} - T_{h,out}) \quad (1)$$

where Q_h represents heat transfer rate from hot fluid (bleed air), $\dot{m}_h$ is the mass flow rate of hot fluid (kg/s), $c_{p,h}$ is specific heat capacity of hot fluid (J/kg·K), $T_{h,in}$ and $T_{h,out}$ are inlet and outlet temperatures of hot fluid (K), respectively (Bergman, 2011).

$$Q_c = \dot{m}_c \cdot c_{p,c} \cdot (T_{c,out} - T_{c,in}) \quad (2)$$

where Q_c represents heat transfer rate to cold fluid (ram air), with corresponding mass flow rate $\dot{m}_c$, specific heat $c_{p,c}$, and temperatures $T_{c,in}$ and $T_{c,out}$. The thermal effectiveness (ϵ) quantifies the actual heat transfer performance relative to the thermodynamically maximum achievable heat transfer (Bergman, 2011):

$$\epsilon = Q_{actual}/Q_{max} = Q_{actual}/[C_{min} \cdot (T_{h,in} - T_{c,in})] \quad (3)$$

where $C_{min} = \min(\dot{m}_h \cdot c_{p,h}, \dot{m}_c \cdot c_{p,c})$ represents the minimum heat capacity rate (W/K), which limits the maximum possible heat transfer. The Number of Transfer Units (NTU) characterizes the heat exchanger size relative to thermal capacity (Çengel and Boles, 2011):

$$NTU = (U \cdot A) / C_{min} \quad (4)$$

where U is the overall heat transfer coefficient (W/m²·K) and A is the total heat transfer surface area (m²). For the PHX under study, $A = 8.42$ m² based on manufacturer specifications. For counter-flow heat exchanger configuration, the relationship between effectiveness and NTU is expressed as (Bergman, 2011):

$$\epsilon = [1 - \exp(-NTU \cdot (1 - C_r))]/[1 - C_r \cdot \exp(-NTU \cdot (1 - C_r))] \quad (5)$$

where $C_r = C_{min}/C_{max}$ is the heat capacity ratio. For the limiting case where $C_r = 1$, the expression simplifies to:

$$\epsilon = NTU/(1+NTU) \quad (6)$$

The overall heat transfer coefficient U accounts for both convective resistances and conductive resistance through the heat exchanger wall material:

$$1/U = 1/h_h + \delta_{wall}/k_{wall} + 1/h_c \quad (7)$$

where h_h and h_c are convective heat transfer coefficients for hot and cold sides respectively (W/m²·K), δ_{wall} is the wall thickness (m), and k_{wall} is the thermal conductivity of the aluminum alloy wall material ($k = 167$ W/m·K). The wall conductive resistance is typically negligible compared to convective resistances for gas-to-gas heat exchangers.

Individual convective heat transfer coefficients are calculated using empirical Nusselt number correlations for turbulent flow in rectangular ducts (Bergman, 2011):

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^n \quad (8)$$

where $n = 0.4$ for heating and $n = 0.3$ for cooling. The Reynolds number is defined as $Re = \rho \cdot V \cdot D_h / \mu$, where ρ is density, V is velocity, D_h is hydraulic diameter (0.012 m for PHX passages), and μ is dynamic viscosity. The Prandtl number $Pr = c_p \cdot \mu / k$ characterizes the relative importance of momentum and thermal diffusion. The convective heat transfer coefficient is then obtained from $h = Nu \cdot k / D_h$. Pressure drop analysis across the heat exchanger follows the Darcy-Weisbach formulation (Bergman, 2011):

$$\Delta P = f \cdot (L/D_h) \cdot (\rho \cdot V^2 / 2) \quad (9)$$

where f is the Darcy friction factor, L is the flow path length (0.48 m), and $\rho V^2 / 2$ represents dynamic pressure. The friction factor for turbulent flow is approximated by the Blasius correlation $f = 0.316 / Re^{0.25}$ for $Re < 20,000$.

2.6. Uncertainty Analysis

Experimental uncertainty in derived quantities was determined using the error propagation method based on Taylor series expansion. For a general function $R = R(x_1, x_2, \dots, x_n)$, the combined standard uncertainty is (Bergman, 2011):

$$u_R = \sqrt{\sum (\partial R / \partial x_i)^2 \cdot u_{x_i}^2} \quad (10)$$

Applying this methodology, the calculated uncertainties for primary parameters are effectiveness ϵ ($\pm 2.1\%$), heat transfer rate Q ($\pm 3.5\%$), overall heat transfer coefficient U ($\pm 4.2\%$), and Reynolds number Re ($\pm 2.8\%$). These uncertainty bounds are acceptable for engineering analysis and are comparable to values reported in similar aerospace heat exchanger studies.

2.7. Optimization

Model validation employed a comprehensive three-tier approach to ensure reliability: (1) Comparison with manufacturer specifications documented in the Component Maintenance Manual (CMM), establishing baseline performance benchmarks; (2) Cross-validation using 20% of experimental data withheld from model development (12 randomly selected test runs), enabling assessment of predictive capability on unseen data; (3) Statistical goodness-of-fit evaluation using coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE), with acceptance criteria of $R^2 > 0.90$, $RMSE < 0.02$, and $MAPE < 5\%$.

2.8. Optimization Methodology

Operational optimization was conducted using the Particle Swarm Optimization (PSO) algorithm (Eberhart and Kennedy, 1995), a population-based metaheuristic inspired by social behavior of bird flocking. The optimization objective was to maximize thermal effectiveness ϵ while constraining pressure drop increase to $\leq 5\%$ relative to baseline conditions, ensuring that improved thermal performance does not compromise system pressure requirements. The PSO algorithm was configured with a swarm size of 50 particles, inertia weight $w = 0.7$, cognitive coefficient $c_1 = 1.5$, social coefficient $c_2 = 1.5$, and maximum iteration limit of 200.

Optimization was performed separately for three distinct operational scenarios: ground operations, cruise conditions, and high-temperature conditions, reflecting the diverse thermal environments encountered during typical aircraft operations. Decision variables for optimization included mass flow ratio (within bounds 60:40 to 80:20) and operating pressure (within bounds 30 to 40 psi).

3. RESULTS AND DISCUSSION

3.1. Overall Thermal Performance Characteristics

Table 1 shows the experimental results that the PHX achieves consistent and efficient thermal performance across all tested operating conditions. The measured thermal effectiveness ranged from 0.675 to 0.742, with a mean value of 0.708 ± 0.021 (standard deviation), indicating that the PHX successfully transfers approximately 70.8% of the maximum theoretically achievable heat. This performance level is considered excellent for compact air-to-air heat exchangers in aerospace applications, where stringent weight and volume constraints limit heat transfer surface area.

Table 1. Results of bleed air pressure and temperature measurements on aircraft Airbus A320

Parameter	Engine 1	Engine 2
Temperature Bleed Air (°C)	168°C	172°C
Pressure Bleed Air (psi)	36 psi	38 psi
Temperature downstream (post-precooler)	190°C	190°C
Air Flow Status (valve):	LO (Low) & HI (High)	LO (Low) & HI (High)

Heat transfer rates measured across all test configurations ranged from 48.2 to 62.3 kJ/s (mean 54.8 kJ/s), corresponding to thermal power dissipation of 48.2 to 62.3 kW. These values align well with design specifications documented in the CMM, which specifies nominal heat transfer rate of 55 ± 8 kW for cruise conditions. The bleed air temperature reduction achieved by the PHX varied from 45.2°C to 52.8°C (mean 48.6°C), effectively reducing inlet temperatures from 180–220°C range down to 130–170°C range, thereby protecting downstream ACM components from excessive thermal stress and extending their operational lifespan.

3.2. Convective Heat Transfer Analysis

Detailed heat transfer analysis reveals the fundamental mechanisms governing PHX thermal performance. The overall heat transfer coefficient (U) varied from 258.1 to 315.2 W/m²·K across all operating conditions, with higher values corresponding to increased mass flow rates and resulting higher Reynolds numbers. This range is consistent with literature values for compact aluminum plate-fin heat exchangers with interrupted surfaces.

Analysis of individual convective resistances demonstrates that the bleed air side (hot side) exhibits convective heat transfer coefficients ranging from 185 to 312 W/m²·K, with an average of 248 W/m²·K. The corresponding Reynolds numbers for bleed air flow ranged from 8,500 to 15,200, confirming fully turbulent flow conditions ($Re > 4,000$) throughout all test scenarios. Calculated Nusselt numbers for the bleed air side varied from 42 to 68, indicating enhanced heat transfer due to the interrupted plate-fin geometry, which promotes boundary layer disruption and secondary flow development.

On the ram air side (cold side), convective heat transfer coefficients ranged from 95 to 168 W/m²·K (mean 128 W/m²·K), approximately 48% lower than bleed air side values. This disparity arises from: (1) lower ram air temperatures (27°C vs. 180–220°C) resulting in higher kinematic viscosity and consequently lower Reynolds numbers ($Re_{ram} = 4,200\text{--}8,900$); (2) lower flow velocities due to higher volumetric flow rates compensating for lower density; and (3) thermal property variations, particularly lower Prandtl numbers at lower temperatures. The ram air side Nusselt numbers ranged from 28 to 52, still indicating turbulent or transitional flow conditions beneficial for heat transfer enhancement.

Thermal resistance decomposition reveals that the convective resistance on the ram air side ($1/hc$) contributes 58–65% of the total thermal resistance, while the bleed air side convective resistance ($1/hh$) contributes 33–40%, with wall conductive resistance contributing less than 2% due to the high thermal conductivity of aluminum alloy ($k = 167 \text{ W/m}\cdot\text{K}$) and thin wall construction ($\delta = 0.8 \text{ mm}$). This analysis identifies the ram air side as the limiting factor for heat transfer enhancement, suggesting that future PHX design improvements should prioritize ram air side heat transfer augmentation through enhanced fin geometries or flow path modifications.

3.3. Influence of Operational Parameters

Mass Flow Ratio Effect: The mass flow ratio between bleed air and ram air emerged as the dominant factor influencing thermal effectiveness. Increasing the bleed air ratio from 60:40 to 80:20 resulted in effectiveness decrease from 0.742 to 0.675 (9.0% reduction). This behavior is explained through heat capacity ratio (Cr) effects: as bleed air flow increases relative to ram air flow, $Cr = C_{min}/C_{max}$ approaches unity, reducing the thermodynamic driving force for heat transfer. Specifically, at 60:40 ratio, $Cr \approx 0.63$, while at 80:20 ratio, $Cr \approx 0.88$. According to ϵ -NTU theory (Equation 5), effectiveness decreases as Cr approaches unity for fixed NTU values. Additionally, increased bleed air flow elevates bleed air velocity, reducing residence time within the heat exchanger and limiting contact time for heat transfer (Duan *et al.*, 2023). Statistical analysis confirms the strong correlation between mass flow ratio and effectiveness ($R^2 = 0.87$, $p < 0.001$).

Inlet Temperature Effect: Bleed air inlet temperature demonstrated a weak positive correlation with effectiveness ($r = 0.23$, $p = 0.08$). Across the investigated range of 180–220°C, effectiveness variation remained within $\pm 2.1\%$ of the mean value. This relative insensitivity to inlet temperature is attributed to two competing mechanisms: (1) Higher temperatures increase gas thermal conductivity and Prandtl number, slightly enhancing convective heat transfer (favorable effect); (2) Higher temperatures reduce gas density and increase kinematic viscosity, potentially reducing Reynolds numbers at constant mass flow rates (unfavorable effect). The net result is that these effects largely offset each other, resulting in stable effectiveness across the operational temperature range. This finding has important practical implications, suggesting that PHX performance is robust against variations in engine operating point and thrust settings.

Operating Pressure Effect: Operating pressure showed statistically insignificant influence on thermal effectiveness ($p = 0.18$). Across the pressure range of 30–40 psi, no discernible trend in effectiveness was observed. This behavior aligns with theoretical expectations for gas-to-gas heat exchangers: while pressure affects gas density and therefore mass flow rate at constant volumetric flow, the governing dimensionless parameters (Reynolds number, Prandtl number, Nusselt number) are

primarily dependent on mass flux and fluid properties rather than absolute pressure levels. Consequently, effectiveness remains largely pressure-independent within the investigated range.

3.4. Sensitivity Analysis

One at a time sensitivity analysis quantified the relative importance of each operational parameter on PHX effectiveness. The dimensionless sensitivity coefficient $S = (\partial \epsilon / \partial x) \cdot (x / \epsilon)$ measures the percentage change in effectiveness resulting from a 1% change in parameter x . Results confirm mass flow ratio as the most influential parameter with $S = 0.45$, indicating that a 1% increase in bleed air ratio causes approximately 0.45% decrease in effectiveness. Inlet temperature exhibited moderate sensitivity ($S = 0.12$), while operating pressure showed minimal sensitivity ($S = 0.06$). These quantitative sensitivity metrics provide valuable guidance for operational strategy development and condition monitoring prioritization. Table 2 shows the performance calculation result from sensitivity analysis.

Table 2. Performance calculation result

Parameter	Value
Effectiveness (ϵ)	0.75 – 0.742 (mean 0,708 $\pm$ 0,021)
Heat Transfer Rate (Q) [kJ/s]	48.2 – 62.3
Bleed Air Temperature Reduction [°C]	45.2 – 52.8
Overall Heat Transfer Coefficient (U) [W/m ² ·K]	258.1 – 315.2
Effectiveness - 60:40 Ratio	0.742
Effectiveness - 80:20 Ratio	0.675
Inlet Temperature correlation vs Effectiveness (r)	0.23 (low positive)
Effectiveness stability (180–220°C) [$\pm$ %]	$\pm$ 2.1%
Signification pressure (p-value)	> 0,05 (insignificant)
Mass flow (S)	0.45
Inlet Temperature sensitivity (S)	0.12
sensitivity pressure (S)	0.06
R ² Model ϵ -NTU	0.962
RMSE Model ϵ -NTU	0.0134
MAPE Model ϵ -NTU [%]	1.89
Cross-Validation Accuracy [%]	96.8
PSO Ground Operation: Ratio & Pressure	68:32 & 34 psi
Effectiveness Increased Ground Operation [%]	+2.8%
PSO Cruise Condition: Ratio & Pressure	72:28 & 36 psi
Effectiveness Increased Cruise [%]	+5.2%
PSO High Temp Condition: Ratio & Pressure	65:35 & 38 psi
Effectiveness Increased High Temp [%]	+8.5%
Maximum Effectiveness Trade-off [%]	+6.2%
Deviation Against CMM Data [%]	2.3%
Effectiveness vs. Average of Other PHXs	+8.2% high
Equivalent to PHX	Boeing 737-800
Good Criteria ($\epsilon >$)	0.68
Sufficient Criteria (ϵ)	0.62 – 0.68
Maintenance Needs Criteria ($\epsilon \leq$)	0.62
Predictive Maintenance Indicator [%/1000 flight hours]	Decline $\epsilon >$ 5%

3.5. Predictive Model Validation

The ϵ -NTU-based predictive model demonstrated excellent accuracy and reliability across multiple validation metrics. The coefficient of determination $R^2 = 0.962$ indicates that 96.2% of variance in measured effectiveness is explained by the model, substantially exceeding the acceptance criterion of $R^2 > 0.90$. Root Mean Square Error (RMSE) of 0.0134 represents only 1.89% of the mean effectiveness value, confirming that prediction errors are minimal. Mean Absolute Percentage Error (MAPE) of 1.89% further validates model accuracy, well within the target threshold of $<5\%$.

Cross-validation using 20% withheld data yielded prediction accuracy of 96.8%, demonstrating that the model generalizes well to unseen operating conditions and is not simply overfitted to training data. Residual analysis reveals that prediction errors are randomly distributed around zero with no systematic bias, and residuals follow an approximately normal distribution (Shapiro-Wilk test, $p = 0.42$), satisfying key assumptions for reliable statistical modeling. Comparison with Component Maintenance Manual (CMM) baseline performance data shows agreement within $\pm 2.3\%$, well within the manufacturer's specified tolerance of $\pm 5\%$, confirming that the model accurately captures real PHX behavior.

3.6. Operational Optimization Results

Particle Swarm Optimization (PSO) successfully identified optimal operating parameters for three distinct flight phase scenarios, balancing effectiveness maximization against pressure drop constraints. For ground operations (ambient temperature 27°C , low ram air velocity), the optimal configuration is mass flow ratio 68:32 and operating pressure 34 psi, achieving effectiveness of 0.728, representing a +2.8% improvement relative to typical baseline operation at 70:30 ratio and 36 psi ($\epsilon = 0.708$). This modest improvement arises because ground conditions already provide substantial ram air cooling capacity, limiting the benefit of parameter optimization.

For cruise conditions (typical cruise altitude FL370, ambient temperature -54°C , high ram air velocity), optimal parameters are mass flow ratio 72:28 and pressure 36 psi, yielding effectiveness of 0.745, a +5.2% improvement over baseline. The more significant improvement at cruise reflects the enhanced ram air cooling effectiveness at high altitude and velocity, enabling better exploitation of increased ram air flow proportions. Additionally, lower ambient temperatures increase air density, further improving heat transfer capacity.

For high-temperature conditions (hot day ground operations, ambient temperature 40°C , engine high thrust setting generating bleed air at 230°C), optimal parameters are mass flow ratio 65:35 and pressure 38 psi, achieving effectiveness of 0.767, an impressive +8.5% improvement. This substantial gain demonstrates the value of optimization under challenging thermal conditions where conventional settings struggle. The lower bleed air ratio (increased ram air proportion) compensates for reduced ram air cooling capacity at elevated ambient temperatures.

Trade-off analysis between effectiveness improvement and pressure drop penalty reveals that unconstrained optimization could achieve effectiveness increases up to +11%, but at the cost of excessive pressure drops exceeding 8%, which would compromise downstream system performance and potentially trigger ECS fault warnings. By constraining pressure drop increase to $\leq 5\%$, the practical optimum yields +6.2% effectiveness improvement while maintaining system stability. This

balanced approach ensures that thermal performance gains do not create unacceptable operational compromises (Chennu, 2018; Lv et al., 2022).

3.7. Performance Benchmarking Against Industry Standards

Comparative analysis positions the tested PHX performance favorably within industry benchmarks. The measured effectiveness (mean 0.708) exhibits only 2.3% average deviation from CMM reference values, comfortably within the manufacturer's specified tolerance band of $\pm 5\%$. This close agreement validates both the experimental methodology and the as-tested PHX condition, confirming that the unit maintains design performance despite accumulated operational hours (approximately 18,500 flight hours at time of testing).

Cross-platform comparison reveals that the A320 PHX effectiveness exceeds the fleet average for similar narrow-body aircraft heat exchangers by 8.2%, as documented by (Wang et al 2020). in their benchmarking study of primary heat exchangers across Boeing 737NG, Airbus A320, and Bombardier CRJ series. Performance is essentially equivalent to the Boeing 737-800 PHX ($\epsilon = 0.71 \pm 0.02$), despite differences in heat exchanger geometry and flow arrangement.

The current study's emphasis on operational parameter optimization aligns with theoretical work, such as that by Beltrame et al., who proposed geometric design optimization, achieving theoretical effectiveness improvements of 12–18% (Beltrame, Colonna and De Servi, 2025). While Alvarenga et al. focused on design-stage improvements, our findings provide a complementary approach, showing practical operational parameter adjustment can yield improvements up to 8.5% without requiring hardware modifications.

Furthermore, the established performance degradation indicator (effectiveness drop $> 5\%$ per 1000 flight hours) is consistent with the degradation rates documented by Wright et al., who investigated atmospheric fouling and reported degradation rates of 3–7% per 1000 flight hours (Wright, Dixon-Hardy and Hegg, 2018). Our criteria provide MRO practitioners with a quantitative threshold for proactive intervention based on this known fouling mechanism. N et al, explored complex secondary flow structures using CFD (N, Ismail and V, 2021), supporting our finding that the ram air side is the limiting factor (contributing 58–65% of total resistance), thus validating the need to prioritize ram air side optimization as suggested by the literature.

3.8. Implications for Maintenance, Repair, and Overhaul (MRO)

The findings establish evidence-based assessment criteria for PHX condition evaluation during routine maintenance inspections. Three performance categories are defined based on measured effectiveness: (1) Good condition: $\epsilon > 0.68$, indicating that the PHX meets or exceeds design specifications and requires no immediate action beyond normal preventive maintenance; (2) Acceptable condition: $0.62 < \epsilon \leq 0.68$, suggesting moderate performance degradation warranting increased monitoring frequency and planning for future maintenance action; (3) Requires maintenance: $\epsilon \leq 0.62$, indicating significant degradation requiring immediate corrective action, likely including PHX cleaning, repair, or replacement.

These quantitative thresholds provide MRO technicians with objective, measurable criteria for maintenance decision-making, replacing subjective assessments. For predictive maintenance implementation, the study establishes that effectiveness degradation exceeding 5% per 1000 flight

hours serve as a reliable indicator for proactive intervention. This degradation rate, derived from longitudinal performance tracking of similar PHX units, typically indicates progressive fouling from atmospheric contaminants (dust, insect debris, corrosion products) accumulating on heat transfer surfaces. Early detection via continuous effectiveness monitoring enables scheduled cleaning during planned maintenance events rather than reactive responses to in-flight ECS anomalies, reducing maintenance costs and avoiding operational disruptions. Integration of these criteria with aircraft Health and Usage Monitoring Systems (HUMS) enables automated performance trend analysis and predictive maintenance alerts.

4. CONCLUSION

This study presents an integrated investigation—experimental, analytical, and computational—of the Primary Heat Exchanger (PHX) in the Airbus A320 Environmental Control System. Experimentally, the PHX showed stable and reliable thermal performance, with effectiveness values between 0.675 and 0.742 (average 0.708 ± 0.021). Heat transfer rates of 48.2–62.3 kJ/s and outlet temperature reductions of 45.2–52.8°C confirm compliance with manufacturer requirements. Convective heat-transfer analysis identified the ram-air side as the primary contributor to total thermal resistance (58–65%), signaling structural and operational limits for further enhancement under typical service conditions.

The ϵ -NTU-based predictive model developed in this study proved highly accurate ($R^2 = 0.962$, RMSE = 0.0134, MAPE = 1.89%) and closely matched CMM specifications (2.3% deviation). This validates the model's potential for routine PHX performance evaluation, trend analysis, and maintenance support in MRO operations. Sensitivity analysis determined mass-flow ratio as the most influential operational parameter ($S = 0.45$), far surpassing inlet temperature or pressure, highlighting flow management's critical role in improving in-service PHX efficiency.

Optimization via Particle Swarm Optimization (PSO) produced actionable recommendations tailored to different flight phases. Effectiveness improvements of 2.8% (ground operations), 5.2% (cruise), and 8.5% (high-temperature scenarios) were achieved without hardware modification—just through optimized mass-flow ratio and pressure adjustments within system limits. PSO-based strategies successfully improved thermal effectiveness for each flight phase while maintaining pressure drop constraints, offering specific, practical guidance for operational efficiency.

From a practical perspective, the study sets quantitative and practical maintenance standards that are important for predictive and condition-based maintenance. The suggested performance categories ($\epsilon > 0.68$: good; 0.62–0.68: acceptable; $\epsilon \leq 0.62$: needs maintenance) and a warning sign (effectiveness drop $> 5\%$ for every 1000 flight hours) give clear. These results help improve planning for maintenance, spot performance issues early, and lessen problems related to ECS operations.

Overall, this research delivers one of the most comprehensive evaluations of PHX performance in commercial aviation. It provides new empirical data, validated predictive tools, and strategies for optimizing operations that are clearly useful for airlines, maintenance groups, and ECS system engineers. Future research should investigate how systems wear down over time, measure how dirt affects performance, improve designs for better air intake, and include real-time control adjustments in new ECS health-monitoring systems.

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