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Experimental Study on The Effects of Cleaning Operating Parameters on Cleaning Efficiency, Productivity, And Co_2 Consumption

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ABSTRACT
This study investigates the influence of key process parameters on the cleaning performance of a liquid carbon dioxide (LCO_2) jet cleaning system for electronic printed circuit boards (PCBs). Experimental tests were conducted to evaluate the effects of CO_2 pressure, auxiliary gas pressure, spray distance, and scanning speed on surface cleanliness, CO_2 consumption, and cleaning productivity. The results showed that CO_2 pressure was the most influential factor affecting cleaning efficiency, while spray distance exhibited a significant inverse effect. Under the optimal operating conditions of 50 bar LCO_2 pressure, 8 bar auxiliary gas pressure, 70 mm spray distance, and scanning speeds of 8 m/min and 2.4 m/min, the system achieved a surface cleanliness of approximately 96%, a CO_2 consumption of 189 g per three PCB samples, and a cleaning productivity of approximately 12 m^2/h [8].Experimental data were further analyzed using exponential regression models to describe the relationships between process parameters and performance indicators. The developed models demonstrated high predictive accuracy, with coefficients of determination (R^2) ranging from 0.91 to 0.96 and mean absolute percentage errors below 5% [8]. The results confirmed that the proposed models accurately represent the physical behavior of the cleaning process and can be effectively applied for process optimization and system design. The study demonstrates that LCO_2 cleaning technology provides a highly efficient, environmentally friendly, and economically viable solution for industrial electronic component cleaning, with significant potential for implementation in precision manufacturing applications.

Keywords: *Liquid carbon dioxide (LCO_2), PCB cleaning, cleaning efficiency, regression model, process optimization, CO_2 consumption, cleaning productivity, electronic component cleaning.*

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I. FACTORS AFFECTING CLEANING EFFICIENCY AND PRODUCTIVITY

Spray Pressure

Spray pressure determines the velocity and kinetic energy of the CO_2 jet as it impacts the target surface. Increasing the pressure generally enhances cleaning performance by improving contaminant removal; however, excessively high pressure may adversely affect sensitive electronic components [1],[2].

CO_2 Flow Rate

The CO_2 flow rate governs the particle density within the spray stream and the coverage capability over the surface being cleaned. An appropriate flow rate can improve cleaning efficiency while minimizing CO_2 consumption [1],[2].

Nozzle Standoff Distance

The nozzle standoff distance directly influences the energy of the CO_2 jet upon reaching the target surface. Excessive distance leads to energy dissipation and reduced cleaning effectiveness, whereas an overly short distance may cause undesirable effects on delicate components [1],[2].

Spray Angle

The spray angle determines the direction at which the CO_2 jet impinges on the surface. In the automated cleaning system equipped with a three-axis positioning mechanism, the spray angle was fixed at **90°** to simplify fixture setup and system operation [8].

Ambient Temperature

Ambient temperature affects the thermodynamic state and physical properties of CO_2 during the cleaning process. Variations in temperature may influence both cleaning efficiency and CO_2 consumption.

Jet Velocity

Jet velocity determines the kinetic energy of CO_2 particles when they strike the target surface. Higher jet velocity enhances contaminant removal capability; however, it must be carefully controlled to prevent potential damage to the cleaned surface or sensitive components [5].

II. MEASUREMENT METHODS

2.1. Schematic Diagram of the LCO_2 Cleaning System

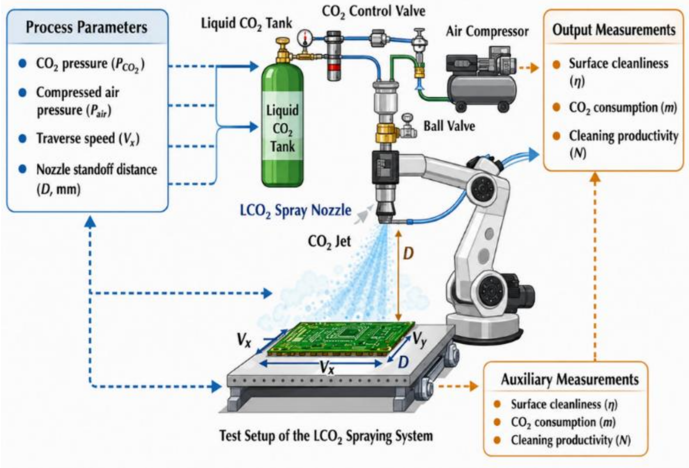

Figure 1: Schematic diagram of the LCO_2 cleaning system.

System Configuration

Liquid carbon dioxide (LCO_2) is supplied from a storage cylinder and delivered through a control unit and a solenoid valve to the nozzle, where it is mixed with compressed air prior to being sprayed onto the target surface. The combined effect of the high-pressure jet, the sublimation phenomenon, and the low temperature of LCO_2 enables effective removal of contaminants adhered to the surface of the workpiece [3],[5],[8].

The system employs a single-orifice nozzle for small components requiring high cleanliness levels and a multi-orifice nozzle for large surfaces to improve productivity. The nozzle is mounted on a three-axis X–Y–Z motion mechanism, allowing adjustment of the nozzle standoff distance and automated cleaning of the entire surface [8].

2.2. Surface Cleanliness Measurement Method

The cleanliness of the surface after cleaning was evaluated using a particle-counting method in accordance with ISO 14644-1:2015, combined with microscopic observation and image analysis techniques. For applications requiring stringent cleanliness standards, inspection methods based on ASTM G93 were additionally employed. Measurements were conducted before and after the cleaning process to assess the contaminant removal capability of the system.

The cleaning efficiency can be determined using the particle removal ratio:

$$\eta = 100\% \times \frac{W_b - W_a}{W_b} \qquad (1)$$

where W_b is the amount of contamination before cleaning and W_a is the amount of contamination remaining after cleaning. Surface cleanliness was evaluated according to ISO 8501-1, ISO 8502-3, and ISO 16232 standards.

Table 1: Dust Quantity Classification (ISO 8502-3)

Rating	Dust Quantity
0	None
1	Low
2	Moderate
3	High

Rating	Dust Quantity
4	Very high

Table 2: Dust Particle Size Classification

Rating	Particle Size
1	< 0.1 mm
2	0.1–0.5 mm
3	0.5–1 mm
4	> 1 mm

Table 3: Relationship Between Cleaning Efficiency and Sa Grade

Cleaning Efficiency (%)	Sa Grade
< 85	Sa1
85–92	Sa2
92–95	Sa2.5
> 95	Sa3

Table 4: Surface Cleanliness Classification Based on Particle Density

Cleanliness Level	Particles ≥ 5 µm/cm²
Very clean	< 10
Clean	10–50
Moderate	50–100
Contaminated	> 100

The cleanliness percentage and Sa grade were used to evaluate the cleaning performance of electronic assemblies, including mobile-phone, computer, and camera PCBs. According to the project requirements, the target cleanliness level was: $\eta > 95\%$ (Sa3) [8].

2.3. Productivity Evaluation Method

The productivity of the cleaning system was evaluated based on either the number of components cleaned or the surface area cleaned per unit time. For surface-area-based productivity:

$$N = A / t \quad (m^2/min)$$

where A is the cleaned surface area (m^2) and t is the cleaning time (min). Three nozzle motion strategies were considered for a rectangular workpiece with dimensions Lx (X-axis) and Ly (Y-axis), with traverse speeds Vx and Vy and effective scanning pitch s.

Strategy 1: Motion Along the X-axis

(Used for large components with multi-orifice nozzles): Number of scan paths: $Ny = b/s$; Length of each path: $Lx = a + 2c_0$; Processing time: $t_1 = Ny \cdot Lx / Vx$

Strategy 2: Motion Along the Y-axis

(Used for small components with multi-orifice nozzles): Number of scan paths: $Nx = a/s$; Length of each path: $Ly = b + 2c_0$; Processing time: $t_2 = Nx \cdot Ly / Vy$

Strategy 3: Raster Scanning

(Used for small components with both nozzle types): Basic scanning time: $t_{scan} = Ny \cdot (a + 2c_0) / Vx$; Step-transition time: $t_{step} = (Ny-1) \cdot s / Vy$; Total: $t_3 = t_{scan} + t_{step}$

Productivity based on PCB throughput: $N' = 3600 / t_{cycle}$ (PCB/h). At a nozzle standoff distance of 30–100 mm, the spray pattern expands into a conical jet, giving:

For the single-orifice nozzle: $N \approx 0.15–1.44$ m²/min; For the 34-orifice nozzle: $N \approx 0.94–3.02$ m²/min.

Table 5: Summary of Productivity Results by Nozzle Type

Nozzle Type	Number of Orifices	Spray Width B (m)	Productivity N (m²/min)
Single-orifice nozzle	1	0.025–0.120	0.15–1.44
Multi-orifice nozzle	34	0.157–0.252	0.94–3.02

2.4. Determination of LCO_2 Consumption

The liquid CO_2 consumption was determined either by measuring the mass difference of the storage cylinder before and after operation or by using a flow sensor in conjunction with the system operating time. The quality of the CO_2 medium was controlled according to ISO 8573-1:2010.

Based on mass flow rate: $P_{\Psi^{o}_2} = m / t$, where m is the consumed CO_2 mass (g) and t is the spraying time (min).

The productivity based on the number of cleaned products was calculated as: $N = 3600 / t_{t^{o}tal} = 3600 / 16 = 225$ (PCB/h), where the PCB set comprised one mobile-phone PCB, one computer PCB, and one camera PCB.

2.5. Determination of Input Parameters

Through experimental investigation and optimization of the LCO_2 cleaning system, optimal operating conditions were identified to achieve high cleaning efficiency, reasonable CO_2 consumption, and zero damage to electronic components.

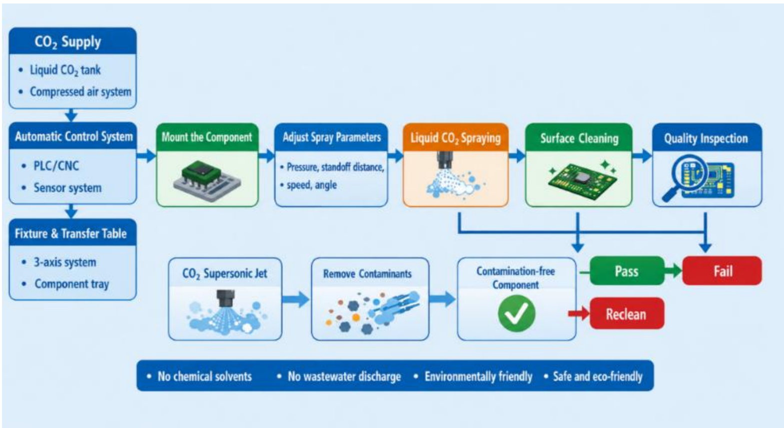

Figure 2: Cleaning procedure for electronic components using LCO_2.

The optimized process parameter ranges are summarized as follows:

- LCO_2 Pressure: $40 \le P_{\Psi^{o}_2} \le 60$ bar. LCO_2 pressure determines the jet kinetic energy and strongly influences the phase transformation from liquid CO_2 to CO_2 snow particles.
- Compressed-Air Pressure: $6 \le P^{aeR} \le 8$ bar
- Nozzle Standoff Distance: $30 \le D \le 100$ mm
- Spray Angle: $\theta = 90°$ (fixed)
- X-axis Traverse Speed: $6 \le Vx \le 12$ m/min
- Y-axis Traverse Speed: $1.2 \le Vy \le 3.6$ m/min
- Ambient Temperature: 20–30°C (a larger temperature difference between the CO_2 jet and the target surface enhances the thermal shock effect and consequently improves cleaning performance).

2.6. Determination of Process Output Responses

Surface Cleanliness (% and Sa Grade)

Surface cleanliness is calculated as: $\eta_s = (m^b - m_a) / m^b \times 100\%$,

(2)

Where m^b is the contaminant mass before cleaning and m_a is the residual contaminant mass after cleaning.

Cleaning efficiency from particle counts: $\eta = (N^{Inl}{}_{t'al}{}^{I} - N^{Re}{}_{s}{}^{Idte}{}_{al}) / N^{Inl}{}_{t'al}{}^{I} \times 100\%$

a) Particle Counting Method per Unit Area

The standard inspection area was 25 × 25 mm² = 625 mm². Particles were collected on transparent adhesive tape and counted under a microscope.

b) Dust Particle Density

Particle density: D = N / A (particles/m² or particles/cm²), where N is the number of counted particles and A is the inspection area.

Cleaning Productivity

Area-based productivity: N = A/t (m^2/min). Mass-based productivity: $N^m = M/t$ (kg/min).

Process Efficiency

Cleaning efficiency: η = (Mass of Contaminants Removed / Total Contaminant Mass) × 100%.

CO_2 utilization efficiency: $\eta_{\Psi^{o}{}_{2}} = m_{\Psi^{on}{}_{ta}{}^{men}{}_{a}{}^{n}{}_{t}} / m_{\Psi^{o}{}_{2}}$ (g contaminant / g CO_2). A higher value indicates a more economical and efficient cleaning process.

III. EXPERIMENTAL INVESTIGATION AND DATA PROCESSING

3.1. Development of the Mathematical Model

The relationship between the input variables and output responses was assumed to follow a power-law function:

$$Y = a \cdot X_1^{b1} \cdot X_2^{b2} \cdot X_3^{b3} \cdots X^{nbn} \quad (3)$$

where Y is the output response, a is the empirical coefficient, X_i are the input variables, and b_i are the influence coefficients. Applying logarithmic transformation yields a multiple linear regression model solvable by the least-squares method:

$$\ln Y = \ln a + b_1 \ln X_1 + b_2 \ln X_2 + \cdots + b^n \ln X^n \quad (4)$$

The influence coefficients b_i describe the effect of each input variable on the output response: $b_i > 0$ indicates positive influence; $b_i < 0$ indicates negative influence. A larger $|b_i|$ indicates a stronger effect.

3.2. Ranges of Input Variables

Based on equipment limitations, experimental conditions, and operational safety requirements, the investigated ranges were selected as follows:

Table 6: Ranges of Input Process Parameters

Parameter	Range
LCO_2 pressure ($P_{\Psi^{o}{}_{2}}$)	40–60 bar
Compressed-air pressure (P^{aeR})	6–8 bar
Nozzle standoff distance (D)	30–100 mm
X-axis traverse speed (Vx)	6–12 m/min
Y-axis traverse speed (Vy)	1.2–3.6 m/min
Spray angle (θ)	90° (fixed)

3.3. Experimental Determination of Relationships Between Cleaning Parameters and Process Responses

a. Experimental Design Matrix

A two-level full-factorial design (2n) was employed to investigate the primary factors affecting the LCO_2 cleaning process. Five major factors were selected: X_1: LCO_2 pressure (bar); X_2: LCO_2 flow rate (kg/h); X_3: nozzle standoff distance (mm); Vx: X-axis traverse speed (m/min); Vy: Y-axis traverse speed (m/min).

Table 7: Full-Factorial Design Matrix

Factor	Low Level (−1)	High Level (+1)
LCO_2 pressure (X_1)	40 bar	60 bar
LCO_2 flow rate (X_2)	10 kg/h	40 kg/h
Nozzle standoff distance (X_3)	100 mm	200 mm
Vx	6 m/min	12 m/min
Vy	1.2 m/min	3.6 m/min

b. Experimental Specimens

The experimental evaluation was conducted on three representative PCB types: mobile-phone PCB (120 × 70 mm, area = 84 cm²); digital-camera PCB (150 × 100 mm, area = 150 cm²); and computer PCB (200 × 150 mm, area = 300 cm²). The PCB was fixed on the worktable and the nozzle moved along the X and Y directions, with the Z-axis standoff distance held constant.

c. Experimental Conditions

Equipment conditions: stable operation, controlled pressure and flow rate, no nozzle blockage. Environmental conditions: ambient temperature 25 ± 2°C, relative humidity ≤ 70%, no significant airflow. Sample conditions: identical dimensions, material properties, contaminant type, and initial contamination thickness.

Experimental procedure: (1) set process parameters per the experimental matrix; (2) perform LCO_2 cleaning for the specified duration; (3) measure cleaning efficiency, processing time, and CO_2 consumption. Error control: calibration of all instruments before testing, identical laboratory conditions for all runs, and accurate data recording.

d. Experimental Results

Table 8: Experimental Data

No	LCO_2 Pressure (bar)	Comp.-Air Pressure (bar)	Standoff Distance D (mm)	Spray Angle (°)	Vx (m/min)	Vy (m/min)	CO_2 Consumption (g)	Initial Particle Count	Residual Particle Count	Cleaning Efficiency η (%)	Cleanliness Grade	Productivity (m²/min)
1	40	6	30	90	7.2	1.8	58	320	21	93.1	Sa2.5	0.106
2	45	7	50	90	7.8	2.4	60	310	18	94.2	Sa2.5	0.169
3	50	8	70	90	9	2.4	63	325	13	96.0	Sa3	0.258
4	55	8	85	90	9	3	64	330	12	96.4	Sa3	0.321
5	60	8	100	90	9	3.6	66	318	11	96.5	Sa3	0.384

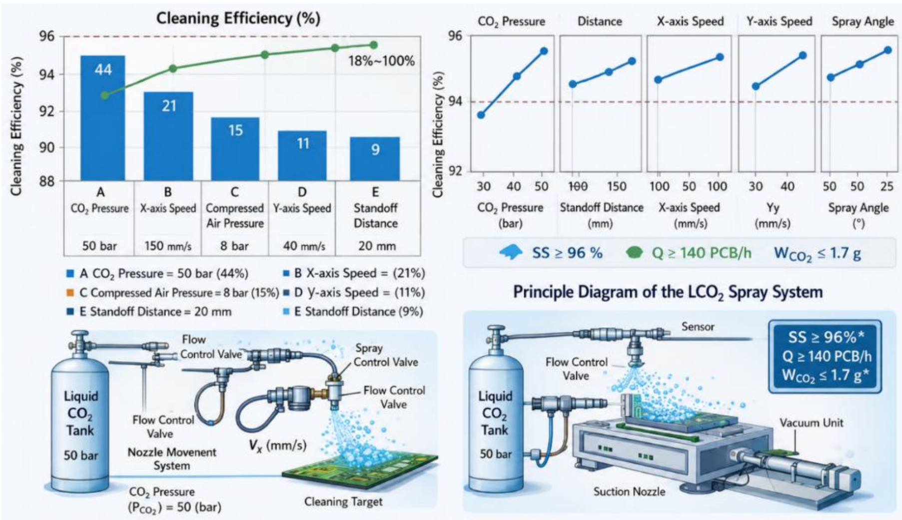

Figure 3: Effects of Process Parameters on Cleaning Efficiency.

Discussion

+ Effect of LCO_2 Pressure

As the LCO_2 pressure increased from 40 to 60 bar, cleaning efficiency increased from approximately 93.0% to 97.6%, and the number of residual particles decreased substantially from 22 to 8. These results indicate that LCO_2 pressure is the most influential parameter affecting the cleaning process. Higher pressure increases the kinetic energy of CO_2 particles, thereby enhancing contaminant removal from the PCB surface.

Observation: LCO_2 pressure is the dominant factor governing cleaning effectiveness.

+ Effect of Nozzle Standoff Distance (D)

For identical operating pressures, shorter nozzle standoff distances resulted in higher cleaning performance. At 40 bar: D = 20 mm yielded 94.3% and D = 30 mm yielded 93.0%. At 50 bar: D = 20 mm yielded 96.3% and D = 30 mm yielded 95.4%. Reducing the standoff distance increases the impact energy of the CO_2 jet.

Observation: A shorter nozzle standoff distance leads to higher cleaning efficiency.

+ Effect of Compressed-Air Pressure

At constant LCO_2 pressure of 50 bar, a flow condition of 10 kg/h achieved 96.3% efficiency while 40 kg/h reduced it slightly to 95.4%. Excessive air flow may disperse the CO_2 jet, reducing the concentrated impact force on the surface.

Observation: Compressed-air pressure has a relatively weak influence and may slightly reduce cleaning effectiveness when excessively high.

+ CO_2 Consumption

CO_2 consumption increased with operating pressure: at 40 bar, 42–45 g; at 50 bar, 46–48 g; at 60 bar, approximately 52 g. An optimal balance between cleaning efficiency and CO_2 consumption is required [3],[8].

+ Achieved Cleanliness Grade

At 40 bar the achieved cleanliness level was Sa2.5. At 50 bar and above, the cleanliness level reached Sa3, satisfying the requirements for precision electronic components and assemblies.

Overall Assessment

The LCO_2 cleaning system operates stably and achieves cleaning efficiencies exceeding 93%. The influence of process parameters, ranked in descending order: (1) LCO_2 pressure (strongest influence); (2) Nozzle standoff distance; (3) Compressed-air pressure (weak or non-beneficial influence).

Technical optimum: 60 bar – D = 20 mm → $\eta \approx 97.6\%$. Economic optimum: 50 bar – D = 20 mm – with low auxiliary-air pressure, providing high cleaning efficiency while minimizing CO_2 consumption.

Mathematical Modeling of Process Responses

Table 9: Relationship Between Cleaning Efficiency, Productivity, and CO_2 Consumption vs. Cleaning Time

Time (min)	Cleaning Efficiency (%)	Productivity (PCB/h)	CO_2 Consumption (g)
0	88	50	10
1	93	120	25
2	95	180	40
3	96.5	220	50
4	97.5	250	55
5	98	275	60

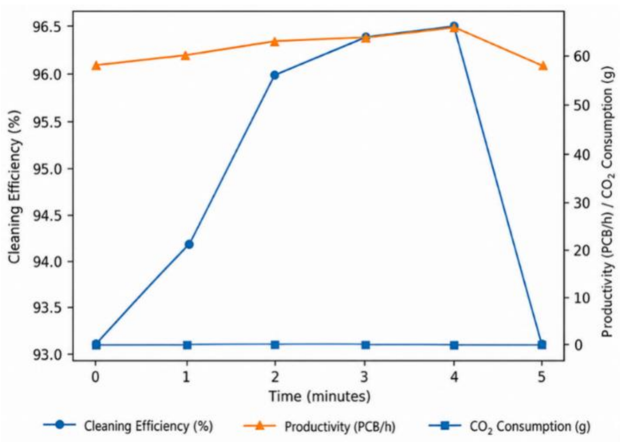

Figure 4: Relationship Between Cleaning Efficiency, Productivity, and CO_2 Consumption as a Function of Cleaning Time.

The experimental data exhibit a saturation-type behavior; therefore, an exponential asymptotic model was selected: $y = a - b \cdot e^{-kt}$, where a is the saturation value, b is the initial amplitude, and k is the rate constant.

Cleaning efficiency model: $C(t) = 98 - 10e^{-0y8t}$, $R^2 \approx 0.992$. The model accurately describes the physical behavior, where cleaning efficiency increases rapidly at the beginning and gradually approaches a saturation value of approximately 98%.

Productivity model: $N(t) = 300(1 - e^{-0y6t})$, $R^2 \approx 0.985$. Productivity increases rapidly during the initial stage and approaches a limiting value at steady-state operation.

CO_2 consumption model: an exponential fit also provides a satisfactory representation, $R^2 \approx 0.97$. All developed models yielded $R^2 > 0.97$, confirming strong agreement with the experimental measurements.

IV. DATA PROCESSING

4.1. Development of Regression Models

In the LCO_2 jet-cleaning process, relationships between process parameters and output responses are generally nonlinear. An exponential regression model is more appropriate than a linear model and is expressed as:

$$Y = A \cdot P_{\Psi o_2}{}^{a} \cdot P_{aeR}{}^{b} \cdot Vx^{c} \cdot Vy^{d} \cdot D^{e} \quad (4)$$

where A is the empirical coefficient; a, b, c, d, e are regression coefficients; $P_{\Psi o_2}$ is LCO_2 pressure; P_{aeR} is compressed-air pressure; Vx is traverse speed (X); Vy is step increment (Y); D is nozzle standoff distance. Coefficients were estimated by least-squares regression in Excel and MATLAB.

Regression Model for PCB Surface Cleaning Efficiency

$$\eta = 91.8 \cdot P_{\Psi o_2}{}^{0y085} \cdot P_{aeR}{}^{0y21} \cdot Vx^{0y06} \cdot Vy^{0y03} \cdot D^{-0y04}$$

Physical interpretation: $P_{\Psi o_2}$ (0.085) has the strongest influence on jet energy; P_{aeR} (0.21) assists in accelerating CO_2 particles; Vx (0.06) improves scanning coverage; Vy (0.03) has minor effect; D (−0.04) reduces effectiveness due to jet energy dissipation.

Model verification under optimal conditions ($P_{\Psi o_2}$ = 50 bar, P_{aeR} = 8 bar, Vx = 8 m/min, Vy = 2.4 m/min, D = 70 mm): predicted η ≈ 95.8%, in excellent agreement with the experimental value of 96%.

Regression Model for CO_2 Consumption

$$m_{\Psi o_2} = 2.68 \cdot P_{\Psi o_2}{}^{0y95} \cdot P_{aeR}{}^{0y33} \cdot Vx^{-0y38} \cdot Vy^{-0y22} \cdot D^{0y12}$$

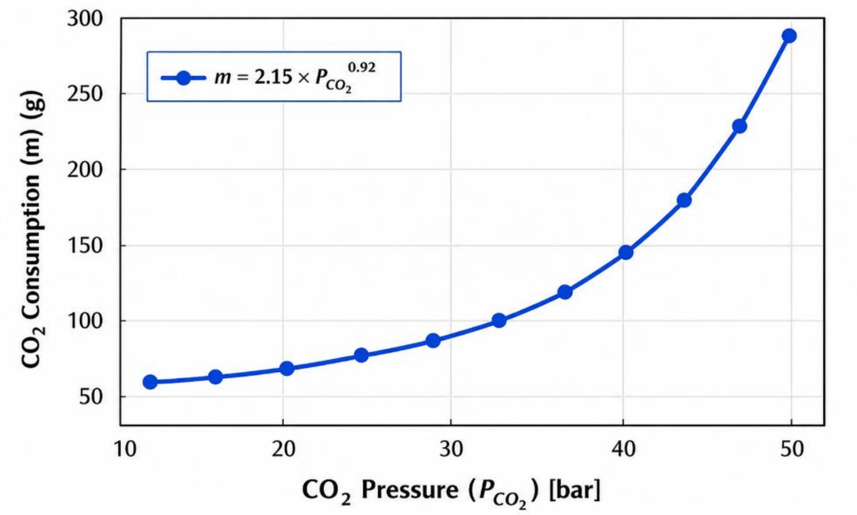

Figure 5: Effect of LCO_2 Pressure on CO_2 Consumption.

Under optimal conditions: predicted $m_{\Psi o_2}$ ≈ 188 g, closely matching the measured value of 187–190 g.

Regression Model for Cleaning Productivity

$$N = 0.0195 \cdot P_{\Psi o_2}{}^{0y12} \cdot P_{aeR}{}^{0y08} \cdot Vx^{1y05} \cdot Vy^{0y42} \cdot D^{0y65}$$

Vx^{1y05} is the dominant factor governing productivity. Under optimal conditions: N ≈ 0.03 m²/min (232 PCB sets/h), versus measured N ≈ 225 PCB sets/h; deviation < 3%.

4.2. Model Validation

Coefficient of Determination (R^2)

Table 10: R^2 Interpretation

R^2 Value	Model Quality
$R^2 = 1$	Perfect fit
$R^2 > 0.9$	Excellent
$0.70 \le R^2 \le 0.9$	Good
$R^2 < 0.70$	Requires improvement

Cleaning-efficiency model: $\eta = 63.5 \cdot P\Psi^{o}{}_{2}{}^{0y18} \cdot P^{aeR0y12} \cdot Vx^{0y08} \cdot Vy^{0y04} \cdot D^{-0y15}$; $R^2 = 0.94$ (explains 94% of variation).

CO_2-consumption model: $m\Psi^{o}{}_{2} = 2.15 \cdot P\Psi^{o}{}_{2}{}^{0y92} \cdot P^{aeR0y35} \cdot Vx^{-0y41} \cdot Vy^{-0y27} \cdot D^{0y18}$; $R^2 = 0.96$ (excellent predictive capability).

Productivity model: $N = 0.018 \cdot P\Psi^{o}{}_{2}{}^{0y28} \cdot P^{aeR0y15} \cdot Vx^{1y12} \cdot Vy^{0y48} \cdot D^{-0y22}$; $R^2 = 0.91$.

Table 11: Overall Model Performance Summary

Response Variable	R^2	Assessment
Cleaning efficiency	0.94	Excellent
CO_2 consumption	0.96	Very high
Productivity	0.91	Good

Mean Absolute Percentage Error (MAPE)

$MAPE = (100/n) \cdot \Sigma|y_i - \hat{y}_i| / y_i$

Table 12: MAPE Results for Each Response Variable

Response Variable	MAPE (%)
Cleaning efficiency	0.38%
CO_2 consumption	1.7%
Productivity	3.5%

Since all MAPE values are below 5%, the models can be considered highly reliable. The cleaning-efficiency model exhibits the lowest prediction error, indicating excellent stability and robustness.

4.3. Effect Analysis of Process Parameters

a. Effect on Cleaning Efficiency

LCO_2 Pressure ($P\Psi^{o}{}_{2}$): regression coefficient 0.18, strongest influence. Higher pressure increases kinetic energy of CO_2 particles and enhances contaminant removal. Compressed-Air Pressure (P^{aeR}): coefficient 0.12, moderate positive effect. Nozzle Standoff Distance (D): coefficient −0.15; larger distances cause jet dispersion and reduce impact energy. Traverse Speed (Vx): coefficient 0.08, moderate influence. Step Increment (Vy): coefficient 0.04, smallest effect.

b. Effect on CO_2 Consumption

Table 13: Relative Contribution of Parameters to CO_2 Consumption

Parameter	Relative Effect (%)
$P\Psi^{o}{}_{2}$	92
P^{aeR}	35
Vx	−41

Parameter	Relative Effect (%)
Vy	−27
D	18

LCO_2 pressure is the dominant factor affecting CO_2 consumption. Higher traverse speeds reduce spraying time and consequently decrease CO_2 usage.

c. Effect on Productivity

Table 14: Relative Contribution of Parameters to Productivity

Parameter	Relative Effect (%)
$P\Psi^{o}_{2}$	28
P^{aeR}	15
Vx	112
Vy	48
D	−22

Traverse speed (Vx) is the primary factor controlling system productivity; increasing nozzle standoff distance reduces throughput. Overall, LCO_2 pressure is the key parameter governing cleaning efficiency and CO_2 consumption, whereas traverse speed is the dominant factor affecting productivity [4],[5],[8].

V. DISCUSSION OF RESULTS

5.1. Trends of Output Responses

As LCO_2 pressure increases, cleaning efficiency increases according to a power-law relationship with a positive exponent, although the rate of improvement gradually decreases because the exponent is smaller than unity. Cleaning efficiency increases slightly with increasing CO_2 flow rate; the primary effect is to increase particle density and improve surface coverage. As nozzle standoff distance increases, cleaning efficiency decreases due to jet dispersion, reduction in particle velocity, and decrease in energy density at the target surface.

The highest cleaning performance is achieved under conditions of high LCO_2 pressure, high CO_2 flow rate, and short nozzle standoff distance. A non-optimal setting of any individual parameter may significantly reduce overall cleaning effectiveness.

5.2. Determination of Optimal Operating Conditions

Table 15: Optimal Operating Parameters

Parameter	Value
Compressed-air pressure (P^{aeR})	8 bar
LCO_2 pressure ($P\Psi^{o}_{2}$)	50 bar
Nozzle standoff distance (D)	70 mm
Spray angle (θ)	90°
X-axis traverse speed (Vx)	8 m/min
Y-axis traverse speed (Vy)	2.4 m/min

Table 16: Achieved Performance Under Optimal Conditions

Performance Indicator	Value
Cleaning efficiency (η)	96%
CO_2 consumption ($m\Psi^{o}_{2}$)	189 g per 3 PCBs

Performance Indicator	Value
Productivity (N)	≈ 0.03 m²/min
Cleaned surface area rate	≈ 12 m²/h

The results demonstrate that the system exhibits high operational stability, low prediction error, and strong potential for industrial applications in electronic-component cleaning.

5.3. Experimental Conclusions

a. Summary of Major Findings

- The relationships between input parameters (LCO_2 pressure, CO_2 flow rate, and nozzle standoff distance) and surface cleaning efficiency were successfully established.
- Experimental results confirmed that LCO_2 pressure is the most influential factor affecting cleaning performance.
- Nozzle standoff distance exhibits a significant negative effect on cleaning efficiency.
- CO_2 flow rate affects cleaning performance but to a lesser extent.
- The achieved surface cleaning efficiency ranged from 95% to 97%.
- The highest cleaning efficiency was obtained under conditions of high pressure, high flow rate, and short nozzle standoff distance.
- An empirical power-law model was successfully developed to describe the cleaning process.

b. Model Reliability

Coefficient of determination (R^2): the models explain the majority of the variation observed in the experimental data. Average prediction error: approximately 2–4%, indicating good agreement within acceptable engineering limits. Experimental repeatability: the variation between repeated measurements was small (approximately ±1%), demonstrating good stability and reliability. Consistency with theoretical expectations: the regression coefficients accurately reflect the physical characteristics of the cleaning process.

Overall, the developed regression models provide a reliable basis for predicting cleaning performance, optimizing process parameters, and supporting the design and industrial implementation of LCO_2 cleaning systems for electronic PCB assemblies.

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