GEOMETRY OPTIMIZATION DRY ICE BLASTING NOZZLE FOR THE NOISE REDUCTION USING EXPERIMENTAL VALIDATION

MOHAMAD NUR HIDAYAT BIN MAT

A thesis submitted in
fulfillment of the requirement for the award of the
Doctor of Philosophy.

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2019

In the name of God, The Most Gracious, The Most Merciful.

Specially for my beloved mother and father

ACKNOWLEDGEMENT

The greatest helps is from Allah s.w.t, The almighty who paves the way and the minds, making the writing of this thesis a success.

A very special thank-you and appreciation are for my supervisor; Associate Professor Dr. Norzelawati Binti Asmuin and co-supervisor; Ir. Dr. Nor Halim Bin Hasan for their limitless patience, optimism, guidance, invaluable advice, and assistance throughout the writing of this thesis.

To the Ministry of Education of Malaysia and the Universiti Tun Hussein Onn Malaysia, thank you so much for the sponsorship and the award of Fundamental Research Grant Scheme (FRGS) K080 and Geran Penyelidikan Pascasiswazah (GPPS) U966 for this research. Alhamdulillah, this study had been published in several international journals.

It would be complete without thanking fellow technicians, postgraduate friends, and colleagues. Their assistaance, advice, ideas, and of course technical support are very much needed, thus, this thesis successfully completed.

My beloved father and mother; Mat Bin Nyan and Fahimah Binti Mohd Lazim have been a great support with their endless prayers. They will always be in my prayers too and I will be forever in their debts.

ABSTRACT

Dry ice blasting provides many advantages to surface cleaning in which the blasting medium sublimate during the surface impact will not leave a secondary contamination. However, on the negative side of dry ice blasting (DIB), it produces a high noise exposure. The noise exposure during a high blasting pressure may reach up to 130 dB which is considered a harmful noise level (standard 90 dB for eight working hours per day). At present, safety measures are taken according to administrative control that encapsulates the whole system with sound insulation. This limitation has made this research work a significant contribution to dry ice blasting industry. The main objectives of this project are to examine the dry ice blasting's flow characteristic on the influence of noise emission and to establish optimum parameters affecting the acoustic noise emission. The experimental validation on the effect of impact force and noise emission for optimum nozzle design is investigated. ANSYS fluent version 18.2 is employed in this study to simulate the fluid flow and acoustic noise in the nozzle. Six (6) different nozzle geometries are analyzed namely divergent length, convergent diameter, expansion ratio, gas inlet diameter, length ratio, and particle inlet angle. The optimum nozzle geometry is fabricated and validated throughout the experimental study on the effect of the impact force and sound pressure level for different pressures. The result shows that the optimum DIB nozzle geometry that satisfy the research objectives for gas inlet length, convergent diameter, particle inlet angle, divergent length, convergent length, gas inlet diameter, expansion ratio are 36 mm, 35 mm, 50°, 230 mm, 45mm, 6 mm and 1.00 respectively. This research is expected to provide a novelty design of dib nozzle geometry that able to protect the society from the hazardous working environment by engineering control.

ABSTRAK

Pembersihan menggunakan ais kering memberikan banyak kelebihan dan bersifat pro-alam sekitar yang mana bahan ais kering tersebut akan mengalami proses pemejalwapan ketika pembersihan, tanpa mengeluarkan kotoran sekunder. Walau bagaimanapun, kelemahan utama semburan menggunakan ais kering ini ialah bunyi bising yang terlalu kuat. Semburan dengan tekanan yang tinggi akan memberi kesan buruk kepada manusia jika bunyi bising tersebut mencapai sehingga 130 dB (kebiasaan 90 dB untuk 8 jam bekerja). Keselamatan yang sedia ada hanya bergantung kepada kawalan pentadbiran dengan mengasingkan bunyi bising. Kekurangan tersebut menjadikan kajian ini penting yang akan memberi sumbangan kepada industri ini. Objektif utama projek ini ialah untuk mengenalpasti karakter aliran ais kering terhadap bunyi bising dan mewujudkan parameter penting yang memberi kesan terhadap bunyi bising dan juga mengesahkan kajian dengan menjalankan ujikaji terhadap daya hentaman dan tahap bunyi bising. Analisa kajian ini menggunakan perisian "CFD, ANSYS Fluent" untuk membuat simulasi aliran cecair dan mengetahui tahap bunyi bising yang dihasilkan daripada nozel. Enam (6) geometri nozel dianalisa iaitu panjang pencapahan, diameter pertemuan, nisbah pengembangan, diameter kawasan masuk gas, nisbah panjang dan sudut masuk zarah digunakan untuk menyiasat kesan terhadap bunyi bising. Bentuk nozel yang optimum telah direkacipta untuk mengesahkan kajian simulasi terhadap kesan daya hentaman dan tahap bunyi bising pada tekanan yang berbeza-beza. Keputusan kajian menunjukkan bahawa bentuk nozel yang optimum yang dapat memenuhi objektif kajian untuk panjang gas masuk, diameter pertemuan, sudut masuk zarah, panjang pencapahan, panjang pertemuan, diameter kawasan masuk gas and nisbah pengembangan ialah 36 mm, 35 mm, 50°, 230 mm, 45mm, 6 mm and 1.00. Kajian ini dijangka akan memberi impak positif kepada masyarakat apabila bunyi bising di tempat kerja dikurangkan melalui kawalan kejuteraan.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

CO_2	-	Carbon Dioxide
CFD	-	Computational Fluid Dynamic
CATIA	-	Computer Aided Three Dimensional Interactive Application
CFX	-	Central Florida Expressway
DIB	-	Dry Ice Blasting
D_{co}	-	Convergent Diameter
Dig	-	Inlet Gas Diameter
ES	-	Evolutionary Strategies
FDE	-	Frequency Domain Experiments
GA	-	Genetic Algorithms
ISO	-	International Organization for Standardization
IEC	-	International Electrotechnical Commission
LR	-	Likelihood Ratio Estimators
L_{di}	-	Divergent Length
L_{ig}	-	Inlet Gas Length
NIOSH	-	National Institute for Occupational Safety and Health
OSHA	-	Occupational Safety and Health Administration
PELS	-	Permissible Exposure Limits
PA	-	Perturbation Analysis
RSM	-	Response Surface Methodology
SPL	-	Sound Pressure Level
SA	-	Simulated Annealing
TWA	-	Time Weighted Average
TS	-	Tabu Search
UTHM	-	Universiti Tun Hussein Onn Malaysia

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General

Chapter 1 explores a research background of noise emission in dry ice blasting industry. It starts with the mechanism of dry ice blasting surface cleaning that consists of three (3) mechanisms which are sublimation, mechanical and thermal effect. These active mechanisms represent the processes for surface removal. This section also outlines the effect of noise emission, the factor affecting the noise level, and a current method to control noise exposure. The main issues on noise emission from the dry ice blasting process are also discussed in problem statements, objectives and scope of the study, limitations, and significance of the study subtopics.

1.2 Background

Dry ice blasting is in fact a carbon dioxide (CO_2) cleaning process in its solid form. During the process, dry ice pallets are accelerated by pressurized air stream and the nozzle is directed toward contaminated surfaces. The process of dry ice blasting is can be according to three combined mechanisms; thermal, mechanical and sublimation effect. The left picture shows the thermal mechanism of dry ice blasting, the middle picture shows the mechanical effect when dry ice pellets hit the surface, and the right picture shows the effect of sublimation process where the dry ice pellets expand their volume and crack the contaminant on the surface. See Figure 1.1 for the three (3) active mechanisms of dry ice blasting.

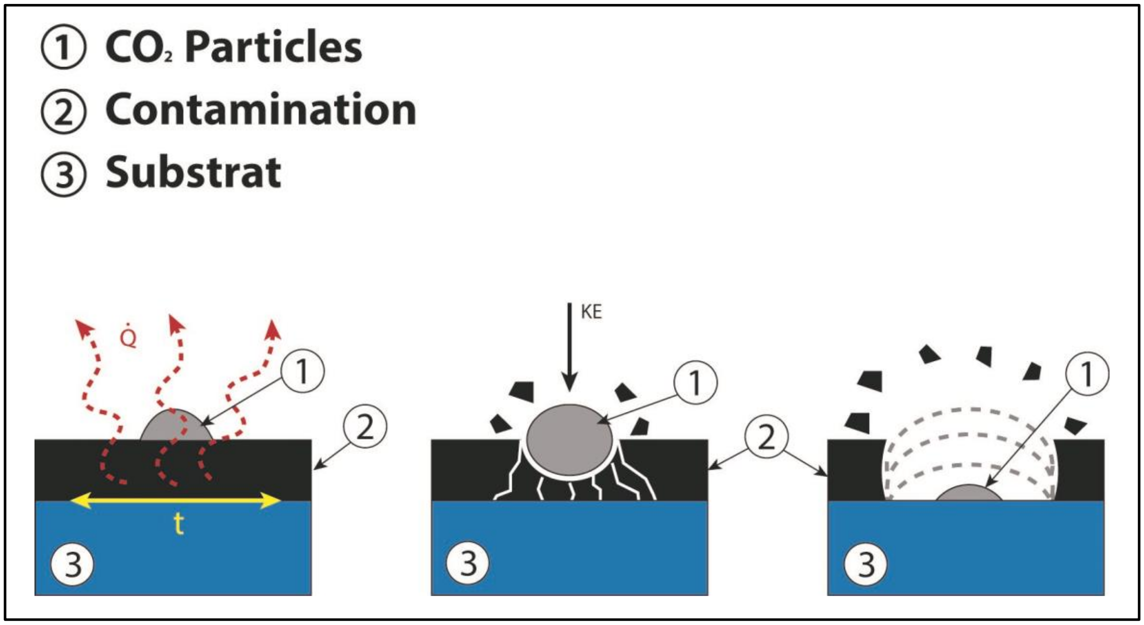

Figure 1.1: Active mechanism of dry ice blasting (Uhlmann & El Mernissi, 2008)

The thermal effect happens because of the differences in thermal coefficient happening between surface contaminant and substrate which cause the embrittle of contaminant. A supersonic speeds hitting on the surface by blasting medium creates a kinetic energy which eventually creates a mechanical effect.

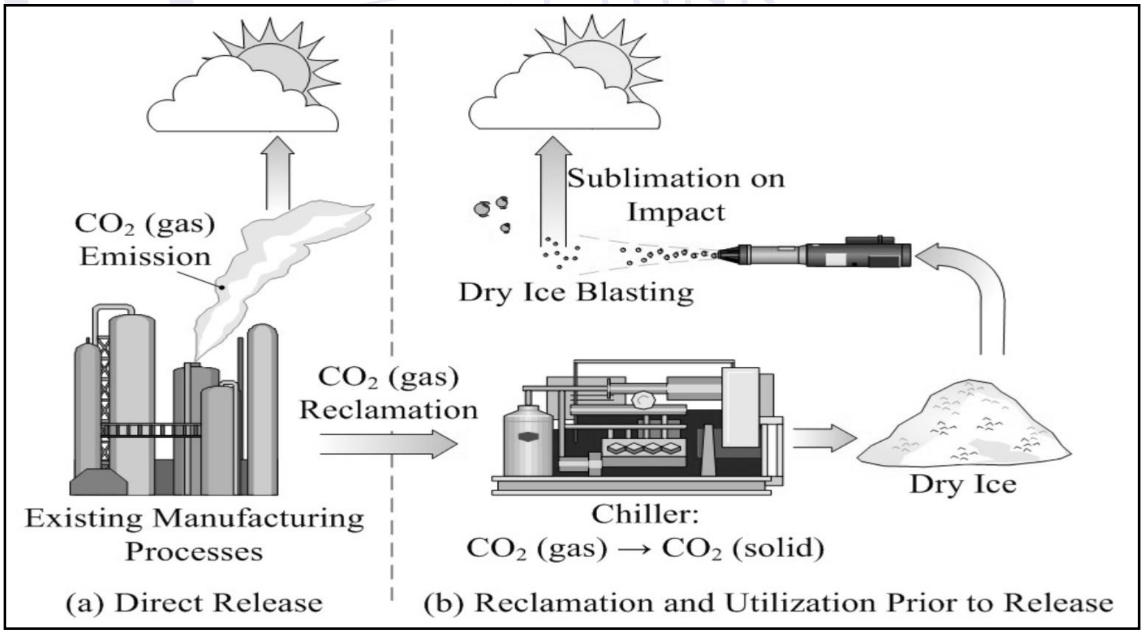

Figure 1.2: Mood of CO_2 released into the atmosphere (Millman & Giancaspro, 2012)

Despite of advantages and zero hazardous to the environment, dry ice blasting for cleaning contaminated surfaces as can be seen in Figure 1.2 is reported to produce high noise exposures up to 130 dBA that is considered as harmful for humans (Uhlmann & El Mernissi, 2008). To make things worse, the noise could occur in low-frequency areas that are undetectabble by humans' ears (Uhlmann & Hollan, 2015). The level of noise emission generated by dry ice blasting is influenced by the nozzle geometry, type of nozzle, shape and surface texture of the surface being blast, the amount of dampness presented in the compacted air supply, the moistness of the day, stand-off distance and location at which the reading is taken. Set surfaces raise noise levels because of stream screech. High humidity raises noise levels because of excellent sound transmission over the dry air, and furthermore due to the addition of dampness to the ready air supply, noise levels rise because the dampness is solidified into precious ice stones and removed with the impacted stream (Uhlmann & Hollan, 2015). Current safety measures rely heavily on organizational measures which do not segregate the levels of noise but instead encapsulating the entire system by sound insulation. The measure is also on personal discretion using safety hearing protection. Noise or any annoying sound is the most well-known word pertaining to dangers in any working environment. 30 million labourers in the United States, gauged by National Institute for Occupational Safety and Health (NIOSH) are exposed to perilous noise. Long exposures to abnormal levels and amounts of noise may cause loss of hearing, promote pressures physically and mentally, diminish efficiency, interfere a communication, and lead to mischances and wounds due to lack of awareness on cautioning signals (Occupational Safety and Health Administration, 2019). This project presented possible technical safety measures to reduce noise emission from dry ice blasting nozzles. Analysis using CFD gained the first insight into the noise emission's flow characteristic particularly in the blasting nozzle design area. Nozzle geometry concerning the turbulent intensity model was presented. Appropriate design measures and critical parameters influence noise reduction were also investigated in this study.

1.3 Problem Statement

Dry ice technology has been used widely in many industries ranging from cleaning electrical component to big blasting jobs due to its versatility. However, high noise emmision coming from a nozle during dry ice blasting process would be its primary disadvantage. The worst case scenarion, at a high blasting pressure, a harmful noise level of up to 130 dBA might be experienced (Uhlmann & El Mernissi, 2008). The situation significantly impairs a human being when the noise emission occurs in the low-frequency area that human ears cannot detect the frequency. Current safety measures rely heavily on organizational measures which do not segregate the levels of noise but instead encapsulating the entire system by sound insulation. The measure is also on workers' own discretion using safety hearing protection. Although there have been many researchers conducted the study on the parameter optimization on the performance of dry ice blasting technology, but they took for granted the effects of noise generation from dry ice blasting nozzle geometry. This limitation has made this research work a significant contribution to dry ice blasting industry as noise emission criticlly needs to be reduced. Therefore, the engineering approach to safety measures is implemented in this research.

1.4 Research Objectives

This study was to fulfill the below stated objectives:

1. To obtain the flow characteristic in terms of particle velocity magnitude and acoustic power level for different nozzle geometries.
2. To investigate optimum parameters that affect both performances of acoustic noise emission and dry ice pellets velocity.
3. To validate the simulation result with experimental work for an optimum nozzle design based on the sound pressure level and impact force.

This project was expected to provide industry players or users of dry ice blasting with a technology that increases the performance and provide information on the economic feasibility and environmental impact and health effect with respect to it.

1.5 Research Questions

1. What is the flow characteristic of dry ice blasting that concerning noise level
2. Does dry ice blasting nozzle geometry influence the acoustic noise level?
3. What is the optimum parameter of nozzle geometry that affects performance dry ice blasting in terms of noise and velocity magnitude?
4. Does experiment show good agreement with the simulation result?

1.6 The Scope of Study and Limitation

This current study ought to study the improvement of existing dry ice blasting nozzle design in terms of particle velocity magnitude and acoustic power level. The type of nozzle selection a double hose convergent-divergent nozzle geometry. The simulation was meant to investigate the flow characteristic as the experiment was difficult to be performed inside the nozzle geometry. Six (6) different nozzle parameters were simulated namely expansion ratio, gas inlet diameter, divergent length, length ratio, convergent diameter, and inlet angle to determine the flow characteristic pertaining acoustic noise emission. These parameters were simulated using a constant pressure of 6 bar and 1.2 kg/s as boundary conditions. A constant pressure of 6 bar was used because the previous researcher was conducted the study done by Dong et. al in 2013 using 6 bar pressure throughout their simulation process. Thus, their simulation result can be comparable with the optimum design nozzle geometry. On the other hand, for the experimental part, the compressed air pressure was set as 2 bar, 3 bar, 4 bar, 5 bar, and 6 bar. These sets of values were referred from previous researcher study done Spur et. al in 1999. In addition, validation study comparing simulation with experimental result can be done by focusing on only 6 bar pressure. Apart from that, this study did not consider the design optimization on the compressor and the equipment of dry ice blasting, also sublimation process of dry ice blasting after the impact. The method of selection for the optimum parameter is based on the Response Surface Method for finding the optimization result. On the other hand, the duration of measuring impact force and sound pressure level was ten (10) seconds on every experiment. The working distance between the load cell sensor to the aperture of

REFERENCES

Abd-Elhady, M. S., Rindt, C. C. M., & Van Steenhoven, A. A. (2009). Optimization of flow direction to minimize particulate fouling of heat exchangers. *Heat Transfer Engineering*, *30*(10-11), 895-902.

Ajoko, T. J. & Tuaweri, T. J. (2017). Design optimisation of convergent-divergent aircraft nozzle. *International Journal of Scientific & Engineering Research*, *8*(1), 9-16.

Alam, M. M. A., Setoguchi, T., Matsuo, S., & Kim, H. D. (2016). Nozzle geometry variations on the discharge coefficient. *Propulsion and Power Research*, *5*(1), 22-33.

Alkhimov, A. P., Kosarev, V. F., & Klinkov, S. V. (2001). The features of cold spray nozzle design. *Journal of Thermal Spray Technology*, *10*(2), pp. 375–381.

Alkhimov, A., Papyrin, A., Dosarev, V., Nesterovich, N., & Shuspanov, M. (1994). *Technique for Applying a Coating*. U.S. Patent 5, 86, 51.

Anderson, I. E., Figliola, R. S., & Molnar, H. M. (1992). *Atomizing Nozzle and Process.* U. S. Patent 5, 125, 574.

Andradottir, S. (1990). A New Algorithm for Stochastic Optimization. *Proceedings of the 1990 Winter Simulation Conference*. New Orlean, USA. IEEE. pp. 32–38.

Azadivar, F. (1992). A Tutorial on Simulation . *Proceedings of the 1992 Winter*. Virginia, USA. ACM Digital Library. pp. 198-204.

Barnard, A. R. (2014). Quantifying acoustic sources through sound power measurements. *Journal of Sound & Vibration*, 56(3), pp. 8-11.

Belbaki, A. & Mebdoua-lahmar, Y. (2017). *Influence of Diverging Section Length on the Supersonic Jet Delivered from Micro-Nozzle: Application to Cold Spray Coating Process.* Springer International Publishing.

Bruns, R. E., Scarminio, I. S., & de Barros, N. B. (2006). *Statistical Design: Chemometrics* (Vol. 25). Amsterdam: Elsevier.

Callender, B., Gutmark, E., & Martens, S. (2005). Far-field acoustic investigation into chevron nozzle. *AIAA Journal*, *43*(1), pp. 87–95.

Chemica Logic Corporation. (1999). *Phase Diagram of CO_2.* Carlisle, MA: Chemicalogic Press. pp. 43-52.

Chen, F. L. & Siores, E. (2001). The effect of cutting jet variation on striation formation in abrasive water jet cutting. *International Journal of Machine Tools & Manufacture*, *41*, 1479-1486.

Chillara, N. (2005). *Abrasive Blasting Process Optimization: Enhancing Productivity, and Reducing Consumption and Solid/ Hazardous Wastes.* Master Thesis, University of New Orleans.

Chung, T. J. (2002). *Computational Fluid Dynamics.* Cambridge University Press.

Cold Jet LLC. (2004). *The Fundamentals of Dry Ice Blast Cleaning.* Retrieved from http://old.coldjet.com/tech-fundamentals.html.

Coles, W. D., Mihaloew, J. A., & Callaghan, E. E. (1958). Turbojet engine noise reduction with mixing nozzle-ejector combinations. *National Advisory Committee for Aeronautics*.

Crunteanu, D. & Cojan, P. C. (2013). Acoustic characteristics of the flow over different shapes of nozzle chevrons. *Incas Bulletin*, *5*(3), pp. 53-59.

De Souza, P. S. & Talukdar, S. N. (1991). Genetic Algorithms in Asynchronous Teams. *Proceedings of the 4th International Conference on Genetic Algorithms*. pp. 375–381.

Department of Occupational Safety and Health. (2019). "*Peraturan - Peraturan Keselamatan dan Kesihatan Pekerjaan (Pendedahan Bising) 2019"*. Retrieved from http://www.dosh.gov.my/index.php/en/peraturan/peraturan-di-bawah-akta-keselamatan-dan-kesihatan-pekerjaan-1994-akta-514/3173-00-peraturan-peraturan-keselamatan-dan-kesihatan-pekerjaan-pendedahan-bising-2019

Dippold, V. (2008). CFD Analyses and Jet-Noise Predictions of Chevron Nozzles with Vortex Stabilization. In *46th AIAA Aerospace Sciences Meeting and Exhibit*. Ohio, USA. pp. 37.

Dong, S., Song, B., Liao, H., & Coddet, C. (2013). Effect of dry-ice blasting on the deposition behavior of molybdenum particles onto aluminum and stainless steel substrates using plasma spraying: From single splat to coating. *Surface and Coatings Technology*, *268*(3), pp. 46-51.

Dykhuizen, R. C. & Smith, M. F. (1998). Gas dynamic principles of cold spray. *Journal of Thermal Spray Technology*, *7*(2), pp. 205-212.

Elbing, F., Anagreh, N., Dorn, L., & Uhlman, E. (2003). Dry ice blasting as pretreatment of aluminum surfaces to improve the adhesive strength of aluminum bonding joints. *International Journal of Adhesion & Adhesives, 23*, pp. 69 – 79.

Foster, R. W. (2005).*Chapter 2.9.5: Carbon Dioxide (Dry-Ice) Blasting*. Good Painting Practice: SSPC Painting Manual Volume 1, 4th ed. Loveland, OH: Cold Jet Inc.

Ghassemieh, E. Versteeg, H. K., & Acar, M. (2006). The effect of nozzle geometry on the flow characteristics of small water jets. *Proceedings of the IMechE Part C: Journal of Mechanical Engineering Science*, *220*(12), pp. 1739-1753.

Gilli, M. & Winker, P. (2011). *Heuristic Optimization Methods in Econometrics.* Handbook of Computational Econometrics. Wiley, pp. 81 -119.

Gilmore, D. L., Dykhuizen, R. C., Neiser, R.A., Roemer, T.J., & Smith, M. F.(1999). Particle velocity and deposition efficiency in the cold spray process. *Journal of Thermal Spray Technology*, *8*(4), pp.576–582.

Gilmour, S. G. (2006). Response surface designs for experiments in bioprocessing. *Biometrics*, *62*(2), pp. 323-331.

Glynn, P. W. (1989). Likelihood Ratio Derivative Estimators for Stochastic Systems. *Proceedings of the Winter Simulation Conference*. pp. 374-380.

Goldsman, L. & Nelson, B. L. (1990). Batch-size Effects on Simulation Optimization using Multiple Comparisons with the Best. In *1990 Winter Simulation Conference Proceedings*. IEEE. pp. 288-293.

Goswami, M., Kumar, S., & Munshi, P. (2015). Correlation between numerical simulation and limited data experimental technique for the estimation of nitrogen flowing in the LMMHD loop. *Journal of Flow Measurement Instrumentation*, *23*(2), pp. 8–14.

Grujicic, M., Saylor, J. R., Beasley, D. E., DeRosset, W. S., & Helfritch, D. (2003). Computational analysis of the interfacial bonding between feed-powder particles and the substrate in the cold-gas dynamic-spray process. *Applied Surface Science*, *219*(3-4), pp. 211-227.

Grujicic, M., Tong, C., DeRosset, W. S., & Helfritch, D. (2003). Flow analysis and nozzle-shape optimization for the cold-gas dynamic-spray process. *Journal of Engineering Manufacture*, *217*(11), 1603-1613.

Grujicic, M., Zhao, C., Tong, C., DeRosset, W. S., & Helfritch, D. (2004). Analysis of the impact velocity of powder particles in the cold-gas dynamic-spray process. *Materials Science and Engineering*, pp. 222–230. doi:10.1016/j.msea.2003.10.312

Gupta, S. S. & Panchapakesan, S. (1979). *Multiple Decision Procedures: Theory and Methodology of Selecting and Ranking Populations.* John Wiley.

Jiao, Z., Li, D., Asgarian, A., Chatterjee, S., Girard, B., Paserin, V., Lavallee, F., & Chattopadhyay, K. (2017). Influence of apex angle and nozzle design on energy and momentum transfer during the water atomization process. *Journal of Powder Metal Science*, *43*(3), pp. 22-34.

Jodoin, B. (2001). Cold spray nozzle mach number limitation. *Journal of Thermal Spray Technology*, *11*(4), 496-507.

Jodoin, B., Ajdelsztajn, L., Sansoucy, E., Zúñiga, A., Richer, P., & Lavernia, E. J. (2006). Effect of particle size, morphology, and hardness on cold gas dynamic sprayed aluminum alloy coatings. *Surface and Coatings Technology*, *201*(6), pp. 3422-3429.

Karpuschewski, B., Emmer, T., Schmidt, K., & Petzel, M. (2013). Cryogenic wet-ice blasting: Process conditions and possibilities. *CIRP Annals - Manufacturing Technology*.

Kuo, C. W., Veltin, J., & McLaughlin, D. K. (2012). Effects of jet noise source distribution on acoustic far-field measurements. *International Journal of Aeroacoustics*, *11*(7-8), pp. 885-915.

Kuo, C. W., Veltin, J., & McLaughlin, D. K. (2014). Acoustic measurements of models of military style supersonic nozzle jets. *Chinese Journal of Aeronautics*, *27*(1), pp. 23-33.

Kuron, M. (2015). *3 Criteria for Assessing CFD Convergence*. Retrieved from https://www.engineering.com/DesignSoftware/DesignSoftwareArticles/ArticleID/9296/3-Criteria-for-Assessing-CFD-Convergence.aspx

Kusuma, H. S., Sudrajar, R. G. M., Susanto, D. F., Gala, S., & Mahfud, M. (2015). Response Surface Methodology (RSM) Modelling of Microwave-Assissted Extraction of Natural Dye from Swietenia Mahagony: A Comparation between Box-Behnken and Central Composite Design Method. *International Conference* *of Chemical and Material Engineering (ICCME) 2015: Green Technology for Sustainable Chemical Products and Processes.* Semarang, Indonesia.

Lehnig. (1997). Nozzle for Cryogenic Particle Blast System. U. S. Patent 5, 660, 580.

Li, C. J., Wang, H. T., Zhang, Q., Yang, G. J., Li, W. Y., & Liao, H. L. (2010). Influence of spray materials and their surface oxidation on the critical velocity in cold spraying. *Journal of Thermal Spray Technology*, *19*(1-2), pp. 95-101.

Li, W., Liao, H., Douchy, G., & Coddet, C. (2007). Optimal design of a cold spray nozzle by numerical analysis of particle velocity and experimental validation with 316L stainless steel powder. *Materials and Design*, *28*, 2129-2137.

Li, W., Liao, H., Li, C., Li, G., Coddet, C., & Wang, X. (2006). On high velocity impact of micro-sized metallic particles in cold spraying. *Journal of Appllied Surface Science*, *232*, 2852-2862.

Liu, Y. (2012). *Analysis of Production Process of Fine Dry Ice Particles and Application for Surface Cleaning*. PhD Thesis. Kyoto University.

Liu, Y., Calvert, G., Hare, C., Ghadiri, M., & Matsusaka, S. (2012). Size measurement of dry ice particles produced from liquid carbon dioxide. *Journal of Aerosol Science*, *48*, pp. 1-9.

Liu, Y., Maruyama, H., & Matsusaka, S. (2011). Effect of particle impact on surface cleaning using dry ice jet. *Aerosol Science and Technology, 45*(12), 1519-1527.

Masa, V. & Kuba, P. (2016). Effi cient use of compresse d air for dry ice blasting. *Journal of Cleaner Production, 11*, pp. 76-84.

Mat, M. N. H. & Asmuin, N. (2018). Optimum design of nozzle geometry of dry ice blasting using CFD for the reduction of noise emission. *International Journal of Integrated Engineering, 10*(5), 130-135.

Mat, M. N. H., Asmuin, N. Z., Hasan, N. H., Zakaria, H., Rahman, M. F. A., Khairulfuaad, R., & Jabbar, B. A. (2019). Optimizing dry ice blasting nozzle divergent length using CFD for noise reduction. *CFD Letters, 11*(6), 18-26.

Millman, L. R. & Giancaspro, J. W. (2012). Environmental evaluation of abrasive blasting with sand, water, and dry ice. *International Journal of Architecture, Engineering, and Construction*, *1*(3), pp. 174-182.

Morris, P. J., Du, Y., & Kara, K. (2010). Jet noise simulations for realistic jet nozzle geometries. *Procedia Engineering*, *6*, pp. 28–37.

Morris, P. J., McLaughlin, D. K., & Kuo, C. W. (2013). Noise reduction in supersonic jets by nozzle fluidic inserts. *Journal of Sound and Vibration*, *332*(17), pp. 3992-4003.

Neiser, R. A., Brockmann, J. E., O'Hern, T. J., Smith, M. F., Dykhuizen, R., Roemer, T. J. & Teets, R. E. (1995). Wire melting and droplet atomization in a high velocity oxy-fuel jet. *Proceedings of the 1995 National Thermal Spray Conference* (NTSC95). Houston, TX.

Neiser, R., Brockman, J., Ohern, T., Smith, M., Dykhuizen, R., Roemer, T., & Teets, R. (1995). Wire melting and droplet atomization in a high-velocity oxy-fuel jet. *Journal of Thermal Spray Science and Technology*, *42*(3), pp. 57–68.

Occupational Safety and Health Administration. (2019). *Occupational Noise Exposure*. United States Department of Labor, Occupational Safety and Health Administration, Washington, D.C. Retrieved from https://www.osha.gov/SLTC/noisehearingconservation/healtheffects.html.

Ozen, M. (2014). *Mesh Metric Spectrum Quality*. California: Ozen Engineering, *Meshing Workshop*.

Peters, R. J., Smith, B. J., & Hollins, M. (2011). *Acoustics and Noise Control*. 3rd ed. Routledge.

Powell, W. B. (2013). *Optimal Learning*. Retrieved on October 23, 2018, from http://www.castlelab.princeton.edu/cso.htm.

Raj, A. S., Joseph, J., Varghese, J. J., Joseph, J. T., & Subnas, L. C. (2014). Acoustics study of a supersonic C-D nozzle. *International Journal of Engineering Research & Technology*, *30*(2), pp. 2063–2066

Ramji, V., Mukesh, R., & Hasan, I. (2016). Design and numerical simulation of convergent divergent nozzle. *Applied Mechanics and Materials, 852*, 617-624.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). *Global Sensitivity Analysis: The Primer*. England: John Wiley & Sons.

Schoeffler, M. (2017). *Arduino Tutorial: HX711 Load Cell Amplifier (Weight Sensor Module) + LCM1602 IIC V1 LCD*. Retrieved from http://www.mschoeffler.de/2017/12/04/arduino-tutorial-hx711-load-cell-amplifier-weight-sensor-module-lcm1602-iic-v1-lcd/

Seiner, J., Ukeiley, L., & Jansen, S. (2005). Aero-performance efficient noise reduction for the F404-400 engine. *AIAA Journal*, *37*(4), pp. 20-28.

Shahabuddin, P. (1995). Rare Event Simulation in Stochastic Models. *Proceedings of the 27th Conference on Winter simulation*. Arlington, Virginia, USA. pp. 178-185.

Shapiro, A. (1996). Simulation Based Optimization. *Proceedings of the 28th Conference on Winter simulation*. Coronado, California, USA. pp. 332-336.

Sherman, R., Grob, J., & Whitlock, W. (1991). Dry surface cleaning using CO2 snow. *Journal of Vacuum Science & Technology*, *9*(4), pp. 1970-1977.

Siemans PLM Software. (2000). *A Guide to Measuring Sound Power*. Granite Park One: Siemens.

Singh, R. P. & Batra, U. (2013). Effect of cold spraying parameters and their interaction an hydroxyapatite deposition. *Journal of Applied Fluid Mechanics*, *6*(4), pp. 555-561.

Soderback, M. (2009). *Determination of Sound Power Levels using Sound Intensity*. Vaasan Ammattikorkeakoulu University Of Applied Sciences: Master's Thesis.

Spur, G., Uhlmann, E., & Elbing, F. (1999). Dry-ice blasting for cleaning: Process, optimization and application. *Wear*, *233-235*, pp. 402-411.

Stevenson, A. N. J. & Hutchings, I. M. (1995). The influence of nozzle length on the divergence of the erodent particle stream in a gas-blast erosion rig. *Wear*, *189*, 66-69.

Stoltenhoff, T., Kreye, H., & Richter, H. J. (2002). An analysis of the cold spray process and its coatings . *Journal of Thermal Spray Technol*, pp. 542–550.

Suri, R. (1983). Infinitesimal Perturbation Analysis of Discrete Event Dynamic Systems: A General Theory. In *The 22nd IEEE Conference on Decision and Control*: IEEE. pp. 1030-1038.

Swaroopini, A. S., Kumar, M. G., & Kumar, T. N. (2015). Numerical simulation and optimization of high-performance supersonic nozzle at different conical angles. *International Journal of Research in Engineering and Technology*, *4*(9), pp. 268-273.

Tokarev, A. O. (1996). Structure of aluminum powder coatings prepared by cold gas dynamic spraying. *Metal Science and Heat Treatment*, *38*(3), pp. 136-139.

Uhlmann, E. & El Mernissi, A. (2008). Pre-treatment by dry ice blasting for adhesive bonding. *Production Engineering*, *2*(2), pp. 133-138.

Uhlmann, E. & Hollan, R. (2015). Blasting with solid carbon dioxide: Investigation of thermal and mechanical removal mechanisms. *Procedia CIRP*, *26*, pp. 544-547.

Uhlmann, E., El Mernissi, A., & Hollan, R. (2018, May 29). Noise Reduction of Dry Ice Blasting. *Metal Finishing News*. Retrieved from http://www.mfn.li/article/?id=535

Uzun, A. & Hussaini, M. Y. (2009). Simulation of noise generation in the near-nozzle region of a chevron nozzle jet. *AIAA Journal*, *47*(8), pp. 1793-1810.

Van Steenkiste, T. H., Smith, J. R., Teets, R. E., Moleski, J. J., Gorkiewicz, D. W., Tison, R. P., Marantz, D. R., Kowalsky, K. A., Riggs, W. L., Zajchowski, P. H., Pilsner, B., McCune, R. C., & Barnett, K. J. (1999). Kinetic spray coatings. *Journal of Surface and Coating Technol*ogy, *111*, pp. 62–71.

Varadaraajan, V. & Mohanty, P. (2016). Design and optimization of rectangular cold spray nozzle: Radial injection angle, expansion ratio, and traverse speed. *Journal of Surface & Coatings Technology, 15*(2), pp. 25–32.

Veltin, J. & McLaughlin, D. (2008). Noise Mechanisms Investigation in Shock Containing Screeching Jets using Optical Deflectometry. In *14th AIAA/CEAS Aeroacoustics Conference (29th AIAA Aeroacoustics Conference.* pp. 2889.

Wang, H. & Qin, Q. (2019). Thermal analysis of a functionally graded coating/substrate system using the approximated transfer approach. *Coatings, 9*(51), 1-17.

Wlezien, R. W. & Kibens, V. (1988). Influence of nozzle asymmetry on supersonic jets. *AIAA Journal*, *26*(1), pp. 27-33.

Xu, J., Nelson, B. L., & Hong, L. J. (2013). An adaptive hypberbox algorithm for high-dimensional discrete optimization via simulation problems. *INFORMS Journal on Computing*, *25*(1), pp. 133–146.

Yin, S., Zhang, M., Guo, Z., Liao, H., & Wang, X. (2013). Numerical investigations on the effect of total pressure and nozzle divergent length on the flow character and particle impact velocity in cold spraying. *Surface & Coatings Technology, 232*, 290-297.