VENTILATION SYSTEM FOR REDUCTION OF PARTICLE CONCENTRATION IN AUTOMOTIVE PAINTING LINE ENVIRONMENT

MUHAMMAD HAFIZAN BIN YOSRI

UNIVERSITI TEKNOLOGI MALAYSIA

VENTILATION SYSTEM FOR REDUCTION OF PARTICLE CONCENTRATION IN AUTOMOTIVE PAINTING LINE ENVIRONMENT

MUHAMMAD HAFIZAN BIN YOSRI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

JULY 2022

DEDICATION

Specially dedicated to my beloved family.

ACKNOWLEDGEMENT

First and foremost, all praise due to Allah SWT for every difficulties and accomplishments throughout my period of study. I could not have completed this project and doctorate thesis without His permission. Alhamdulillah.

I wish to express my respect and gratitude to Assoc Prof Ir Dr. Pauziah Muhamad for being a truly great supervisor, mentor and source of inspiration. My unconditional love and appreciation to my parents, Yosri Yusof and Azizah Abd Latif: I am always grateful for your love, support, guidance and advice, my true source of motivation. To my beloved wife; Norfazrina, my son and daughter, you always be my inspiration throughout this journey. My sincere appreciation goes to my little brother and sisters. Your words of encouragement have inspired me to do my very best, despite the unexpected calamity and the challenges that we faced. Thank you for standing by me through thick and thin. I hope this doctorate thesis can be my little token for you.

Finally, the financial support from Ministry of Higher Education (MoHE) is gratefully acknowledged.

ABSTRACT

In the painting production process, repairing of paint work defects by running the part through the process again, together with the requisite quality control routines, account for a very large proportion of the operating costs. At current defective rate of 37 per cent rejection due to dust, not only it deteriorates the quality and the performance of productivity, but it also brings negative impact to the operation cost and company revenue. Hence, this research focuses on identifying the air flow patterns for existing painting booth utilising Computational Fluid Dynamic (CFD) to understand the concentration and movement of dust particles. The data gathered from the CFD simulation is used to remodel the mechanical design of air ventilation system for the painting booth by focusing on the size and location of the exhaust system. Based on this, the optimum value for air flow velocity which is also an important variable in the movement and concentration of particles can be defined. However, the range for the tested air flow supply is subjected to the capability of current painting booth Air Supply Unit (ASU) which is from 0.1 m/s ~ 0.5 m/s. During CFD simulation process, Renormalization Group (RNG) k-ε turbulence model has been used to predict the particles movement and concentration. Eight new designs based on current painting booth have been proposed and validated. Painting booth of model I found to be the best solution to minimize and reduce the dust particle concentration with 98.13 per cent of average particles escaped with air flow rate of 16103 m3/min. An experimental data has been collected using the air flow meter in a small-scale model of painting booth together with smoke visualization to validate findings from numerical simulation, CFD. It is found that the average relative error for model A, was recorded at range of 1.04 to 3.08 per cent. In summary, the relative error between numerical and experimental data is less than 10 per cent which is acceptable and in a good agreement. So far, this is the first study that has been conducted to understand the dust particles movement with the impact of the ventilation system and multiple air velocity setting in context of Malaysia automotive painting industry.

ABSTRAK

Dalam proses pengecatan, pembaikan kerosakan cat pada produk memerlukan pengulangan proses iaitu pengecatan kali kedua, dituruti dengan rutin kawalan kualiti telah menyumbang kepada kenaikan kos operasi syarikat. Kerosakan produk disebabkan habuk pada kadar 37 peratus, bukan sekadar menurunkan kualiti pengeluaran, bahkan membawa kesan negatif kepada kadar operasi dan keuntungan syarikat. Justeru itu, projek penyelidikan ini akan memfokuskan kepada menilai keberkesanan penggunaan *Computational Fluid Dynamic* (CFD) bagi mengenal pasti corak aliran udara yang menjadi kawasan tumpuan habuk di dalam kebuk pengecatan yang digunakan sekarang. Keputusan dan data yang diperolehi daripada simulasi CFD akan digunakan untuk menghasilkan model sistem mekanikal aliran udara yang baharu di dalam kebuk pengecatan yang memfokuskan kepada saiz dan lokasi sistem ekzos. Walaubagaimanapun, kadar aliran udara adalah bergantung kepada kemampuan Unit Bekalan Udara (ASU) kebuk pengecatan iaitu dari 0.1 m/s ~ 0.5 m/s. Semasa proses simulasi CFD, model gelora *Renormalization Group* (RNG) k-ε telah digunakan untuk meramalkan pergerakan dan tumpuan zarah habuk tersebut. Lapan (8) reka bentuk mekanikal baru kebuk pengecatan dan satu reka bentuk sedia ada telah dicadangkan untuk diuji. Model garisan pengecatan I dengan purata 98.13 peratus zarah terbebas dan kadar aliran udara pada 16103 m^3 /min telah dipilih berdasarkan keberkesanan untuk mengurangkan zarah habuk di dalam model baru kebuk pengecatan. Selain simulasi menggunakan CFD, data eksperimen telah juga dikumpul dengan menggunakan alat meter aliran udara di dalam model berskala kecil bersama-sama visualisasi asap untuk mengenal pasti vektor aliran udara. Data tersebut telah digunakan sebagai rujukan untuk membandingkan antara data eksperimen dan simulasi bagi menilai keberkesanan proses simulasi. Purata relatif ralat untuk model A direkodkan pada julat 1.04 ke 3.08 peratus. Secara kesimpulannya purata relatif ralat di antara data eksperimen dan simulasi bagi model A adalah kurang daripada 10 peratus iaitu boleh diterima dan dianggap baik. Setakat ini, kajian ini adalah kajian pertama dijalankan untuk memahami pergerakkan zarah habuk yang melibatkan impak dari sistem pengudaraan dan beberapa pemalar kelajuan angin dalam konteks industri pengecatan komponen kereta di Malaysia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

MOA	-	Memorandum Of Agreement
UTM	-	Universiti Teknologi Malaysia
HVAC	-	Heating, ventilation, and air conditioning
HDD	-	Hard disk drive
OT	-	Operation theatre
LCD	-	Liquid crystal display
FFU	-	Fan filter unit
WAM	-	Welding automation machine
AAM	-	Automated assembly machine
LAF	-	Laminar airflow
OR	-	Operation Room
RNG	-	Re-Normalisation Group
LRN	-	Low Reynolds number
SST	-	Shear stress transport
RSM	-	Reynolds-stress model
LES	-	Large eddy simulation
DES	-	Detached eddy simulation
RNG	-	Renormalization Group
RANS	-	Reynolds Averaged Navier-Stokes
DNS	-	Direct Numerical Simulation
IEA	-	International Energy Agency
TKE	-	Turbulent kinetic energy
ASU	-	Air supply unit
RH	-	Relative humidity
ABS	-	Acrylonitrile butadiene styrene
PBT	-	Polybutylene terephthalate
PP	-	Polypropylene
kV	-	Ionization energy
DRW	-	Discrete random walk
AOZ	-	Animal occupied zone

PWM	-	Pulse Width Modulation
DC	-	Direct current
PPE	-	Personal protective equipment
HEPA	-	High Efficiency Particulate Air Filters
OEM	-	Original equipment manufacturer
CADR	-	clean air delivery rate
CFM	-	Cubic Feet Per Minute

LIST OF SYMBOLS

τ	-	time constant
E	-	electric field
V	-	velocity
q	-	ion charge
λ.	-	air conductivity
Φ	-	variables
$\Gamma_{\phi,eff}$	-	effective diffusion coefficient
S_ϕ	-	source term of an equation
u_i	-	velocity component in *i* direction
T	-	air temperature
k	-	kinetic energy of turbulence
ε	-	dissipation rate of turbulent kinetic energy
Ω	-	specific dissipation rate of turbulent kinetic energy
P	-	air pressure
H	-	air enthalpy
μ_t	-	eddy viscosity
G_ϕ	-	turbulence production for ϕ
S	-	rate of the strain
v_t	-	turbulent eddy viscosity
C_μ	-	empirical constant
Gk	-	turbulence kinetic energy caused by the mean velocity gradients
G_b	-	turbulence kinetic energy caused by buoyancy
Y_M	-	fluctuating dilatation
αk	-	inverse effective Prandtl numbers for k
$\alpha\varepsilon$	-	inverse effective Prandtl numbers for ε
S_k	-	user-defined source terms
S_ε	-	user-defined source terms
μ_{t0}	-	value of turbulent viscosity
Ω	-	characteristic of swirl number

α_s	-	swirl constant
C	-	model constants
$F_D(u - up)$	-	drag force per unit particle mass
u	-	fluid phase velocity
up	-	particle velocity
μ	-	molecular viscosity of the fluid
ρ	-	fluid density
ρ_p	-	density of the particle
d_p	-	particle diameter
Re	-	relative Reynolds number
CD	-	drag coefficient
Cc	-	Cunningham correction

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Recently, the top and highest rejection of almost all painting lines in automotive industry is contributed by dust ranging between 30% and 40%. For example in coating industries, dust have an effect on appearance issue. The repairing of paint work defects by running the part through the process again, together with the requisite quality control routines, account for a very large proportion of the operating costs involved. Hence, in order to reduce the airborne contamination contributed by dust particle, the Computational Fluid Dynamic (CFD) [1] has been utilized to understand the air flow pattern that will affect the dust particle concentration in the painting booth environment. Therefore, suggestions for a better air ventilation system in the painting line have been proposed to achieve a better environment with less dust particle contamination. This will eventually present benefits to the painting industries by achieving higher production parts pass rate for the finish product.

The result obtained from numerical simulation was analysed to improve existing painting booth design by focusing on the size and location of the exhaust system. On top of that, air flow velocity within the range of 0.1~0.5m/s was tested to get the optimum speed that is able to reduce the particle concentration inside painting booth. The air flow range was set based on the capability of current painting line Air Supply Unit (ASU). Meanwhile, the Renormalization Group (RNG) k-ε turbulence model was selected to be applied in CFD simulation to predict the particles movement and concentration. In total, Eight (8) new models of painting booth that benchmark the existing painting booth design have been proposed and validated. Next, the experimental data was conducted using air flow meter in a small-scale model of painting booth followed by smoke visualization to verify the airflow vector. Finally, this data was used to compare between experiment and numerical simulation in order to measure the effectiveness of analysis and findings.

Apart from parts quality, the significance of controlling dust in a production line is also crucial which may have an impact on the workers' health [2]. All issues that have been addressed above pose a direct impact on the deterioration of performance in indoor environment which is related to the indoor air pollutant (IAP) [3]. In general, IAP comes from many sources such as poor ventilation system, workers activities, garment wear by personnel (overall, shoes, gloves), product (plastics, metal, liquid etc.) and processing method (part cleaning process, jig maintenance, painting sequence). Generally, machine is known to consist many complicated mechanisms and most of them are very sensitive to the dust particle. This dust particle has the ability to reduce the machine performance to manufacture a quality product which may result in increased machine maintenance cost. Hence, many researchers found significant impact on machine and product quality performance caused by dust contamination. Oyebisi [4] realized the dust and particle will affect the performance of electronic components whereby the dust particle attacks the ceramic capacitor while Hata *et al.* [5] found that dust particle would disturb and reduce the performance of the equipment such as ball bearing and sensors. As for the workers, dust particle has become a risk to air pollution. Bascom *et al.* [6] described that operators who work in high dust particle concentration will face high potential risks of contracting critical illness such skin and lung cancer, asthma and eye related illness such as cataracts and pterygia. Finally, it can lead to low productivity and increase the medical treatment for the workers involved.

1.2 Problem Background

Combat Coating (M) Sdn. Bhd. is a company based in Batang Kali, Selangor. The company is under the Memorandum of Agreement (MOA) with Universiti Teknologi Malaysia (UTM) to conduct investigation and find solutions to increase the company's productivity by reducing the main issue which is dust defects. In the production process, elimination of paint work defects by reworking or running the part through the process again, together with the requisite quality control routines, account for a very large proportion of the operating costs involved. The defects are frequently attributable to dust, fibers, burr, cratering, sagging, etc. Combat Coating (M) Sdn. Bhd has been providing the painting services in automotive industry since 1995, has taken this fact on board, and responded with the research offered to come out with the innovative solutions to solve dust in painting process. Contamination contributed by dust particle has been identified as the highest rejection in automotive painting line and it is crucial to understand the particle movement and concentration in the painting line environment. The dust rejection has contributed to 37% from the total rejection in painting line at Combat Coating (M) Sdn. Bhd. and becomes a long time issue for the company to resolve. As at 2019, in total, there were 43577 pieces of painted part affected by dust issue and it has become the top rejection compared to other types of defects. The rejection due to dust not only deteriorate the quality and productivity performance, but it also brings negative impact to the operation cost and company revenue.

At current rejection of 37%, it's very difficult to maintain the OEE (Overall Equipment Effectiveness) at 85% since the target of producing a good product is not achieved [7]. Since the highest contributor of the defect comes from dust, this defect is chosen for this study in order to reduce their impact on the good parts production efficiency. Based on this fact, this research is crucial to understand the movement of dust particle inside the painting booth environment and further action is needed to minimize the contamination on the painted part. So far, there is no specific study conducted to understand the dust particle movement influence by the ventilation system and multiple air velocity setting in the context of Malaysia's automotive painting industry.

The details of the rejection breakdown can be referred in Figure 1.1 and Figure 1.2 below [8]. The total defective part of 37% is considered absolute number after referring to the inspection standard provided by Original Equipment Manufacturer (OEM). The judgement criteria are based on the size of the dust ranging from 0.1 mm to 1.5 mm in diameter. In addition, the acceptable level of the dust defect needs to be referred to the location of the part on actual car condition. The details of judgement criteria are as listed in Figure 1.3 below while Figure 1.4 explain the painting booth layout at Combat Coating (M) Sdn. Bhd.

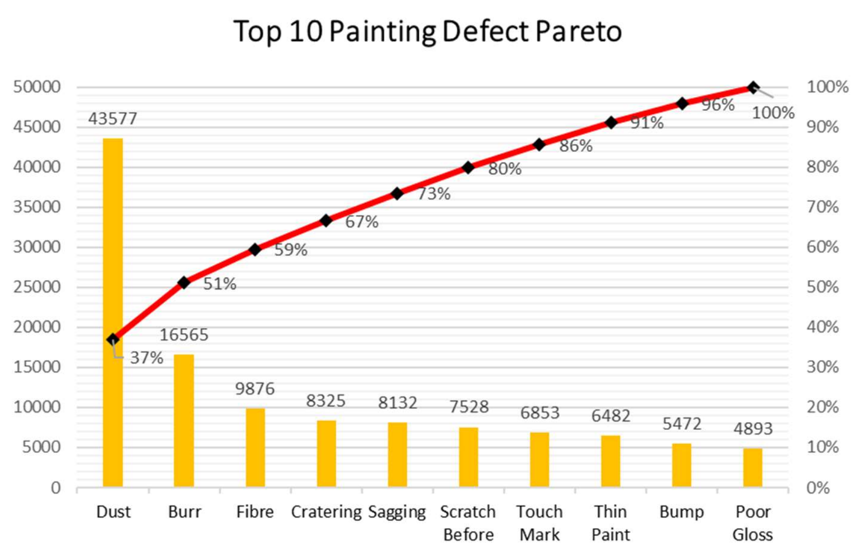


Figure 1.1 Pareto chart of Top 10 painting defects in 2019 [8]

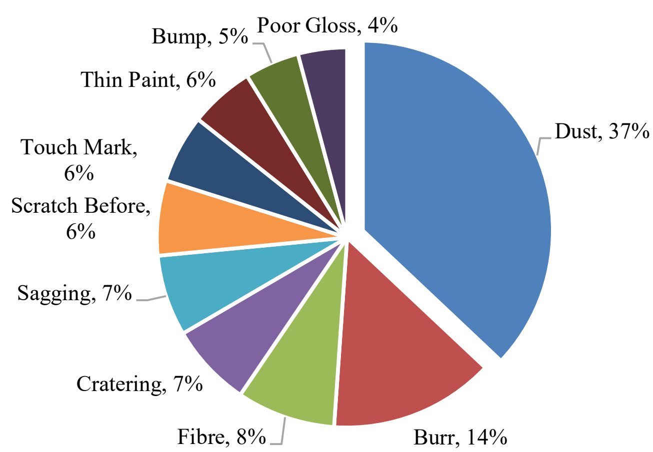
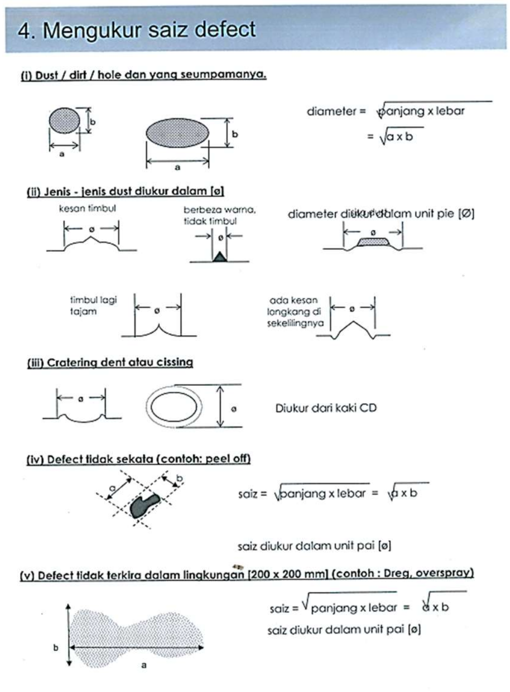
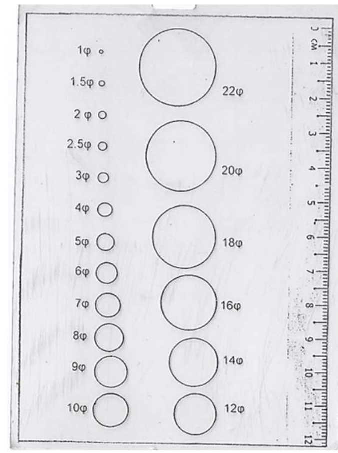


Figure 1.2 Pie chart of top 10 painting defects in 2019 [8]



(a)



(b)

GENERAL APPEARANCE QUALITY (VIS/TGS 9)											
No	Inspection		OUTER				Inner			Notes	
			Zone A	Zone B	Zone C	Zone D	Zone B	Zone C	Zone D		
1	Habuk Berbiji Habuk Besi Sealer Seed Adhesive Sealer Seed Habuk Sanding Seed in Promer	Saiz 1 Pcs Sama warna/tidak sama warna Kesan timbul/ Tidak timbul	Max 1.5 Ø	Max 2 Ø	Max 3 Ø	Max 6 Ø	Max 3 Ø	Max 6 Ø	Max 10 Ø	Cara mengukur dust i) Dust berbukit	iv) Dust timbul
		Lebih dari 1 Boleh dikira dalam kawasan 300 x 300	Max 1 Ø x 3 pcs	Max 1 Ø x 5 pcs	Max 1 Ø x 10 pcs	Max 2 Ø x 10 pcs	Max 1.5 Ø x 5 pcs	Max 2 Ø x 10 pcs	Max 3 Ø x 10 pcs		
		Tidak terkira (Dreg) dalam kawasan 300 x 300	Max 20 Ø	Max 30 Ø	Max 50 Ø	Max 80 Ø	Max 60 Ø	Max 100 Ø	Max 150 Ø	ii) Bebenang	v)Lebihan dust
2	Dust Berbukit	Saiz 1 pcs	Max 2 Ø	Max 2.5 Ø	Max 3.5 Ø	Max 5.5 Ø	Max 4.5 Ø	Max 7 Ø	-----		
3	Habuk Bebenang Dust Liner Dirt Liner Bebenang Sealer	Kesan timbul	Max 3 mm	Max 4 mm	Max 7 mm	Max 12 mm	Max 16 mm	Max 30 mm	Max 60 mm	iii) Dust berkaki	vi) Tidak sama warna
		Kesan tidak timbul	Max 5 mm	Max 6 mm	Max 8 mm	Max 20 mm	Max 20 mm	Max 40 mm	Max 80 mm		

(c)

Figure 1.3 Judgement criteria for dust defect from OEM. (a) Method used to measure the dust size, (b) Dust gauge, (c) Dust inspection criteria [9]

Prior to this, continuous Kaizen or Improvement activity has been conducted to counter the dust issue at the painting booth. Some of the activities have been grouped into 4M section (Material, Machine, Method and Man) and listed as follows [10]:

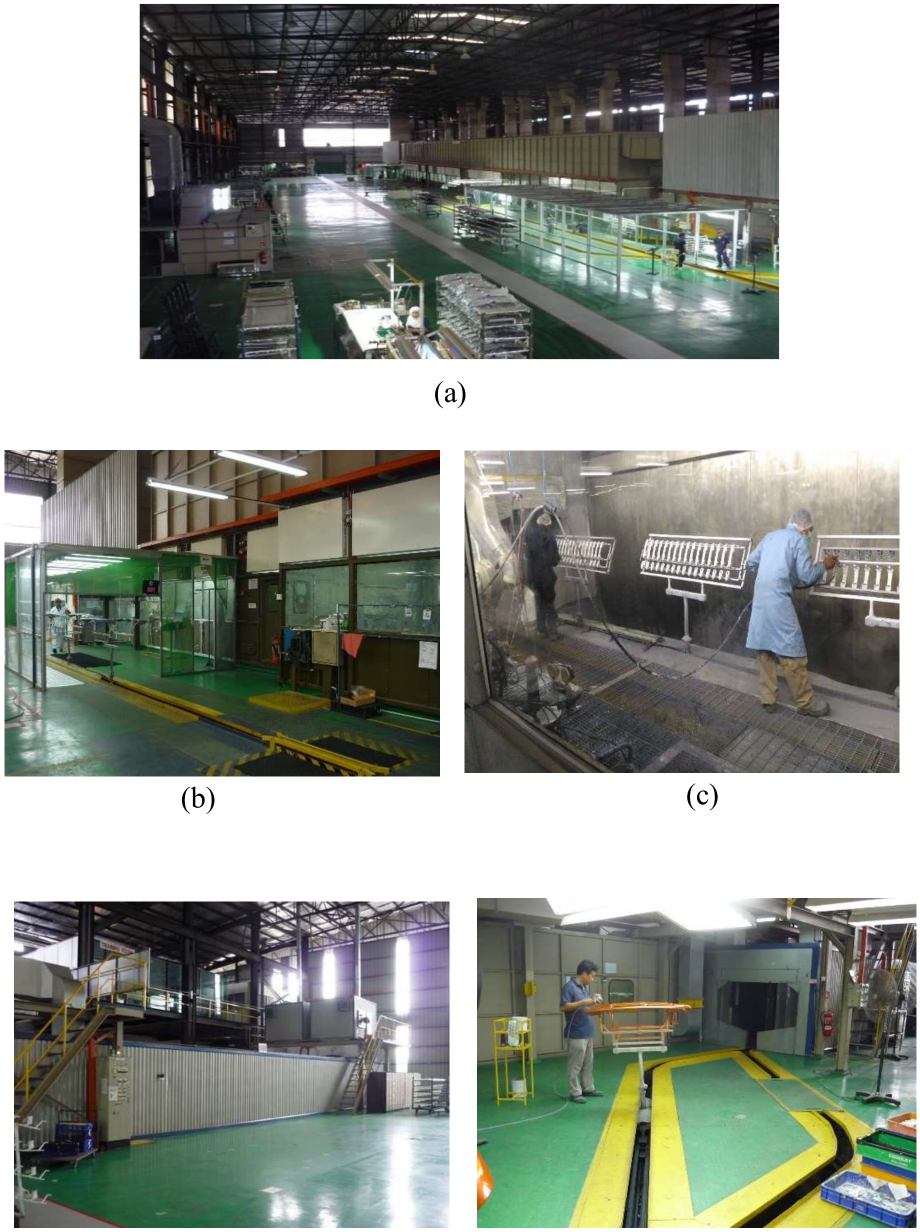
1. Material
   a. Provide 2 sets of overall for all operators for daily change.
   b. Trial on multiple type of cleaning solvent at preparation area to find most effective cleaning solvent to remove dust and stain before painting process.

2. Machine
   a. Installation of Ionizer device to minimize dust attachment on the painted part surface.
   b. Increase the frequency of ceiling filter change from every 12 month to 6 month.
   c. Installation of air shower room before entering the painting booth.
   d. Provide washing machine & dryer facility to wash all operators overall on daily basis.

3. Method
   a. Establish Miruka Board to visualize the wiping rag condition that facilitates operator to monitor the effectiveness of cleaning process.
   b. Increase the frequency of jig cleaning by monitoring the overspray condition and not by timing based.
   c. Introduction of flaming process to remove overspray at painting jig to replace previous chemical cleaning process.
   d. To apply finer filter mesh (150 micron) for solid colour paint for better dust filtration.
   e. To conduct particle counter verification every 6 month after ceiling filter installation to monitor the particle count.
   f. To have isolation room that covers all raw materials (work in progress) from dust contamination at preparation area.

4. Man
   a. To ensure all sprayers are following and wearing the standard personal protective equipment which include overall, glove, hood, safety goggle to comply to safety regulation and avoid contamination to the painted part.

Figure 1.4 below explain the painting booth layout at Combat Coating (M) Sdn. Bhd.



(a)

(b) (c)

(d) (e)

Figure 1.4 (a) Combat Coating (M) Sdn. Bhd. painting line layout. (b) Preparation area, (c) Painting booth, (d) Oven and (e) Final inspection [11]

1.3 Research Objective

The objectives of this research are:

a. To investigate the air flow pattern of existing painting booth design that has a strong influence on the dust concentration in painting booth.

b. To investigate the relation between location of exhaust opening and flow characteristics.
c. To analyse the ventilation performance on the dust concentration based on different configuration of exhaust opening.

1.4 Scope of the Research

The scopes of this research are:

a. The study covers the impact of ventilation system design and air flow velocity setting on the reduction of dust particle inside the painting line.

b. The new proposed ventilation system will focus on the outlet size and the position inside the painting booth. The design will benchmark existing painting line system in terms of mechanical structure and other functional items such as air supply system (ASU), painting jig and conveyor system.

c. The air flow velocity ranges from 0.1m/s to 0.5 m/s which is based on ASU capability will be tested during CFD simulation using the RNG k-ε turbulence model.

1.5 Significant Contribution from This Project

At the end of this research, both parties from industry and university shall benefit from the outcomes of the project. The potential contribution will cover the area as per below details:

a. Discover and understand the air flow pattern and particle concentration in the painting line environment by application of CFD simulation and validation through experimental methods. From here, a new design of ventilation system for painting line can be proposed and validated in order to get the optimum design which can control and minimize the dust contamination.

b. Able to determine the suitable parameter setting related to air flow velocity which affects the turbulence occurrence and particle concentration in automotive painting line.

c. Reduction of defective part contribute by dust shall be the main key factors that can improve production efficiency and profitability to the company.

d. The result and finding from this study may become a benchmark and benefit other industries that focus on the particle movement, concentration and reduction in closed environment such as hospital and pharmaceutical industries.

1.6 Organization of the Thesis

In Chapter 1, the introduction to the dust issue in automotive painting line has been brief and its impact to the company productivity and profitability. Further action to understand the root caused and necessary step has been put into plan as part of research objective. Meanwhile, the scope of research that focus on existing painting booth capability has been listed as part of parameter setting and limiting factor throughout the research activity. Finally, the significant contribution of the research outcome that will improve company productivity has been targeted as research outcome.

Chapter 2 starts with the overview of painting booth main structure and history of its development. The characteristics of the main issue, which is dust has been discussed and how the dust concentration related to the air velocity has been discussed. In addition, the air flow characteristics inside the painting booth need to be explored together with the air ventilation system before the new design can be proposed. Finally, the application of CFD to understand the air flow characteristics and its application has been discovered.

Chapter 3 begins with basic operation of painting booth and new design proposal. Next, the application of CFD and its crucial process such as convergence study, sensitivity study of grid resolution and boundary condition has been listed to ensure the right method is applied during simulation. The Renormalization Group (RNG) k-ε Model has been selected to be applied during numerical simulation based on the suitability of this model to be applied in painting booth design. The last section in this chapter explains the experimental set-up and procedure as part of validation process in this research.

Chapter 4 starts with validation process of existing model A by comparing the numerical simulation against the experimental result. Once the data has been validated, simulation process for the new design proposal can be proceed and final design with optimum value of air velocity and less particle concentration can be discovered.

Finally, Chapter 5 will review the achievement of the research objective and recommendation for future works.

REFERENCES

1. Daniel Holbrook. Controlling Contamination: The Origins of Clean Room Technology. *History and Technology*, 2009. 25(3): 173-191.
2. Rosmaini Ahmad, Zahid A. Khan, Mohzani Mokthar and Indra Putra Almanar. Implementation of Dust Control System Using Management and Planning Tools (MPT): A case study. *Management of Environmental Quality, an International Journal*, 2006. 7(4): 390-408.
3. Roy, Misha, Shamim and Das. Indoor Air Pollution: Sources. Health Impact and Control. *Journal of Eco Chronicle*, 2018. 75-82.
4. Oyebisi. On Reliability and Maintenance Management of Electronic Equipment in the Tropics. *Technovation*, 2000. 517-522.
5. Hata T., Kobayashi N., Kimura F. and Suzuki H. Representation of Functional Relations Among Parts and its Application to Product Failure Reasoning. *Proceedings of CIRP International Seminar on Design*, 2000.
6. Bascom R., Kesavanathan J. and Swift D.L. Human Susceptibility to Indoor Contaminants. *Occupational Medicine*, 1995.
7. Esmaeel R, Zakuan N, Jamal N and Taherdoost H. Understanding of Business Performance From the Perspective of Manufacturing Strategies: Fit Manufacturing and Overall Equipment Effectiveness. *Procedia Manufacturing. Elsevier,* 2018. 998–1006.
8. Combat Coating (M) Sdn Bhd. *Outgoing Quality Inspection Passrate Report*, 2019.
9. Perusahaan Otomobil Kedua Sdn Bhd. *Painting Appearance Standard*, 2018.
10. Combat Coating (M) Sdn Bhd. *Kaizen Improvement Activity Report*, 2018.
11. Combat Coating (M) Sdn Bhd. *Overview of Painting Layout Overview*, 2018.
12. Everything You Need to Know About Spray Booths. *PAC Group*, 2020. https://www.pacgroup.co.uk/news/everything-you-need-to-know-about-spray-booths.
13. Choosing the Right Paint Booth. *Direct Industry*, 2021. https://guide.directindustry.com/choosing-the-right-paint-booth.
14. Combat Coating (M) Sdn Bhd. *Key components of paint booth*, 2019.

15. Spray Booth Types Airflow. Booth *Brothers Inc*, 2021. https://www.boothbrothers.ca/2013-06-25-17-38-26/spray-booth-types-airflow.html.
16. S. Bysko, J. Krystek, and Sz. Bysko. Automotive Paint Shop 4.0. *Computers & Industrial Engineering*, 2018. DOI: 10.1016/j.cie.2018.11.056.
17. J. Salcedo-Hernández, J. García-Barruetabeña, I. Pastor-López and B. Sanz-Urquijo. Predicting Enamel Layer Defects in an Automotive Paint Shop. *IEEE Access, vol. 8*, 2020. DOI: 10.1109/ACCESS.2020.2969816.
18. Akhtar, Sohail, Adarsh Tandiya, Medhat A. Moussa and Cole Tarry. An Efficient Automotive Paint Defect Detection System. *Advances in Science, Technology and Engineering Systems Journal*, 2019.
19. Feng L. and Mears L. Analysis of HVAC Energy in Automotive Paint Shop. *International Manufacturing Science and Engineering Conference. Volume 2: Materials; Biomanufacturing; Properties, Applications and Systems; Sustainable Manufacturing*. 2015. https://doi.org/10.1115/MSEC2015-9281
20. Paduloh . Analysis Of Productivity Based On KPI Case Study Automotive Paint Industry. *Journal of Engineering and Management in Industrial System*, 2020.
21. PPG Industries. *Paint Defect Diagnosis*, 2015.
22. Rodger Talbert. *Paint Technology Handbook*, 2008.
23. Jatuporn Thongsri. A Problem of Particulate Contamination in an Automated Assembly Machine Successfully Solved by CFD and Simple Experiments. *Mathematical Problems in Engineering Volume 2017*, 2017.
24. Guangping Xu and Jiasong Wang. CFD Modeling of Particle Dispersion and Deposition Coupled With Particle Dynamical Models in a Ventilated Room. *Atmospheric Environment 166*, 2017.
25. Kosutova K., van Hooff T. and Blocken B. A Numerical Study of Non-Isothermal Mixing Ventilation in an Enclosure to Evaluate RANS Turbulence Model Performance. *Proceedings of the 14th International Conference of Indoor Air Quality and Climate (Indoor Air 2016),* 2016.
26. Gao N.P. and Niu J.L. Modeling Particle Dispersion and Deposition in Indoor Environments. *Atmospheric Environment* 41, 2007.

27. Naosungnoen, Jiranan & Thongsri Jatuporn. Simulation of Airflow in a Cleanroom to Solve Contamination Problem in an HDD Production Line. *International Journal of Mechanical Engineering and Robotics Research,* 2018.
28. Xu T., Lan C.H., and Jeng M.S. Performance of Large Fan Filter Units for Cleanroom Applications. *Building and Environment*, 2007. 2299–2304.
29. Ichiya. Design Theory For a Laminar Flow Type Clean Room And Image Processing on Remotely Detected Particulates. *Aerosol Science & Technology*, 1987. 47-56.
30. Xinming Jin, Lijun Yang, Xiaoze Du and Yongping Yang. Numerical Investigation of Particle Transport Characteristics in an Isolated Room With Single-Sided Natural Ventilation. *BUILD SIMUL,* 9, 2016. 43–52. DOI 10.1007/s12273-015-0235-6.
31. Caiqing Yang, Xudong Yang and Bin Zhao. The Ventilation Needed to Control Thermal Plume and Particle Dispersion From Manikins in a Unidirectional Ventilated Protective Isolation Room. *BUILD SIMUL*., 2015. DOI 10.1007/s12273-014-0227-6.
32. Gao NP, Niu JL, Perino M and Heiselberg P. The Airborne Transmission of Infection Between Flats in High-Rise Residential Buildings: *Tracer gas simulation. Building and Environment*, 2008.1805–1817.
33. Jiranan Naosungnoen and Jatuporn Thongsri. Airflow and Temperature Simulation in a Big Cleanroom to Reduce Contamination in an HDD Manufacturing Factory. *IOP Conf. Ser.: Mater. Sci. Eng,* 2019. 361.
34. Srebric, J., Vukovic, V., He, G., and Yang, X. CFD Boundary Conditions for Contaminant Dispersion, Heat Transfer and Airflow Simulations around Human Occupants in Indoor Environments. *Building and Environment, 2008.* 294-303.
35. Jatuporn Thongsri. Optimum Airflow to Reduce Particle Contamination Inside Welding Automation Machine of Hard Disk Drive Production Line. *International Journal of Precision Engineering and Manufacturing*, *Volume 16(Issue 3)*, 2015. 509-515.
36. J. Tongsri and V. Pongkom. A Simulation of the Number of Particles Trapped by the Circulating Filter of a Hard Disk Drive and Their Trajectories. *Applied Mechanics and Materials, vol. 548- 549*, 2014. 953–957.

37. Zhiqiang John Zhai , Zhao Zhang , Wei Zhang and Qingyan Yan Chen. Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part 1—Summary of Prevalent Turbulence Models. *HVAC&R Research,* 2007. 853-870.
38. Quarini J. Applications of Computational Fluid dynamics in Food and Beverage Production. *Food Science and Technology Today,* 1995. 234-237.
39. D. Maher, A. Hana, and H. Sammouda. Numerical Approximation of Air Flow, Temperature Distribution and Thermal Comfort in Buildings. *Scientific African, vol. 8*, 2020.
40. J. Atkinson, Y. Chartier,C. Lúcia,P. Jensen, Y. Li and W.Seto. Natural Ventilation for Infection Control in Health-Care Settings. *WHO Publication/Guidelines*, 2009.
41. S. Cao, D. Zhu and Y. Yang. Associated Relationship Between Ventilation Rates and Indoor Air Quality. *RSC Adv.,* 2016. 111427–111435.
42. H. Wang, C. Huang and D. Liu. Fume Transports in a High-Rise Industrial Welding Hall With Displacement Ventilation System and Individual Ventilation Units. *Build. Environ.,*2012. 52: 119–128.
43. P. Tao, A. Li and J. Zhang. Scaling Model Study of the Air Distribution in a Powerhouse Under Different Ventilation Conditions. *Building Simulation 7*, 2014. 389–400.
44. H. Wang, C. Huang and Y. Cui. Experimental Study on the Characteristics of Secondary Airflow Device in a Large Enclosed Space Building. *Energy Build.,*2018. 347–357.
45. S.J. Cao and J. Meyers. Influence of Turbulent Boundary Conditions on RANS Simulations of Pollutant Dispersion in Mechanically Ventilated Enclosures With Transitional Slot Reynolds Number. *Build. Environ.,* 2013. 397–407.
46. C. Xu, P. Nielsen, L. Liu, R. Jensen and G. Gong. Human Exhalation Characterization With the Aid of Schlieren Imaging Technique. *Build. Environ*., 2017. 190–199.
47. S. B. Thool and S. L. Sinha. Computational Fluid Dynamics Modeling and Investigation of Horizontal Airflow Ventilation System in Surgical Site in Hospital. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE),2014.* 40-46.

48. M. Pereira and A. Tribess. A Review of Air Distribution Patterns in Surgery Rooms Under Infection Control Focus. *Rev. De. Eng. Térmica 4*, 2016. 113–121.
49. Shi-Jie Caoa, Dongdong Cena, Weirong Zhangb and Zhuangbo Fenga. Study on the Impacts of Human Walking on Indoor Particles Dispersion Using Momentum Theory Method. *Building and Environment,* 2017. 195–206
50. B. Blocken and J. Persoon. Pedestrian Wind Comfort Around a Large Football Stadium in an Urban Environment: CFD Simulation, Validation and Application of The New Dutch Wind Nuisance Standard. *J. Wind Eng. Industrial Aerodynamics,* 2009. 255–270.
51. ASHRAE Handbook. HVAC Applications, Ventilation of the Industrial Environment. *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Atlanta*. 2015.
52. Z. Cao. Performance evaluation of different air distribution systems for removal of concentrated emission contaminants by using vortex flow ventilation system. *Building and Environment,* 2018. 211–220.
53. P. Heiselberg, Y. Li, A. Andersen, M. Bjerre and Z. Chen. Experimental CFD Evidence of Multiple Solutions in a Naturally Ventilated Building. *Indoor Air,* 2004. 43–54.
54. Sasan Sadrizadeh , Sture Holmberg and Ann Tammelin. A Numerical Investigation of Vertical and Horizontal Laminar Airflow Ventilation in an Operating Room. *Building and Environment,* 2014. 517~525.
55. Bin Zhao. Numerical Investigation of Particle Diffusion in a Clean Room. *Indoor Built Environ.,* 2005. 69~79.
56. T.W. Lee, H. Singh and J. Lee. Computational Simulations and Optimization of Flow and Temperature Distributions in a Large-Scale Power Plant Building. *Building Simulation,* 2011. 341–349.
57. Mendez C, San Jos e JF, Villafruela JM and Castro F. Optimization of a Hospital Room by Means of CFD For More Efficient Ventilation. *Energy Build.,*2008. 49~54.
58. Which Airflow Style is Best for My Paint Booth. *Global Finishing Solution*, 2020, https://globalfinishing.com/2020/04/07/which-airflow-style-is-best-for-my-paint-booth.

59. Paint Spray Booths. *Yale School of Medicine*, 2021, https://medicine.yale.edu/intmed/prep/shop/spray.
60. T. Van Hoof, B. Blocken, G.J, and Van Heijst. On the Suitability of Steady RANS CFD for Forced Mixing Ventilation at Transitional Slot Reynolds Numbers. *Indoor Air 23,* 2013. 236–249.
61. P.V. Nielsen. Computational Fluid Dynamics and Room Air Movement. *Indoor Air 14 (Suppl. 7)*, 2014. 134–143.
62. Erhan Pulat and Hifzi Arda Ersan. Numerical Simulation of Turbulent Airflow in a Ventilated Room: Inlet Turbulence Parameters and Solution Multiplicity. *Energy and Buildings 93,* 2015. 227–235.
63. Andrea C. Landázuria,b,n, A. Eduardo Sáeza and T. Renée Anthony. Three-Dimensional Computational Fluid Dynamics Modeling of Particle Uptake by an Occupational Air Sampler Using Manually-Scaled and Adaptive Grids. *Journal of Aerosol Science 95*, 2016. 54–66.
64. Adisorn Khaokom and Jatuporn Thongsri. Feasibility Study for Installing Machine in Production Line to Avoid Particle Contamination Based on CFD Simulation. *IOP Conf. Ser.: Mater. Sci. Eng.,* 2017. 241.
65. Seo, I.H., Lee, I.B., Moon, O.K., Hong, S.W., Hwang, H.S., Bitog, J.P., Kwon, K.S., Ye, Z.Y. and Lee, J.W. Modelling of Internal Environmental Conditions in a Full-Scale Commercial Pig House Containing Animals. *Biosystems Engineering 111*, 2012. 91-106.
66. Hao Li, Li Rong and Guoqiang Zhang. Evaluation of Turbulence Models and Mesh Types for CFD Simulation of Air Distribution in a Mechanical Ventilated Pig House Containing Animal Models. *CIGR-AgEng conference*, 2016. 26–29.
67. Georgios K. Ntinas, Xiong Shen, Yu Wang and Guoqiang Zhan. Evaluation of CFD Turbulence Models for Simulating External Airflow Around Varied Building Roof With Wind Tunnel Experiment*, BUILD SIMUL,* 2019. DOI 10.1007/s12273-017-0369-9.
68. Noh K.C., Kim H. S., and Oh M. D. Study on Contamination Control in a Minienvironment Inside Clean Room for Yield Enhancement based on Particle Concentration Measurement and Airflow CFD Simulation. *Building and Environment*, 2010. 825-831.

69. Naphon, P., Ratchaneekorn, S. and Kurujareon, J. Heat Transfer and Flow Characteristics in the Hard Disk Drive Tester. *International Communications in Heat and Mass Transfer,* 2009. 820-826.
70. Liu, N., Zhang, Q. and Sundaravadivelu K. A Numerical Simulation of Particle Trajectory in Thin Hard Disk Drive. *IEEE Transactions on Magnetics*, 2013. 2590-2593.
71. Jatuporn Thongsri. Numerical Investigation of Airflow Inside an Environmental Chamber for HGA Mechanical Test and a Scheme for Improving the Flow. *International Journal of Advanced and Applied Sciences,* 2015. 51-56.
72. S.C. Hu and C.C. Chen. Locating the Very Early Smoke Detector Apparatus (VESDA) in Vertical Laminar Clean Rooms According to the Trajectories of Smoke Particles. *Building and Environment*, 2007. 366–371.
73. J.Tongsri and M.Pimsarn. Optimum Airflow to Reduce Particle Contamination Inside Welding Automation Machine of Hard Disk Drive Production Line. *International Journal of Precision Engineering and Manufacturing*, 2015. 509–515.
74. ANSYS FLUENT 12.0 User's Guide. *Convergence and Stability*.
75. Calati, Michele; Doretti, Luca; Gatto, Cristiano and Mancin, Simone. 3D CFD Simulation of a New Ventilated Roof. *International High Performance Buildings Conference. Paper 358*, 2021. https://docs.lib.purdue.edu/ihpbc/358.
76. Etheridge D.W. and Sandberg. Building Ventilation Theory and Measurement. *John Wiley & Sons*, 1996.
77. Yakhot, V. and S.A. Orszag. Renormalization Group Analysis of Turbulence. *Journal of Scientific Computing*, 1986.
78. Rouaud O and Havet M. Computation of The Airflow in a Pilot Scale Clean Room Using K–e Turbulence Models. *Int J Refrig.,* 2002. 351–61.
79. Gebremedhin K.G. and Wu B.X. Characterization of Flow Field in a Ventilated Space and Simulation of Heat Exchange Between Cows and Their Environment. *J Therm Biol.,* 2003. 301–19
80. Yusuf Cihat Aydin and Parham A. Mirzaei. Wind-Driven Ventilation Improvement With Plan Typology Alteration: A CFD Case Study of Traditional Turkish Architecture. *BUILD SIMUL.,* 2017. 239–254. DOI 10.1007/s12273-016-0321-4

81. Kuznik, F., Rusauen, G. and Brau J. Experimental and Numerical Study of a Full Scale Ventilated Enclosure: Comparison of Four Two Equations Closure Turbulence Models. *Build. Environ.,* 2007. 1043-1053.
82. Chao and Wan. A Study of the Dispersion of Expiratory Aerosols in Unidirectional Downward and Ceiling-Return Type Airflows using a Multiphase Approach. *Indoor Air,* 2016. 296–312.
83. Gao N. P. and Niu, J. L. Modelling Particle Dispersion and Deposition in Indoor Environments. *Atmos. Environ.,* 2007. 3862–3876.
84. Sasan Sadrizadeh, Alireza Afshari , Taghi Karimipanah, Ulf Håkansson and Peter V. Nielsen. Numerical Simulation of the Impact of Surgeon Posture on Airborne Particle Distribution in a Turbulent Mixing Operating Theatre. *Building and Environment*, 2016. DOI: 10.1016/j.buildenv.2016.10.005
85. Yu Zhou, Yelin Deng, Peng Wu and Shi-Jie Cao. The Effects of Ventilation and Floor Heating Systems on the Dispersion and Deposition of Fine Particles in an Enclosed Environment. *Building and Environment*, 2017. 192-205
86. Z. Zhang and Q. Chen. Comparison of the Eulerian and Lagrangian Methods for Predicting Particle Transport in Enclosed Spaces. *Atmos. Environ*.,2007. 5236-524
87. CFD FLUENT. *Chapter 19: Discrete Phase Models*. 2001.
88. Ventilation for Acceptable Indoor Air Quality. ANSI/ASHRAE Standard 62.1-2019
89. Occupational Safety and Health Administration (OSHA), Standard 29 CFR 1910.107.1997.
90. Zhang Z., Zhai Z.Q., Zhang W. and Chen Q. Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part 2 - Comparison With Experimental Data From Literature. *HVAC&R Research,* 2007. 871–86.
91. Puangburee Lamai, Busayaporn, Wutthikrai, Kaewbumrung, Mongkol and Thongsri Jatuporn. Evaluation and Improvement of Ventilation System Inside Low-Cost Automation Line to Reduce Particle Contamination, 2020. 10.37936/ecti-eec.2020181.210333.

92. Yi Wang, Mengfan Quan, Yu Zhou, Yingxue Cao, Chunbo Xie and Limei Li. Experimental Study on the Flow Field and Economic Characteristics of Parallel Push-Pull Ventilation System. *Energy and Built Environment, Volume 1, Issue 4*, 2020. 393-403, https://doi.org/10.1016/j.enbenv.2020.03.006.
93. Cao, Zhixiang Wang, Yi Wang and Meng. A Comparison of Concentrated Contaminant Removal in Enclosure by Using Mixing Ventilation and Vortex Ventilation, 2018.
94. Cao, Zhixiang Zhang, Chen Zhai, Chao Wang, Yi Wang, Meng Zhao, Tongtong Lv, Wenchao Huang and Yanqiu. Evaluation of a Novel Curved Vortex Exhaust System for Pollutant Removal. *Building and Environment*. 2021.
95. Wang, Yi Zhai, Chao Zhao, Tongtong Cao and Zhixiang. Numerical Study on Pollutant Removal Performance of Vortex Ventilation With Different Pollution Source Locations. *Building Simulation*, 2020.
96. Paulius Skerys. Review and Evaluation of Different Paint Booths Depending on Their Air Flow. *JAUNŲJŲ MOKSLININKŲ DARBAI. Nr. 48 (2),* 2018. ISSN 1648-8776.
97. Li, Jia Uttarwar, Rohan Huang and Yinlun. CFD-Based Modeling and Design for Energy-Efficient VOC Emission Reduction in Surface Coating Systems. *Clean Technologies and Environmental Policy*, 2013.
98. Christian Horton, Terry Ratliff, Matt Seasor and Lauren Wiegand. Paint System Redesign. *Design Engineering Technolog*y, 2020.
99. IDS Blast Paint , Air Ventilation System, 2019.
100. Daniel Axelsson. Design and Development of a Spray Booth, *Linkoping University*, 2007.
101. Mohd. Robi. Effectiveness of Local Exhaust Ventilation Systems in Reducing Personal Exposure. *Journal of Applied Sciences 14 (13): 1365 - 137*1 , 2014.
102. Wang, Cong & Sadrizadeh Sasan. Numerical Assessment of a Novel Ventilation Strategy for Operating Rooms in Comparison with Turbulent Mixing and Laminar Air Flow, 2018.
103. Parastoo Sadeghian . Numerical Investigation on the Impact of Different Supply Air Terminal Devices on the Performance of the Newly Combined Ventilation and Heating System, *IOP Conf. Ser.: Mater. Sci. Eng,* 2019.

104. Alsved, Malin Civilis, Anette Ekolind, Peter Tammelin, Ann Andersson, Annette Jakobsson, Jonas Svensson, Tobias Ramstorp, Matts Sadrizadeh, Sasan Larsson, Per-Anders Bohgard, Mats Santl-Temkiv and Löndahl Jakob. Temperature Controlled Airflow Ventilation in Operating Rooms Compared With Laminar Airflow and Turbulent Mixed Airflow. *Journal of Hospital Infection*, 2017.

105. P V Nielsen. A Benchmark Test for Room Air Distribution: The Backward Facing Step Flow. *IOP Conf. Ser.: Mater. Sci. Eng*., 2019.

106. P V Nielsen. The Status of Computational Fluid Dynamics. *CLIMA*, 2016.

107. Yi, Qianying Janke, David Thormann, Lars Zhang, Guoqiang Amon, Barbara Hempel, Sabrina Nosek, Štěpán Hartung, Eberhard Amon and Thomas. Airflow Characteristics Downwind a Naturally Ventilated Pig Building with a Roofed Outdoor Exercise Yard and Implications on Pollutant Distribution. *Applied Sciences*, 2020.

108. Franke, Jörg Baklanov and Alexander. Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment: COST Action 732 Quality Assurance and Improvement of Microscale Meteorological Models, 2007.

109. Qianying Yi, Marcel König, David Janke, Sabrina Hempel, Guoqiang Zhang, Barbara Amon and Thomas Amon. Wind Tunnel Investigations of Sidewall Opening Effects on Indoor Airflows of a Cross-Ventilated Dairy Building. *Energy and Buildings, Volume 175*, 2018. 163-172,

110. Yanqiu Huang, Yi Wang, Li Liu, Peter V. Nielsen, Rasmus L. Jensen and Fanliao Yan. Reduced-Scale Experimental Investigation on Ventilation Performance of a Local Exhaust Hood in an Industrial Plant, *Building and Environment, Volume 85,* 2015. 94-103, https://doi.org/10.1016/j.buildenv.2014.11.038.

111. I.B. Celik, U. Ghia, P.J. Roache, C.J. Freitas, H. Coleman and P.E. Raad, Procedure for Estimation and Reporting of Uncertainty Due to Discretization in CFD Applications, *J. Fluid Eng. 130*, 2008.

LIST OF PUBLICATIONS

1. **Yosri, M. H.,** Muhamad, P. & Mohd Yatim, N. (2021). Evaluation of Air Flow Pattern for Conceptual Design of Automotive Painting Line Using Computational Fluid Dynamic (CFD) for Better Dust Particle Reduction. *CFD Letters 11, no. 2,* p. 42-49. **(Q3, IF:0.39)**

2. **Yosri, M. H.,** Muhamad, P. & Mohd Yatim, N. (2019). Application of Air Ionizer to Remove Electrostatic Discharge (ESD) Dust for Plastics Material in Automotive Painting Process. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 59, Issue 1 (2019),* p. 29-37. **(Q3, IF:0.28)**

3. **Yosri, M. H.,** Muhamad, P., Kee Quen, L., & Mohd Yatim, N. (2020). Analysis of Air Flow Around the Painting Line for Dust Reduction: An Experimental and Numerical Study. *CFD Letters*, *12*(9), (2020), 36–50. https://doi.org/10.37934/cfdl.12.9.3650. **(Q3, IF:0.39)**