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CLEANROOM OPTIMISATION OF INLET-OUTLET CONFIGURATION AT VARIOUS ACH FOR PARTICLE DISPERSION IN ISO CLASS 5 SEMICONDUCTOR CLEANROOM STANDARD

Zharif Samsudin[1], Sh Mohd Firdaus Sh Abdul Nasir[1, 2*], Hazimi Ismail[1, 2]

[1]Centre of Mechanical Engineering Studies, College of Engineering, Universiti Teknologi MARA Cawangan Pulau Pinang, 13500 Permatang Pauh, Penang, Malaysia.
muhdzharifsamsudin91@gmail.com https://orcid.org/0009-0006-6175-2136

[2]Advanced Mechanics Research Group, Centre of Mechanical Engineering Studies, College of Engineering, Universiti Teknologi MARA Cawangan Pulau Pinang, 13500 Permatang Pauh, Penang, Malaysia.
sh.firdaus@uitm.edu.my https://orcid.org/0000-0002-9681-7829
hazimi0172@uitm.edu.my https://orcid.org/0009-0005-0477-4681

*Corresponding Author

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Abstract:

The performance of modular cleanrooms is highly dependent on effective airflow distribution and thermal control to minimize contamination and ensure product quality. This study investigates the influence of inlet–outlet configuration and operating parameters on airflow and temperature distribution inside a modular semiconductor cleanroom. Computational Fluid Dynamics (CFD) simulations were conducted to evaluate airflow vector patterns, mean air velocity, and temperature contours at different cross-sectional and working height levels. ANSYS Fluent was used for CFD simulation. Four key parameters, namely inlet size (number of FFUs), outlet size, inlet air temperature, and inlet air velocity, were optimized using the Taguchi method. Signal-to-noise (S/N) ratio analysis based on the larger-the-better criterion was employed to identify the optimal parameter levels for maximizing mean air velocity, while analysis of variance (ANOVA) was used to determine the contribution of each parameter. The results indicate that inlet air velocity is the most significant factor, contributing 56.16% to airflow performance, followed by inlet size, outlet size, and inlet air temperature. The optimal operating condition was identified as 6 FFU, a combined outlet configuration of two large outlets, size (1090 × 1096 mm) and one small outlet, size (534 × 1096 mm), an inlet air temperature of 294 K, and an inlet air velocity of 0.4 m/s. Under the optimal condition, the CFD predicted mean air velocity was 0.44 m/s, which showed good agreement with the experimental result of 0.45 m/s, with a deviation of approximately 2%. The optimized configuration demonstrates improved airflow uniformity and stable temperature distribution at the working height level, confirming the reliability of the proposed optimization framework. This study provides a practical framework for optimizing cleanroom airflow design by identifying the optimal combination of FFU number, inlet velocity, and outlet configuration to improve airflow uniformity, reduce contamination risk, and enhance energy efficiency in ISO Class 5 cleanrooms.

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Keyword:

Airflow, ANOVA, CFD Analysis, Cleanroom, Optimization, Taguchi Method

Introduction

Cleanrooms play a critical role in semiconductor manufacturing by maintaining extremely low concentrations of airborne particles to ensure product integrity and high production yield (Mecart Cleanrooms, 2016; International Organization for Standardization, 2015). Cleanroom performance is commonly classified according to ISO 14644-1, which defines cleanliness levels based on particle concentration per unit volume (International Organization for Standardization, 2015)]. Achieving and maintaining the required cleanliness level depends on several key parameters, including airflow distribution, air change rate per hour (ACH), inlet–outlet air configuration, temperature, humidity, and pressure control (Yang & Gan, 2007; Yang et al., 2021). Inadequate air distribution or improper ventilation design can result in particle accumulation, non-uniform airflow, and reduced contamination control, particularly under operational conditions (Permana & Wang, 2024).

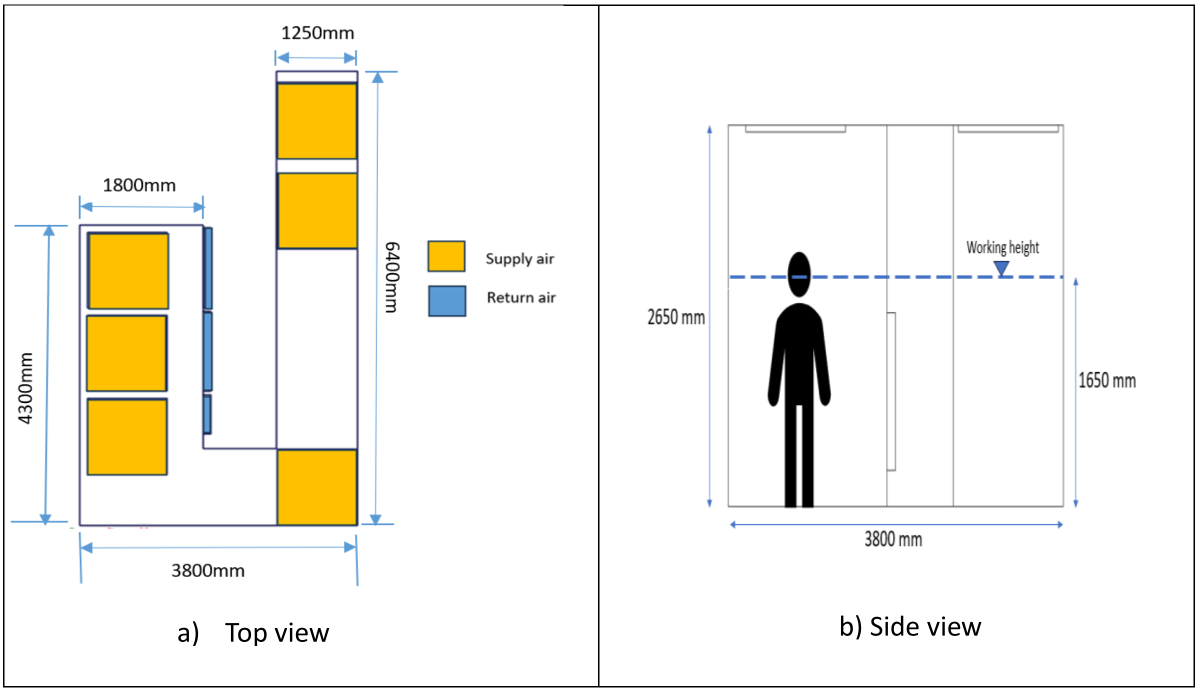
Previous studies have shown that inlet–outlet configurations significantly influence airflow patterns and contaminant dispersion within cleanroom environments (Eslami et al., 2016; Saidi et al., 2011; Srebric et al., 2008). Saidi et al. (2013) and Zhao et al. (2004), further demonstrated that improper diffuser placement can generate recirculation zones at the working height level, increasing particle residence time and reducing removal efficiency. Similarly, ACH has been identified as a dominant factor affecting cleanliness recovery time, particle removal efficiency, and airflow uniformity (Waring & Siegel, 2008; Zhou et al., 2020; Loomans et al., 2020; Chen et al., 2022). While increasing ACH can enhance contaminant removal, excessive ventilation rates may lead to diminishing returns and higher energy consumption without proportional improvements in cleanliness performance (Loomans et al., 2020; Persily & Emmerich, 2012). To address these challenges, Computational Fluid Dynamics (CFD) has been widely adopted as an effective and economical tool for analysing airflow behaviour, thermal distribution, and particle transport in cleanrooms (Tung et al., 2009; Sun & Wang, 2010). CFD based studies have proven effective in predicting airflow uniformity and validating design modifications prior to implementation, significantly reducing experimental cost and disruption (Choi & Edwards, 2012; Chen, 2009). Despite extensive research, determining the optimal combination of inlet–outlet configuration, ACH, and inlet air parameters that balances contamination control, airflow uniformity, and operational efficiency remains a challenge, particularly for modular cleanroom systems.

Therefore, this study employs CFD analysis integrated with Taguchi-based optimization and statistical analysis to systematically investigate airflow distribution and optimize ACH-related parameters, with the aim of improving air quality and overall cleanroom performance in modular semiconductor cleanrooms.

Methodology

Numerical Setup

This study adopted a combined numerical and experimental approach to investigate and optimize airflow performance in a modular ISO Class 5 semiconductor cleanroom. Computational Fluid Dynamics (CFD) was employed to simulate airflow distribution and mean air velocity under different inlet–outlet configurations and operating parameters. The cleanroom geometry was developed to represent an existing cleanroom, ISO Class 5 environment in accordance with ISO 14644-1 requirements, incorporating ceiling-mounted fan filter units (FFUs) (Supply air), return air outlets, and a defined working zone at operational height. Figure 1 shows the CFD layout for existing the cleanroom design.



a) Top view

b) Side view

Figure 1: CFD Layout for The Existing Cleanroom Design

The CFD model was constructed using steady-state, incompressible airflow assumptions. Boundary conditions were specified based on cleanroom operating conditions, including inlet air velocity, inlet air temperature, outlet configuration, and air change rate per hour (ACH).

Figure 2 shows the boundary condition area and Table 1 shows the boundary condition for numerical solution. These parameters were selected based on cleanroom design guidelines and previous studies (Eslami et al., 2016; Srebric et al., 2008; Saidi et al., 2011; Zhou et al., 2020; Loomans et al., 2020; Chen et al., 2022). The primary performance indicator was the mean air velocity within the critical working zone, which is directly related to contamination control and airflow uniformity in ISO Class 5 cleanrooms.

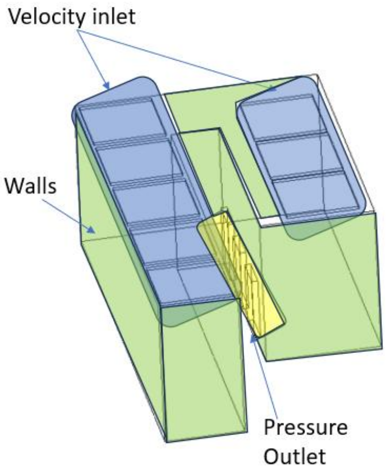


Figure 2: Boundary Condition Area

Table 1: Boundary Condition for Numerical Solution

Parameter	Type	Value
Supply air	Velocity inlet	Velocity: 0.4 m/s Temperature: 294K
Return air	Pressure Outlet	Temperature: 295K
Wall	Temperature wall	Temperature: 295K

Optimization Setup

A Taguchi design of experiments (DOE) method, 5^4 factorial experiment was applied to systematically evaluate the influence of multiple design parameters while minimizing the number of simulation cases. Four control factors which is FFU inlet size (quantity), outlet size, inlet air temperature, and inlet air velocity were considered at predefined levels. Table 2 shows the Taguchi Method for this research.

Table 2: Taguchi Method Parameter for This Study

			Level		
Parameter	**1**	**2**	**3**	**4**	**5**
Inlet size (Quantity FFU)	4	5	6	7	8

Outlet size (mm)	3 nos (534x1096)	4 nos (534x1096)	2 nos (1090x1096)	1 nos (1090x1096), 3 nos (534x1096)	2 nos (1090x1096), 1 nos (534x1096)
Inlet air temperature (K)	290	291	292	293	294
Inlet air velocity (m/s)	0.25	0.3	0.35	0.4	0.45

L25 orthogonal array was used to generate the simulation matrix. For each case, CFD simulations were conducted to obtain the corresponding mean air velocity. The signal-to-noise (S/N) ratio was calculated using the larger-the-better quality characteristic to identify optimal parameter combinations that maximize airflow performance and robustness. Subsequently, analysis of variance (ANOVA) was performed to determine the relative contribution and statistical significance of each factor on the airflow response. A regression model was then developed to predict mean air velocity based on the significant parameters identified.

Experimental Setup

Experimental measurements were conducted in the ISO Class 5 cleanroom under the optimal operating conditions derived from the Taguchi analysis. Figure 3 shows the experimental measurement method. The CFD predicted results were validated against experimental data, and the percentage error between numerical and measured mean air velocities was evaluated to assess the accuracy and reliability of the proposed optimization framework.

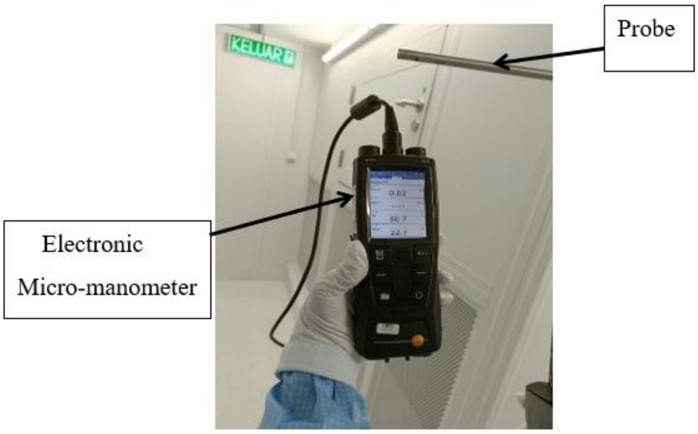


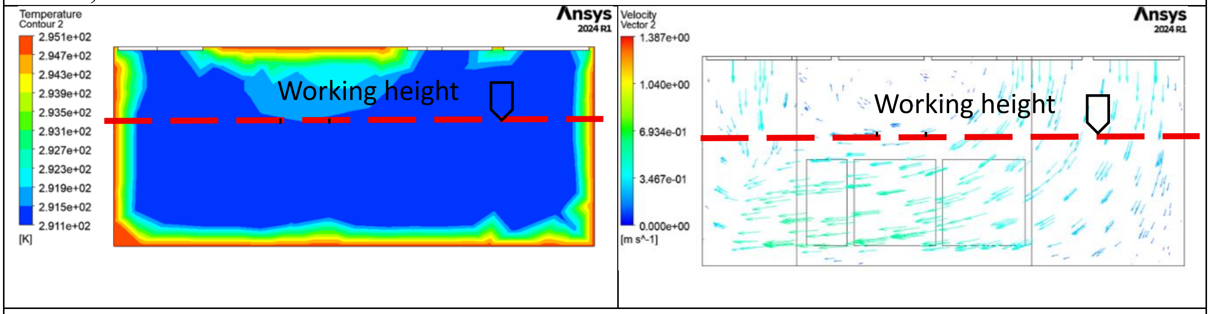
Figure 3: Experimental Measurement Method

Result And Discussion

Numerical Result

CFD simulations were conducted to evaluate the effects of inlet–outlet configuration and operating parameters on airflow performance in an ISO Class 5 cleanroom. The results indicate that airflow distribution and mean air velocity within the working zone are strongly influenced by the inlet air velocity and FFU configuration. Higher inlet air velocities produced more uniform airflow patterns, indicating improved air distribution and enhanced contaminant removal efficiency at the working height level (Eslami et al., 2016; Srebric et al., 2008; Saidi et al., 2011; Zhou et al., 2020; Loomans et al., 2020; Chen et al., 2022). Figure 4 shows the optimum and non-optimum CFD result.

Optimum CFD result, Outlet size 2 numbers (1090 x1096), 1 number (534 x1096),6 FFU, 291K, 0.4m/s



Non Optimum CFD result, Outlet size 3 numbers (534 x1096), 4 FFU, 290K, 0.25m/s

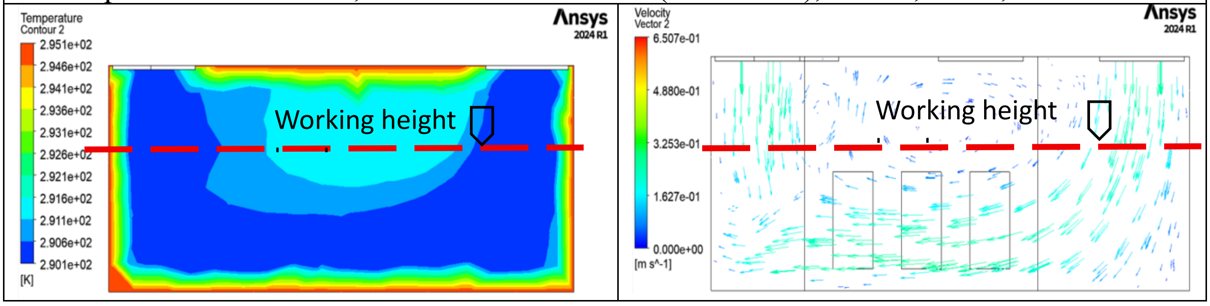


Figure 4: Optimum And Non-Optimum CFD Results

Optimization Result

Taguchi signal-to-noise (S/N) ratio analysis using the larger-the-better criterion was applied to maximize mean air velocity while maintaining robustness against parameter variations. Figure 5 shows the main effects plot for S/N ratios of mean air velocity (Va) while the corresponding numerical values are summarized in Table 3. The S/N response trends show that inlet air velocity was the most significant factor, demonstrating its dominant role in controlling airflow uniformity compared to other parameters, followed by FFU quantity and outlet size, whereas inlet air temperature showed a lease significant factor. The optimal parameter combination identified through the S/N ratio resulted in a significant improvement in airflow performance at the working height, supporting the effectiveness of the Taguchi method for cleanroom airflow optimization.

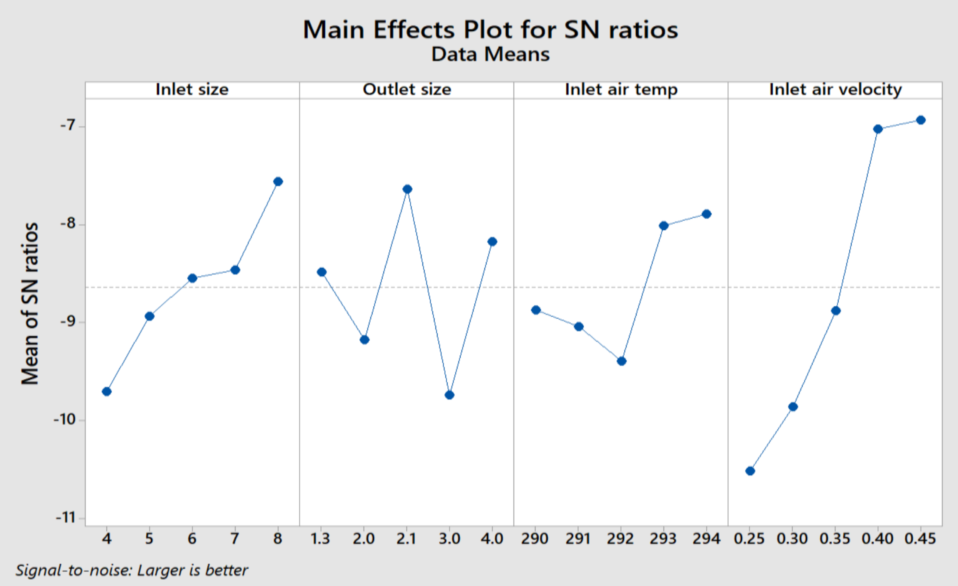


Figure 5: Main effects plot for S/N ratios of Mean air velocity (Va)

Table 3: S/N ratio analysis value of Mean air velocity, Va

Level	**Parameters**			
	Inlet Size (Quantity FFU)	**Outlet size (mm)**	**Inlet air temperature (K)**	**Inlet air velocity (m/s)**
1	-9.701	-8.483	-8.874	-10.514
2	-8.932	-9.177	-9.039	-9.855
3	-8.549	-7.634	-9.390	-8.878
4	-8.462	-9.739	-8.012	-7.022
5	-7.557	-8.169	-7.888	-6.932
Delta	2.144	2.105	1.502	3.582
Rank	2	3	4	1

Regression Model

The ANOVA results are consistent with the S/N ratio analysis, where inlet air velocity shows the highest contribution and rank, confirming its dominant influence on airflow performance, contributing more than 50%, with a statistically significant p-value ($p < 0.05$). Outlet size and FFU quantity exhibited moderate contributions, while inlet air temperature had a negligible effect.

The regression model provides a predictive relationship between process parameters and mean air velocity, enabling estimation of airflow performance under different operating conditions as per Equation 3.1.

$$Va = -3.52 + 0.01720\, I - 0.0003\, O + 0.01200\, T + 0.848\, V \qquad (1)$$

Where;

I = Inlet Size
O = Outlet Size
T = Inlet air Temperature
V = Inlet air Velocity

Va = Velocity average

The predicted mean air velocity values showed good agreement with CFD results, with most prediction errors remaining within ±10% as per shows in Table 4. Minor deviations, including negative percentage errors, were attributed to model simplifications, interaction effects not captured in the linear regression, and localized flow recirculation near outlets. Nevertheless, the high coefficient of determination (R^2) indicates that the regression model provides a reliable representation of airflow behaviour in the ISO Class 5 cleanroom.

Table 4: The comparison of the CFD simulation results and Predicted value of Mean air velocity, Va

Sample No	Inlet Size, I	Outlet Size, O	Inlet air Temperature, T	Inlet air Velocity, V	CFD mean air velocity, Va	Predicted Mean air velocity (Eq), Va	Va Percentage different (%)
CT1	4	4	291	0.3	0.3	0.29	-2%
CT2	5	1.3	294	0.25	0.32	0.31	-4.7%
CT3	6	2.1	291	0.4	0.42	0.41	-1.5%
CT4	7	2	290	0.4	0.45	0.42	-7%
CT5	8	3	294	0.4	0.48	0.484	1%

Comparison Between Experimental and CFD Results

Experimental validation under optimal operating conditions demonstrated close agreement with CFD predictions, with an error of approximately 2% between simulated and measured mean air velocities as per Table 3.3. The small deviation (~2%) indicates that the CFD model reliably represents real cleanroom conditions and can be used for design optimization. Overall, the integrated CFD, S/N ratio, and ANOVA approach successfully identified an optimal inlet–outlet configuration and operating parameters that enhance airflow uniformity and support contamination control requirements for ISO Class 5 cleanrooms.

Table 5: Experimental Validation Vs CFD Prediction Under Optimal Operating Condition

Parameter	Value	CFD result, Mean air velocity (m/s)	Experimental result Mean air velocity (m/s)	Percentage different (%)
Inlet size (Qty FFU)	6	0.44	0.45	2%
Outlet Size (mm)	2 nos (1090x1096), 1 nos (534x1096)			
Inlet Temperature (K)	294			

Inlet air velocity (m/s)	0.4

Conclusion

This study successfully optimized airflow and thermal performance in an ISO Class 5 cleanroom using an integrated CFD, Taguchi S/N ratio, and ANOVA approach. The results show that a higher inlet air velocity or a larger number of FFUs does not necessarily produce the best airflow uniformity, highlighting the importance of optimized parameter selection rather than maximum input values. The optimal condition, consisting of six FFUs with an inlet air velocity of 0.4 m/s and an inlet air temperature of 294 K, achieved stable airflow and acceptable thermal distribution at the working height level. The CFD simulation results were in close agreement with experimental measurements, with a deviation of approximately 2%. Additionally, the regression equation derived from the optimization study closely represents the actual cleanroom operating condition, confirming the reliability of the proposed method.

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Author Contribution Statement: All authors contributed significantly to the development of this manuscript. [Dr Ir Sh Mohd Firdaus] was responsible for the conceptualization, methodology, and overall supervision of the study. [Zharif Samsudin] handled data collection, analysis, and interpretation of results. [Hazimi Ismail] contributed to the literature review, drafting, and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

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