Response Surface Analysis of DIB Nozzle Geometry on Acoustic Power Level using Central Composite Design of Experiment

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Abstract. The critical process parameters in manufacturing dry ice blasting nozzle geometry directly related to particle jet velocity. Many studies focused on its performance without considering the noise emission due to high operating pressure. This paper, a numerical simulation study was performed using Ansys Fluent to investigate the effect of nozzle geometry of single-hose dry ice blasting on the acoustic power level. The process of modelling the two-way mass momentum and energy exchange between two phases was successfully solved iteratively in the two-way mass momentum model and the energy exchange between the two phases. It was found that the value of noise emission reaches a maximum level when the shortest convergent angle of 20° with a minimal convergent length of 50 mm and a maximum length of 300 mm is introduced. Besides, the peak value of acoustic power level swell up to 146 dB occurs at a nozzle area ratio of 20 without influencing by convergent angle and extending the divergent length highly influencing noise reduction as less than 143.5 dB for a divergent length of 700 mm.

1. Introduction
One of the advantages of using dry ice blasting (DIB) system is an environmentally friendly system [1]. This is because the process is clean from any secondary waste upon surface cleaning [2]. Despite environmental friendly benefit, a massive problem still occurs in dry ice blasting industries in which the cleaning operator need to deal with excessive noise emission from the system due to high pressure [3]. Recent findings reported that noise generation measures to the system can surpass the standard noise limit of 85 dB(A) for 8 hours working day [4]. In addition to noise emission, the highest noise from the blasting operation was found coming from nozzle geometry due to the particle to particle collision inside the nozzle cavity and compressed by supersonic gas and the main critical process even difficult to conduct indoor environment such as manufacturing and shop floor [5]. At present, many operators adapt isolation working conditions when operate dry ice blasting due to high noise from the scene and some of them instruct their workers and the surrounding to wear earplugs or earmuff during the process. These techniques are not as efficient as compare to the engineering approach to curb the noise pollution in the industry in which the study was found that, the nozzle configurations play a crucial role to reduce noise
generated from the system [6]. Therefore, this research focuses on different nozzle parameters of a single hose geometry by using the central composite design of an experiment to plot response surface analysis concerning the acoustic power level that represents the intensity of noise generation. The novelty approach in this research is to maximize the possibility of nozzle geometry towards the contribution to noise emission.

2. Methodology

2.1. Geometrical Modelling

The two-dimensional model creation was designed using Ansys design modeler while the based nozzle dimension was referred from a previous literature study [7]. The detail of the nozzle dimension and the desired operating condition [8] is presented in Table 1. Nozzle dimension consists of Inlet Diameter (Di), Throat Diameter (Dt), Exit Diameter (De), Divergent Length (Ld), Convergent Length (Lc), and Throat Length (Lt). There are three main sections in nozzle geometry which are convergent, throat and divergent section.

| Parameters                     | Value         | Nozzle Outline Geometry |
|--------------------------------|---------------|-------------------------|
| Inlet diameter (Di)            | 39.73 mm      |                         |
| Throat diameter (Dt)           | 10.16 mm      |                         |
| Exit diameter (De)             | 28.96 mm      |                         |
| Divergent length (Ld)          | 558.80 mm     |                         |
| Convergent length (Lc)         | 127 mm        |                         |
| Throat length (Lt)             | 52.83 mm      |                         |
| Inlet Pressure                 | 600 kPa       |                         |
| Exit pressure (Pe)             | 101.33 kPa    |                         |
| Inlet stagnation pressure (Ps) | 603.88 kPa    |                         |
| Inlet stagnation Temperature (Ts)| 273.37 K   |                         |
| The temperature of Dry Ice Particle | 194.50 K       |                         |
| The density of Dry Ice Particle | 1560 kg/m³  |                         |
| Heat Capacity of Dry Ice Particle | 519.16 J/kg/K |                         |
| Shape Factor of Dry Ice Particle | 0.76         |                         |

2.2. Nozzle meshing

The governing equation employs a Finite Volume Method (FVM) to solve the model solution. FVM requires the model to be divided into small fragments name mesh. Every mesh has a centroid point that will be used to compute the solution in the matrixes form. After that, the throat and corner division is essential to refine the mesh near that section [9]. Edge sizing was implemented near the throat section since the throat in a narrower cross-sectional area [10]. Maintaining a good quality mesh is essential for solution accuracy and stability [12]. The proximity and curvature option were selected since the domain is the combination of cylindrical and rectangular [13]. The smoothing was set to high since the medium of flow is a high-speed gas-particle. This analysis found that the average skewness level is approximately 0.03 and the lowest value of skewness gives better accuracy in calculating the solution [11]. Thus, the result of mesh generation can be further analysed.
2.3. Numerical boundary conditions
The governing equation of mass, momentum, and energy utilizing the Eulerian-Lagrangian approach for two fluid phases of compressed air and dry ice particles. Ansys Fluent exploits density-based solver in the numerical solution since the flow is compressible high-speed Reynold number. Due to high-speed flow, the turbulence effect is considered and the average Reynold Navier-Stokes (RNG) equation is applied in the governing equation. The RNG k-ε turbulence model is introduced to the wall treatment function of the nozzle geometry. This turbulence model is used due to the optimization of result accuracy inside viscous sub-layer and lower computational load.

2.3.1 Conservation of Momentum
The trajectory of particles is determined from the integration of time domain on a Lagrangian flow description with influence by drag, negligible of a particle to particle interaction and rotation.

\[
\frac{d\bar{u}_p}{dt} = F_d(\bar{u} - \bar{u}_p)
\]  

(1)

Since the flow under Lagrangian flow description, the time domain is the main parameters in the analyses while \(\bar{u}, \bar{u}_p, \) and \(F_d\) represent average fluid velocity, average particle velocity and drag force respectively.

\[
F_d = \frac{18\mu \cdot C_D \cdot Re}{\rho_p \cdot D_p \cdot 24}
\]  

(2)

\[
C_D = C_{DI} = \left[0.66 + 0.26 \tanh(2 \ln M_s) + \exp[-2.5(\ln M_s/1.4)^2]\right]
\]  

(3)

The drag for directly correlate with Reynold number, \(Re\), particle density, \(\rho_p\), particle diameter, \(D_p\), dynamic viscosity, \(\mu\) and friction coefficient, \(C_D\) of function slip Mach, \(M_s\).

2.3.2 Conservation of Energy and Mass
Energy transfer between particle to gas interaction through convection and mass transfer as below

\[
m_p \cdot C_p \cdot \frac{dT_p}{dt} = h_A \cdot (T_{\infty} - T_p) + \frac{dm_p}{dt} \cdot h_f
\]  

(4)

The total energy change relates directly to differences in fluid temperature, \(T_{\infty}\) and particle temperature, \(T_p\), particle mass flow rate, \(\frac{dm_p}{dt}\), the particle mass, \(m_p\) particle specific heat, \(C_p\) particle surface area, \(A_p\) a liquid gas mixture of enthalpy, \(h_f\), and film coefficient, \(h\).

3. Results and Discussions

3.1. Response Surface on Acoustic Power Level
Figure 1 demonstrated the response surface of different nozzle geometry concerning the acoustic power level. Figure 1a shows the value of the acoustic power level decreases with a further increase of convergent angle while the value of the acoustic sound reaches a maximum level when the convergent length is approximately around 200 mm length between the convergent angle of 0 to 15°. Besides, Figure 1b presented the response of convergent angle with nozzle area ratio toward the response of acoustic noise level. The value of acoustic level increases with the increment of nozzle area ratio that swells up to 146 dB for area ratio of 20. Figure 1c shows the response surface of convergent length with the nozzle area ratio against the acoustic level. The trend shows increasing in acoustic power level value with increasing nozzle area ratio without influencing convergent length. Figure 1d shows the result of a response surface for divergent length with a convergent angle concerning to power level. The acoustic
power level drop in value as lower as 143.5 dB with less influence by convergent angle and convergent length as shown in Figure 1e. Furthermore, Figure 1f presented the trend of acoustic power level decreases with further increasing and decreasing of divergent length nozzle area ratio respectively that fall around 137 dB.

**Figure 1.** Response surface chart of input variable concerning acoustic power level
4. Conclusions
The response surface analysis has been carried out on four input variables and two output parameters using the CCD approach. Based on the simulation results, it was found that:

- The value of the acoustic power level reaches the maximum level when the shortest convergent angle of 20° with the minimal convergent length of 50 mm and 300 mm.
- The peak value of acoustic power level swell up to 146 dB occurs at a nozzle area ratio of 20 without influencing by convergent angle.
- Extending the divergent nozzle length highly influencing noise reduction in a cavity as less than 143.5 dB for a divergent length of 700 mm.

References
[1] Onofre E, Godina R, Carvalho H and Catarino 2020 J. Clear Prod. 272 122987
[2] Gogoi A, Mazumder P, Tyagi K T, Tushara Chaminda T G, Kyoungjin A A and Kumar M 2018 Gr. for Sust. Dev. 6 169-180
[3] Vansant J and P.-W. Koziel 2019 Springer 73-104
[4] Dighe S and Gadgil H 2018 Inter. J. Multiphase Flow 99 347-362
[5] Vijay M M, Xu M M, Panarella E, Yan W, Tieu A H and Daniels B R 2017 US9718091B2 Google Patents
[6] Bastos L P, Deschamps C J, Silva A R 2017 App. Acoustics 127 240-249
[7] Hamed A, Lehnig T and Président V 2001 ISOABE Conf. Citeseer
[8] Dong S J, Song B, Hansz B, Liao H L and Coddet C 2012 M. R. Inno. 16 61-66
[9] Mat M N H, Asmuin N Z, Md Basir M F et al. 2020 J. Therm. Anal. Calorim. 1-15
[10] Mat M N H, Asmuin N Z, Md Basir M F et al. 2020 Powder Technology 364 152-158
[11] Mat M N H, Asmuin N Z, Md Basir M F 2020 et al. Eur. Phys. J. Plus 135 260
[12] Mat M N H, Asmuin N Z, Md Basir M F et al. 2021 J Therm Anal Calorim 143 2343–2354
[13] Mat M N H, Asmuin N Z, Hasan N H, Zakaria H et. Al. 2019 CFD Letters 11(6) 18-26

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