CFD Letters 11, Issue 6 (2019) 18-26

Penerbit Akademia Baru

CFD Letters

Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

Open Access

Optimizing Dry Ice Blasting Nozzle Divergent Length using CFD for Noise Reduction

Mohamad Nur Hidayat Mat[1], Nor Zelawati Asmuin[1*], Nor Halim Hasan[2], Hanis Zakaria[1], Muhammad Faqhrurrazi Abd Rahman[1] , Riyadhthusollehan Khairulfuaad[1], Balasem Abdulameer Jabbar[1]

[1] Department of Mechanical Engineering, Fakulti Kejuruteraan Mekanikal, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia
[2] Department of Occupational Safety and Health Sarawak, Ministry of Human Resources Malaysia, Malaysia

ARTICLE INFO

Article history:
Received 21 March 2019
Received in revised form 14 May 2019
Accepted 9 June 2019
Available online 3 July 2019

Keywords:
Acoustic power level; CFD; dry ice blasting; nozzle geometry; noise emission; optimum

ABSTRACT

The primary disadvantage of dry ice blasting (dib) is high noise emission. The process may reach an alarming sound level of up to 130 dBA (safe noise exposure 85 dBA for eight working hours) at high blasting pressure. Present safety measures rely entirely on administrative control by encapsulating the entire system with sound insulation or using personal protective equipment. This limitation has made this research a significant work by controlling the noise with the engineering approach. Therefore, the research objective is to optimize dib nozzle geometry in term of divergent length on the effect of the noise level and to study the noise development characteristic inside nozzle geometry using CFD analysis. The research study employed a Computational Fluid Dynamic (CFD) method to evaluate the effect of different divergent length on the acoustic power level. The simulation was carried out using density based, standard k-epsilon turbulence model and also broadband shock noise model were activated in ANSYS Fluent to monitor Acoustic Power Level of the simulated nozzle. The result shows that the lowest value of the acoustic power level that is responsible for producing the lowest noise emission is 230 mm.

1. Introduction

Dry ice blasting cleaning process is a pro-environmental process where the process does not produce secondary waste to the environment. The process used a carbon dioxide (CO_2) in a solid form known as dry ice pellet that is accelerated toward contaminated surfaces. There are three active mechanisms of dib cleaning process which are thermal, mechanical and sublimation effect, as shown in Figure 1. The thermal effect causes the contaminant to break up due to differences in thermal coefficient between surface contaminant and substrate. The mechanical effect will result in the contaminant to fracture due to the kinetic energy of the blasting medium reaches supersonic speeds upon the surface impact. On the other hand, the sublimation effect occurs due to the direct change

---

[*] *Corresponding author.*
E-mail address: norzela@uthm.edu.my (Nor Zelawati Asmuin)

of CO_2 from the solid to the gaseous phase cause the volume increase of about 600-fold [1-3]. The primary advantages of dry ice blasting are relatively low abrasiveness of blasting medium and environmental friendly as the blast media which is small pallets of CO_2, immediately disappear upon impact and return to their natural state in the atmosphere producing little waste other than the contaminate being removed. Also, carbon dioxide released from the dry ice blasting process is no new carbon dioxide released into the atmosphere, so it does not increase CO_2 concentration in the atmosphere. Nozzle geometry plays an essential role in optimizing the cleaning performance for surface treatment. A good design of nozzle geometry can increase dib cleaning performance in which the best design can provide excellence particle passage due to its favorable convergent and divergent acceleration characteristic [4-6].

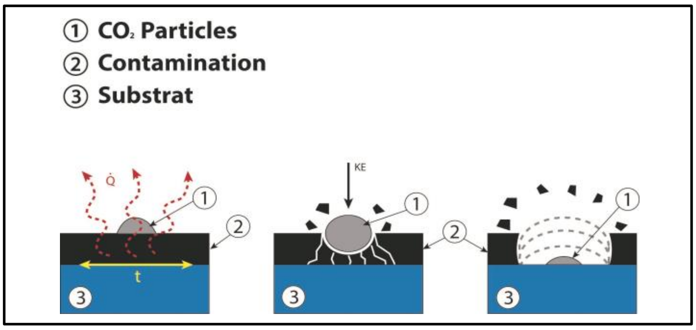


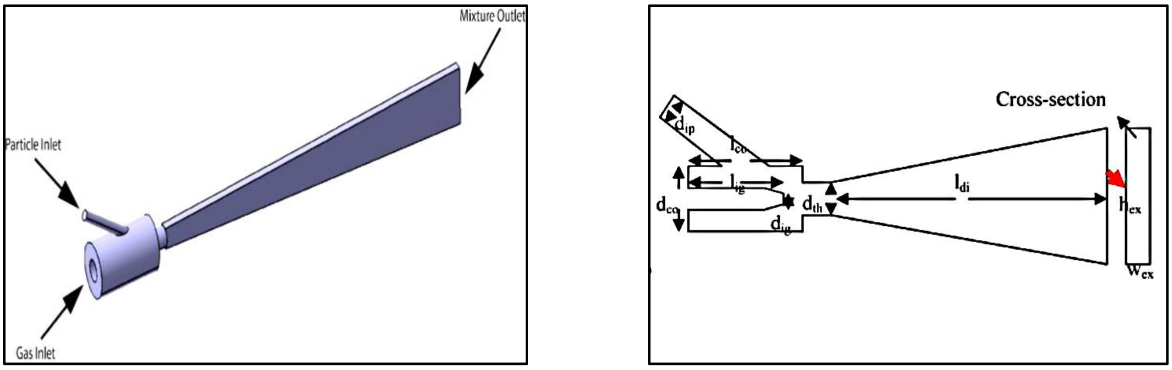
Fig. 1. Active mechanism of dib surface cleaning [7]

Besides, the acoustic noise generated from the supersonic nozzle is a function of the jet velocity to high power and the jet area which is predominantly from the exit of the nozzle [8, 9]. However, it was reported that from the experimental result of identifying noise generation from the dry ice blasting nozzle, they concluded that three primary noise sources were coming from dry ice blasting nozzle. Initially, noise originally comes from within the aperture area that the compressed air jet impinges on the still air. The noise also comes out during the collision of the workpiece surface and above a certain blasting pressure in the free jet between the outlet edge and the workpiece surface [4, 10]. The noise level was influenced by some issues which were surfaces being blasted, the property of compressed gas and air humidity. The pitted surface could cause high amplitude due to jet screech whereas high humidness will raise noise levels due to higher sound transmission than dry air [11, 12]. Apart from that, it was reported that there were a few techniques to reduce noise emission coming from the nozzle geometry. New nozzle design concepts such as chevrons, corrugations, beveled nozzles, and other non-axisymmetric geometries are expected to help to reduce the noise [13]. It has been reported that another way to reduce noise emission is involving the mixing rate between the jet potential core and the surrounding air flow. This is to shorten the length of the high turbulence, and noise-producing region [14, 15]. A potential way to accomplish this is by altering the nozzle geometry at the exit plane in a way that it enhances the turbulence within the shear layer surrounding the potential core of the nozzle geometry [16]. When the nozzle is operating off-design, however, there will be two additional noise mechanisms associating with the interaction between the turbulence in the nozzle shear layer and the nozzle's shock-cell structure. The first one is a broadband shock–associated noise. As the name would suggest, it produces noises at all frequencies, even though its peak frequency is higher than that of jet turbulence mixing noise [15, 17, 18]. It was found from a numerical simulation that air flow velocity and turbulence effect have a significant relationship with the acoustic noise generation for different nozzle geometry [19-22]. Based on the previous literature review, it was found that none of all the researchers briefly explained the selection of nozzle divergent length correlated on acoustic noise emission which. In addition, there has been no report on the optimum range of divergent length and concerning acoustic noise generation and development inside a nozzle geometry. The experiment was performed to investigate the noise generation from the nozzle. However, the result was limited to external fluid flow after the nozzle exited, and it was not on the noise inside. Therefore, this shows that none of the researchers has done CFD investigation on acoustic noise inside nozzle geometry especially in optimizing divergent length. In contrast, they have claimed that the noise was coming from the aperture of the nozzle to the cleaning surface. Hence in this study, the research gap have been identified from previous literature will be studied briefly in terms of the relationship on the acoustic noise emission and the optimal range of nozzle divergent length concerning acoustic noise generation and fluid flow characteristic inside the nozzle geometry.

2. Methodology

2.1 Geometrical Modelling

The three-dimensional model of dry ice is designed using CATIA V5R20 as shown in Figure 2(a) while the schematic of a dry ice blasting nozzle as shown in Figure 2(b). The dry ice particle feeder is placed at the beginning of the convergent zone and injects dry ices at an angle of 30° to the nozzle axis. Some parameters are used to define the geometry of dry ice blasting nozzle, which are convergent nozzle length, l_{co}, nozzle convergent diameter, d_{co}, gas inlet diameter, d_{ig}, gas inlet insertion length in the convergent section, l_{ig}, dry ice inlet diameter d_{ip}, throat diameter, d_{th}, divergent length, l_{di}, exit width, w_{ex} and exit height, h_{ex}. The expansion ratio is defined as the area ratio of the nozzle exit to the throat.



(a) (b)

Fig. 2. Dual hose dib nozzle geometry (a) Geometrical modelling (b) Schematic diagram

2.2 Meshing for DIB Nozzle Geometry

The model created by the below dimension meshed in mesh mode of Ansys component systems as shown in Figure 3. Meshing is nothing but converting an infinite number of particle model in a finite number of particles. Meshing cell requirement has to be done in high efficiency and accuracy. Typically, the refine (smaller cells) mesh is for big solution gradients and fine geometrical detail while coarse mesh (giant cells) could be elsewhere. Maintaining a good quality mesh is essential for solution accuracy and stability. However, the solution may deteriorate when mesh cell deviates from an ideal shape. There are four processes of generating machine in Ansys mesh mode. It starts with specifying the global mesh setting, inserting a local mesh setting, generating the mesh and checking mesh quality. The proximity and curvature option were selected as the convergent section is a curve object (Cylinder). The smoothing was set to high since the medium of flow is a high-speed gas particle which is air. The meshing size needs to be selected from by using Grid Independent Test.

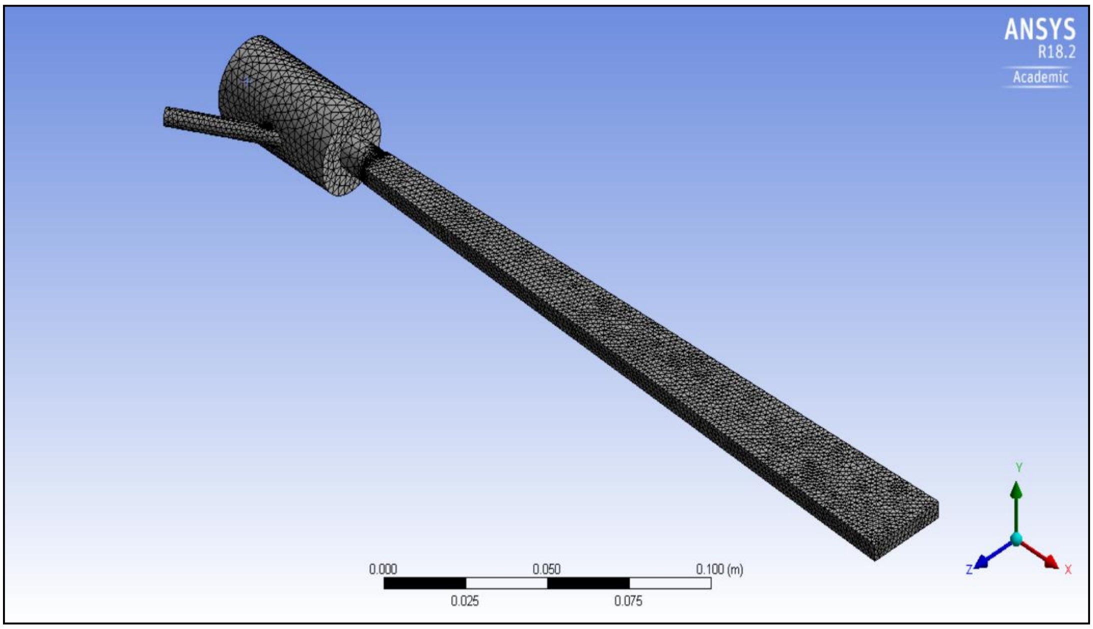


Fig. 3. A Meshed model of the nozzle (ANSYS R18.2)

2.3 Grid Independent Test

A model of nozzle geometry was recreated from previous literature study on the modeling of dry ice blasting and its application in thermal spray [23]. Grid-independent test was required for this project to maintain the accurateness of the model. Maintaining the independent grid test as low as possible is essential to ease simulation time and keep accuracy. Typically, the sequence of GID was created from coarse, medium and fines meshed to show the solution changes between medium and fine mesh. Table 1 shows the result of GID for nozzle geometry. The number of GID was generated until nine tests. The selection of GID was based on the lowest value of skewness mesh metric and the highest orthogonal mesh metric. It was found that the lowest value of skewness among all was number three and the highest number of orthogonal mesh metric value was number three. Therefore, GID of number three was selected in this study for further simulation analysis.

Table 1
Grid independent test for based model

No	Number of Nodes	Number of Elements	Skewness Mesh Metric	Orthogonal Mesh Metric
1	108784	70372	0.25852	0.73965
2	108639	70217	0.24637	0.75190
3	108571	70163	0.24631	0.75197
4	112386	72759	0.26249	0.73578
5	112512	72801	0.25245	0.74583
6	112611	72876	0.25206	0.74621
7	115079	74531	0.26447	0.73385
8	114335	73944	0.25472	0.74365
9	114246	73875	0.25473	0.74363

The main properties of dry ice pellets involved in this study are listed in Table 2

Table 2
Property of dry ice pellets

Parameters	Values
Temperature/ °C	-78.50
Density/ kgm^{-3}	1560
Heat capacity/ Jkg^{-1}K^{-1}	519.16
Thermal conductivity/Wm^{-1}K^{-1}	0.0107

2.4 CFD – Simulation Method

The Computational Fluid Dynamics (CFD) has been utilized in this to study to solve a governing equation pertaining the fluid flow inside a nozzle geometry. In addition, Ansys Fluent simulation software was employed as a CFD solver to predict the gas flow field and particle acceleration in dry ice blasting nozzle. In this numerical study, however, due to the orientation and location of the dry ice particle feeder, which is placed on the periphery of the nozzle, a two-dimensional simulation is not adequate to reveal all of the aspects of the flow field and particle trajectory. Therefore, a complete three-dimensional analysis is conducted to find the effect of nozzle geometry. A hybrid scheme is used to generate hexahedral and tetrahedral elements throughout the domain. Tetrahedral elements are adapted to the regions where the hexahedral scheme is not suitable and will result in a high skewness. This ensures a higher grid quality and more accurate results. The no-slip condition was used at the nozzle wall and the substrate surface because the gas velocity near the wall zone is much low.

2.5 Model Verification

The simulation was performed using Fluent while the reference model is taken from previous literature that is simulated using Gambit simulation software. Therefore, model validation of the nozzle geometric is required for this research. The validation is done by comparing the highest maximum particle velocity of the nozzle from the previous literature study as presented in Table 3. The model validation is based on the modeling of dry ice blasting and its application in thermal spray done by Dong *et al.,* [23]. Based on the value of the relative error presented below, the table shows that the maximum relative error for the geometrical modeling is 1.287 %. According to Goswami *et al.,* [24], the acceptable limit for numerical simulation for comparing two simulated models is below than 10%. Since the maximum value is below than acceptable limit and this means that the geometrical simulation is acceptable for further simulation on different nozzle geometry.

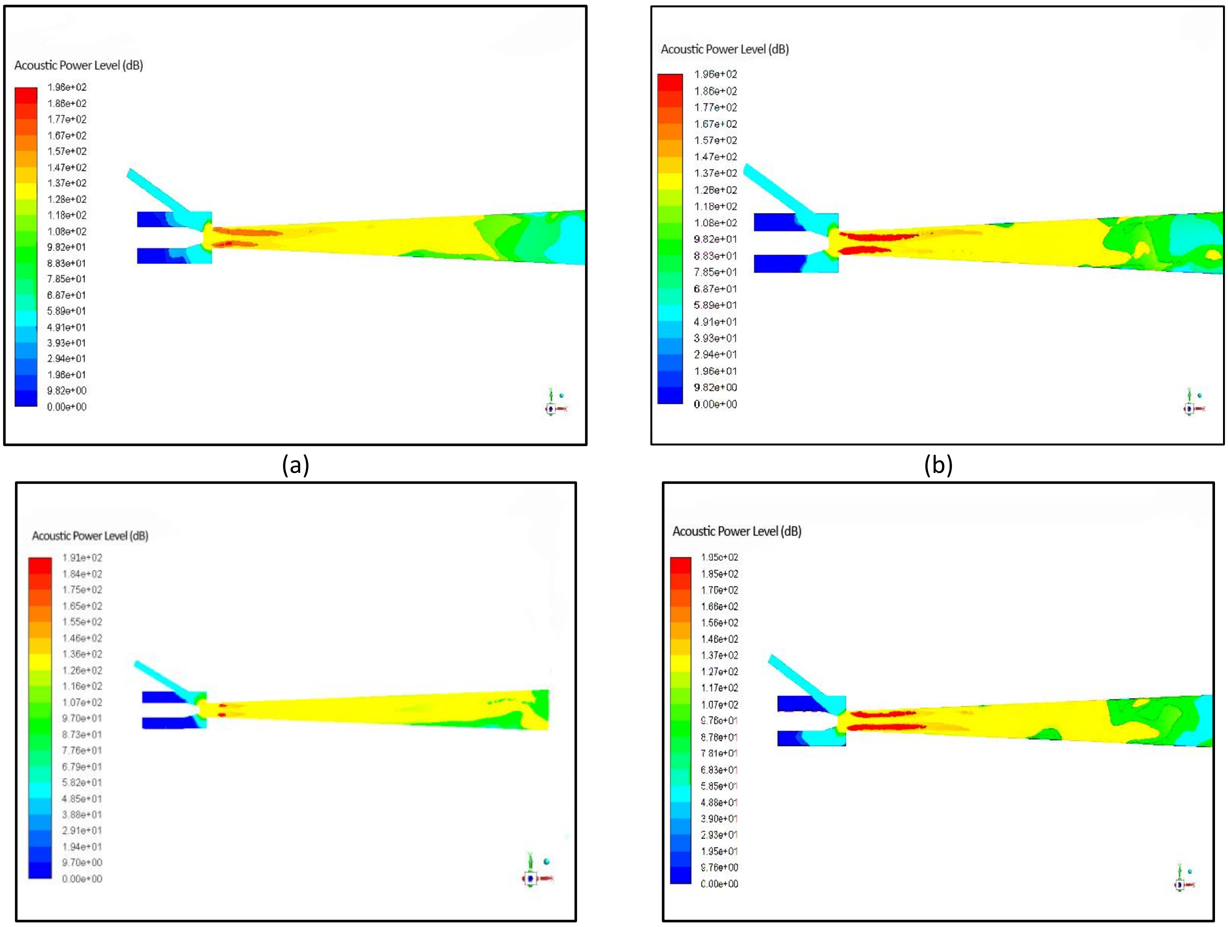
Table 3
Verification of based model geometry

Pressure Inlet (MPa)	Particle Velocity By CFD Gambit (ms-2)	Particle Velocity By CFD Fluent (ms-2)	Relative Error (%)
0.2	53.75	53.90	0.279
0.4	72.50	73.00	0.690
0.6	85.50	84.40	1.287
0.8	87.50	88.40	1.029

3. Results

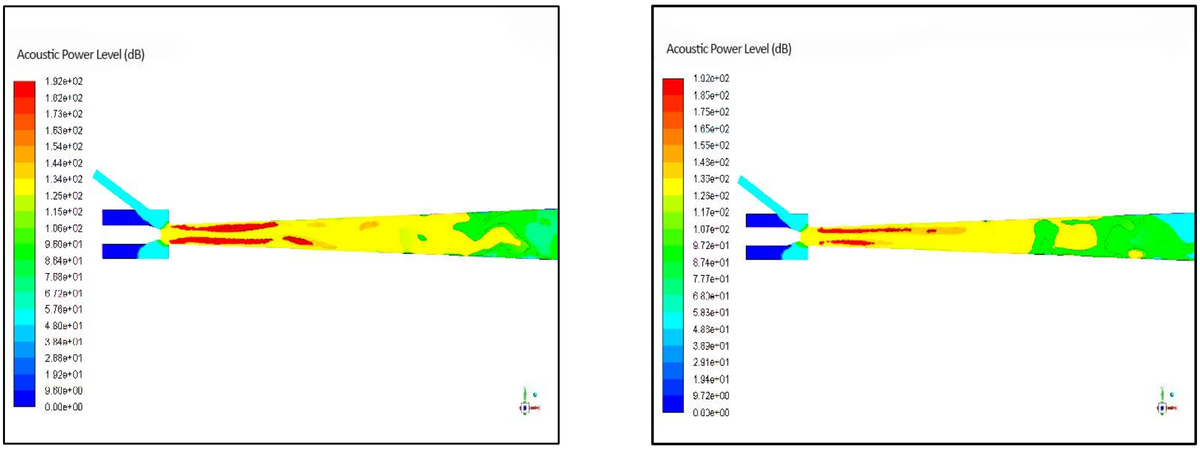
3.1 Characteristics of Acoustic Power Level

The simulated results on the acoustic power level for five (5) different divergent lengths which were 190 mm, 210 mm, 230 mm, 250 mm, 270 mm and 290 mm are presented in Figure 4. A relative difference acts as an indicator for the performance evaluation. The maximum acoustic power level occurred at the divergent length of 190 mm and 210 mm which both of them represent the value of 196 dB. Besides, the lowest acoustic power level occurred at the divergent length of 230 mm. This length however refers to the based model. Another critical finding showed that all the nozzles experienced a maximum acoustic power level at the divergent section just after the throat section [25-28]. This can be seen on the yellow colour contour develop at the divergent length. After some point, it can be seen that the green colour region continue to develop at the end of divergent length. This occurs due to friction between the nozzle wall, and the dry ice pellet hit the surface along the wall [18]. Thus, air friction produces a loud noise. The total average value for this yellow region was 137 dB. Just before the outlet section, the noise started to drop as presented in the green color region. In summary, the selection of nozzle based on acoustic performance should be referred to the nozzle that provides the lowest noise emission. Hence, a nozzle length of 230 mm was selected in this study because it offered the lowest acoustic power compared to all models.



(a) (b)

(c) (d)



(e) (f)

Fig. 4. Simulation results on acoustic power level characteristic for different divergent length. (a) 190 mm divergent length, (b) 210 mm divergent length, (c) 230 mm divergent length, (d) 250 mm divergent length, (e) 270 mm divergent length, (f) 290 mm divergent length

3.2 Acoustic Power Level against Divergent Length

The results of the acoustic power level against divergent length are presented in Figure 5. The figure demonstrates that an overall trend of acoustic power level is decreasing with the increment of divergent length. However, the lowest acoustic power level occurred at the divergent length of 230 mm which represent 191 dB while the highest value of acoustic power level occurred at the divergent length of 190 mm and 210 mm that both of them represent 196 dB. The trend line is also presented in the graph. The gradient of the trendline seem to be negative. This means that increasing divergent length will cause the value of acoustic power level drop. However, the at the length of 230 mm shows lowest acoustic power level from the rest. According to Ghassemieh *et al.,* [29] and Soderback [30], the highest particle velocity responsible for low friction thus, reducing acoustic noise because of friction along the divergent length. Therefore, it is believed that the length of 230 mm has the highest flow characteristic to cause the lowest particle friction along the wall.

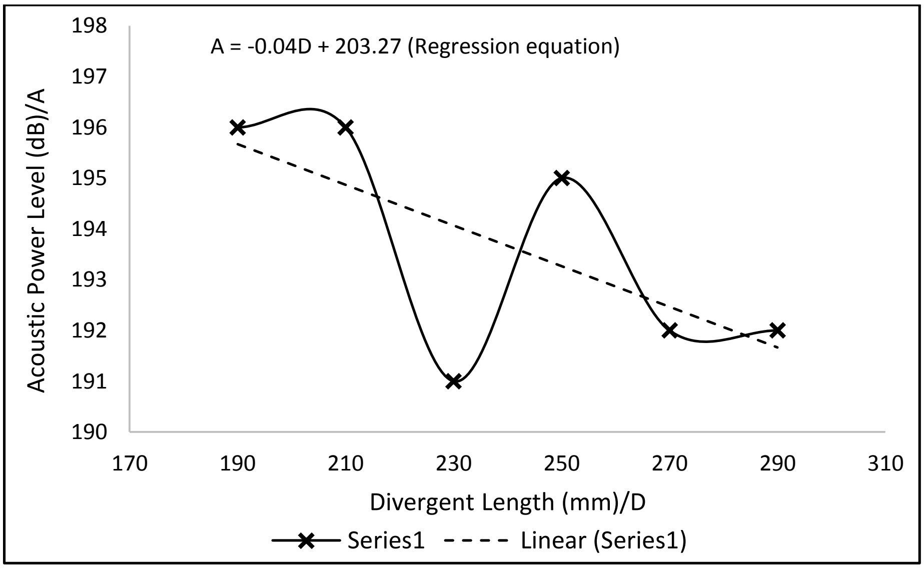


Fig. 5. Acoustic power level against different divergent length

4. Conclusions

The noise generated by the steady flow for the dual hose C-D Nozzle of dib was analyzed by utilizing the Broadband noise source model. In the present study, a 3-D simulation has been carried out for six (6) different nozzle divergent length. Based on the simulation result, it was found that the lowest value of the acoustic power level that is responsible for producing the lowest noise to the surrounding is 230 mm. Besides, CFD-simulation provides an excellent understanding of noise development inside nozzle geometry by providing a good indicator of acoustic power level with different color contours. It was found that the highest noise emission development occurred in the divergent section as presented in the yellow color region.

Acknowledgment

The author acknowledges financial support from the Ministry of Education Malaysia under Fundamental Research Grant Scheme (FRGS) K080 and Universiti Tun Hussein Onn Malaysia under Geran Penyelidikan Pascasiswazah (GPPS) U966. The author also acknowledges NA, HZ, MFAR, RK, and BAJ from UTHM and NHH from Department of Occupational Safety and Health Sarawak for their consulting with this work.

References

[1] Spur, G., E. Uhlmann, and F. Elbing. "Dry-ice blasting for cleaning: process, optimization and application." *Wear* 233 (1999): 402-411.
[2] Uhlmann, Eckart, and A. El Mernissi. "Pre-treatment by dry ice blasting for adhesive bonding." *Production Engineering* 2, no. 2 (2008): 133-138.
[3] Uhlmann, E., and R. Hollan. "Blasting with Solid Carbon Dioxide–Investigation of Thermal and Mechanical Removal Mechanisms." *Procedia CIRP* 26 (2015): 544-547.
[4] Noise Reduction of Dry Ice Blasting. http://www.mfn.li/article/?id=535 (accessed Mar. 28, 2019).
[5] Liu, Yi-Hung, Graham Calvert, Colin Hare, Mojtaba Ghadiri, and Shuji Matsusaka. "Size measurement of dry ice particles produced from liquid carbon dioxide." *Journal of Aerosol Science* 48 (2012): 1-9.
[6] Liu, Yi-Hung. "Analysis of production process of fine dry ice particles and application for surface cleaning." (2012).
[7] Mat, Mohamad Nur Hidayat, and Norzelawati Asmuin. "Optimizing Nozzle Geometry of Dry Ice Blasting Using CFD for the Reduction of Noise Emission." *International Journal of Integrated Engineering* 10, no. 5 (2018).
[8] Arun Raj , Jaison Joseph, Jeffrey John Varghese , Joseph Tom Joseph , Subnas L C. "Acoustics Study of a Supersonic C-D Nozzle. " *International Journal of Engineering Research & Technology (IJERT)* 3, no. 2 (2014): 2063-2066.
[9] Karpuschewski, B., T. Emmer, K. Schmidt, and M. Petzel. "Cryogenic wet-ice blasting—process conditions and possibilities." *CIRP Annals* 62, no. 1 (2013): 319-322.
[10] Shin, Seoungyoung, Akira Matsunaga, Hiroyuki Marubayashi, and Toshiyuki Aoki. "Effects of nozzle-lip length on reduction of transonic resonance in 2D supersonic nozzle." *Open Journal of Fluid Dynamics* 3, no. 02 (2013): 69.
[11] Cold jet Cold Jet Dry Ice Blasting Acoustics Guide.
[12] Jet, C. Two hose vs One hose systems. 2–3. (2017).
[13] Papamoschou, Dimitri, Philip Morris, and Dennis McLaughlin. "Beamformed flow-acoustic correlations in high-speed jets." In *15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference)*, p. 3212. 2009.
[14] Ramji, V., Raju Mukesh, and Inamul Hasan. "Design and Numerical Simulation of Convergent Divergent Nozzle." In *Applied Mechanics and Materials*, vol. 852, pp. 617-624. Trans Tech Publications, 2016.
[15] Kanmaniraja, R., R. Freshipali, J. Abdullah, K. Niranjan, K. Balasubramani, and VR Sanal Kumar. "3D numerical studies on jets acoustic characteristics of chevron nozzles for aerospace applications." *International Scholarly and Scientific Research & Innovation* 8 (2014): 1510-1516.
[16] Alam, M. M. A., T. Setoguchi, S. Matsuo, and H. D. Kim. "Nozzle geometry variations on the discharge coefficient." *Propulsion and Power Research* 5, no. 1 (2016): 22-33.
[17] Paliath, Umesh, and Philip J. Morris. "Numerical simulation of jet noise from different jet nozzle geometries." *The Journal of the Acoustical Society of America* 118, no. 3 (2005): 1873-1873.
[18] Morris, Philip J., Yongle Du, and Kursat Kara. "Reprint of: Jet Noise Simulations for Realistic Jet Nozzle Geometries." *Procedia IUTAM* 1 (2010): 28-37.
[19] Erwin Sulaeman , S. M. Afzal Hoq, Abdurahim Okhunov , Irfan Hilmy , Marwan Badran. " Convergence and Error

Analysis of a Bi-quadratic Triangular Galerkin Finite Element Model for Heat Conduction Simulation." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 54 , no. 1 (2019): 78-86.

[20] Beng, Soo Weng, and Wan Mohd Arif Aziz Japar. "Numerical analysis of heat and fluid flow in microchannel heat sink with triangular cavities." *Journal of Advanced research in fluid mechanics and thermal sciences* 34 (2017): 1-8.

[21] M. K. Wong, L. C. Sheng, C. S. Nor Azwadi, G. A. Hashim. " Numerical Study of Turbulent Flow in Pipe with Sudden Expansion. " *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 6, no. 1 (2015): 34-48.

[22] Crunteanu, Daniel, and Petre-Claudiu Cojan. "Acoustic characteristics of the flow over different shapes of nozzle chevrons." *Incas Bulletin* 5, no. 3 (2013): 53.

[23] Dong, S. J., B. Song, B. Hansz, H. L. Liao, and C. Coddet. "Modelling of dry ice blasting and its application in thermal spray." *Materials Research Innovations* 16 (2012): 61-66.

[24] Goswami, Mayank, Sanjeev Kumar, and Prabhat Munshi. "Correlation between numerical simulation and limited data experimental technique for estimation of nitrogen flowing in LMMHD loop." *Flow Measurement and Instrumentation* 46 (2015): 80-86.

[25] Sulaiman, Ibrahim Mohammed, Mustafa Mamat, Muhammad Yusuf Waziri, and Audu Omesa Umar. "Numerical Method for Solution of Fuzzy Nonlinear Equations." *Journal of Advanced Research in Modelling and Simulations* 1, no. 1 (2018): 13-18.

[26] Sharafatmandjoor, S., and CS Nor Azwadi. "Numerical Simulation of the Dynamics of a Droplet in a Low-gravitational Field." *Journal of Advanced Research Design* 16, no. 1 (2016): 15-20.

[27] Zulakmal, Muhammad Yahya, Ahmad Fudholi, Nurul Shahirah Rukman, Nurul Syakirah Nazri, Nilofar Asim Chan Hoy Yen, Sohif Mat, and Kamaruzzaman Sopian. "Computational Fluid Dynamics Analysis of Thermoelectric Generators Performance under Solar Photovoltaic-Thermal (PVT) System." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 56, no. 2 (2019) 223-232

[28] Kadhim Sharaf, Hussein, Nawal Aswan Abdul Jalil, and Sadeq Salman. "A simulation on the effect of ultrasonic vibration on ultrasonic assisted soldering of Cu/SAC305/Cu joint." *Journal of Advanced Research in Applied Mechanics* 36, no. 1 (2017) 1-9

[29] Ghassemieh, E., Hendrik K. Versteeg, and Memis Acar. "The effect of nozzle geometry on the flow characteristics of small water jets." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*220, no. 12 (2006): 1739-1753.

[30] Soderback, M. Determination Of Sound Power Levels using Sound Intensity (Master Dissertation), Vaasan Ammattikorkeakoulu University, Applied Sciences, Vaasa, Finland, 2009.