Computational Analysis of Acoustic Transient Phenomena with MTMM for Vibro Cleaner

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Abstract: - In cleaning Industries, Vibro Cleaner has unique impact for removal of contaminations like rust, dirt, oil etc. from critical objects. This is completely safe for humans and non-hazardous for nature. The aim of this research is to improve the efficiency of vibro cleaning process by using multiple transducers model matrix (MTMM) with 40 kHz frequency transducers. For the investigation, COMSOL Multiphysics software has been used by clubbing acoustic and CFD approaches in pressure acoustic transient module. By effect of cavitation erosion phenomenon, recommended results in cleaning erosion rates have been achieved and importance of placement of transducer also has been found out using different matrix in various models. Here among all matrix, The Erosion rate 9.62 x 10^{-3} kg/m^{2}s has been obtained maximum in transducer matrix of 2 transducers at bottom with 1 transducer at each 4 sides of tank.

Keywords: - Cavitation Erosion Phenomenon, Multiple Transducers Model Matrix, Acoustic Transient, Erosion rate.

1. INTRODUCTION

Vibro Cleaner is one of the ultra-cleaning process devices. It is developed based on micro level cleaning with sonic fluid flow to remove contaminations like rust, dirt, and other sticky materials from the surface of the objects. It is the most preferable process for cleaning of non-reachable areas and critical components. It works based on cavitation effects to clean the components like watch parts, lenses, coins, tools other medical instruments by means of piezoelectric transducers. The Multiple Transducers Model Matrix (MTMM) has been introduced to covert electrical signals into sound waves [14,15] and then pressure waves into liquid media through tank wall transience between transducer and liquid media with 40 kHz frequency. Due to pressure phase difference of negative and positive in liquid media, small, tiny bubbles have been generated by effects of cavitation phenomenon which strikes over the surface of object to clean the surface. The cavitation effect gives its results in contaminations removal erosion rate. But in industries, various components are required to clean, based on criticality of the object as well as mass of parts leads to choose required erosion rate and other acoustic properties [11,12]. The aim of this research is to improve the efficiency of cleaning process by using multiple transducers in different model matrix. The various possible combinations of multiple transducers have been studied to check the effectiveness over the cleaning process by FEM method [13] in COMSOL Multiphysics software [1-4].

The bubble are just empty spaces which collapse and implode as fast as created. The rapid implosion of bubbles produces enormous vacuum energy which gives cleaning power near to the object surface to remove the contaminations. It is known as cavitation effect [7,9,10].

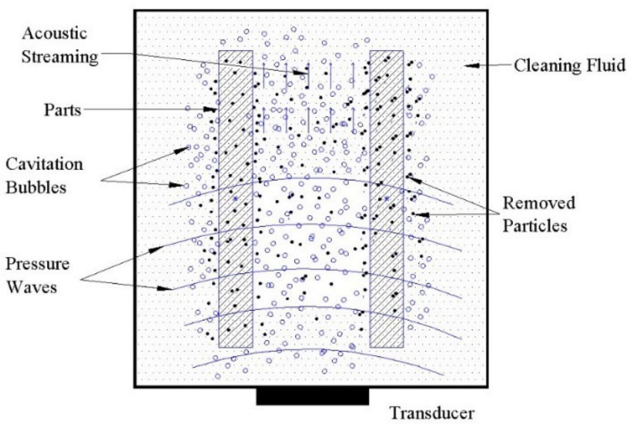

Figure 1. Working Principle of Vibro Cleaning

COMSOL Multiphysics is one of the leaning simulation software used in industries to get remarkable results. By using pressure acoustic transient modules with frequency domain, two modules like acoustic and CFD have been coupled to get strengthen results of the investigation [8].

2. TECHNICAL THEORY AND EQUATION

2.1. Pressure Acoustic Transient

The models have been developed using pressure acoustic transient module with frequency domain solver. Transducers have been used to generate pressure waves by means of sound pressure level into liquid media through tank wall transience. The tank is covered as a domain in sound hard boundaries while fluid as sound soft boundaries. Spherical wave radiation has been applied to create turbulence in liquid media for cavitation effect [5, 6].

$$\nabla.\left(\frac{-1}{\rho_C}(\nabla.\mathrm{p_t}-\mathrm{q_d})\right)-\frac{K_{eq.}^2.\mathrm{p_t}}{\rho_C}=Q_m \quad (1)$$

2.2. Electrostatics – Piezoelectric Transducer

The term electrostatics has been applied to the piezoelectric transducer because it converts electrical signals in to mechanical sound waves and that waves directly transfer to the tank wall in the form of vibration. For electric input 230 V power is used [5,6].

$$D=D_r+e.\varepsilon_{el}+\epsilon_{0vac}\,(\epsilon_{rS}+JC^{-1}-1).E, J=F^T.F \quad (2)$$

2.3. Fluid Flow – Bubbly Flow k-ε model

The Cavitation effect creates bubbles due to phase difference of negative and positive pressure. Because of this bubbly flow has been used to generate turbulence in the moving fluid. Bubbly Flow k-ε model gives more stringent than another model [5, 6].

$$\frac{\mathrm{d}(m_v V)}{\mathrm{d}t}=F_t \quad (3)$$

$$F_D=\frac{1}{\tau_p S}m_P M(u'-V) \quad (4)$$

$$F_{rad}=-2\pi r_P^3\left[\frac{1}{3}\kappa_s\,Re\left(f_0^{fl}\rho^*\nabla\rho\right)-\frac{1}{2}\rho\,Re\left(f_1^{fl}u^*\cdot\nabla u\right)\right] \quad (5)$$

2.4. Particle Tracing for Fluid Flow

The Particle tracing module is used to trace the trajectories of particles in the presence of an external field. Fluid-based particle tracing helps to investigate the motion of fluid particles in liquid media. The forces like Drag and Acoustophoretic Radiation force have been predefined and fluid flow has been computed with it to get appropriate results [5, 6].

$$\Delta m_i=\frac{c_i\rho m_P V_i^2}{4H_V\left(1+m_P r_P^2/l_P\right)}F(\alpha_i) \quad (6)$$

$$F(\alpha_i)=\begin{cases} cos^2\,\alpha_i & tan\,\alpha_i>\frac{P}{2} \\ \frac{2}{P}\left[sin(2\alpha_i)-\frac{2}{P}sin^2\,\alpha_i\right] & tan\,\alpha_i\le\frac{P}{2}\end{cases} \quad (7)$$

$$P=\frac{K}{1+m_P r_P^2/I_P} \quad (8)$$

$$I_P=\frac{2}{5}m_P r_P^2 \quad (9)$$

3. COMPUTATIONAL MODEL AND ANALYTICAL SIMULATION

For computational model development, COMSOL Multiphysics software has been used. The square shaped tank of size 220 mm x 220 mm x 200 mm (W x B x H) with 1 mm wall thickness has been used to investigate the effects of multiple transducers. The stainless-steel material is used to make tank due to its high elasticity and more durability with anti-corrosive properties. The capacity of tank is 10 litters approximately. The PZT-4 piezoelectric transducers have been used with frequency of 40 kHz and 230 V power. The square type tank has been chosen because it has wide access to attached transducers like sides and bottom faces than cylindrical shaped tank. For Investigation, five types of combinations have been made like; Model-1: 2 transducers at boom (2B), Model-2: 2 transducers at bottom and 1-1 on two opposite sides (2B-1-2OS), Model-3: 2 transducers at bottom and 1-1 on each four sides (2B-1-4ES), Model-4: 1 transducer at bottom and 1-1 on two opposite sides (1B-1-2OS), Model-5: 1 transducer at bottom and 1-1 on each four sides (1B-1-4ES).

For investigation, SS tank and MS specimen have been set as solid domains and water as liquid domain. Piezoelectric transducers have been set as electrostatic which has been used to transmit sound energy into acoustic properties in liquid media through tank wall transient. After setting all the parameters, study has been applied with frequency domain which gives results of sound pressure level, acoustic pressure and von misses stresses etc. Also, for particle trajectories, the time dependent solver has been applied with particle tracing module to study the movement of particles. With the help of drag force, acoustophoretic radiation force, Erosion phenomenon has been studied which gives the results of particle trajectories and erosion rate. The erosion rate has been found out using Finnie erosion model.

For meshing, Mesh type fine has been applied to reduce the simulation file size. It contains maximum and minimum element size of 20.5 and 2.5 respectively with 1.45 growth rate and 0.5 curvature factor. Resolution of the narrow region are applied as 0.6. Refer fig.3 for mesh model. For used material properties, refer table 1 and 2.

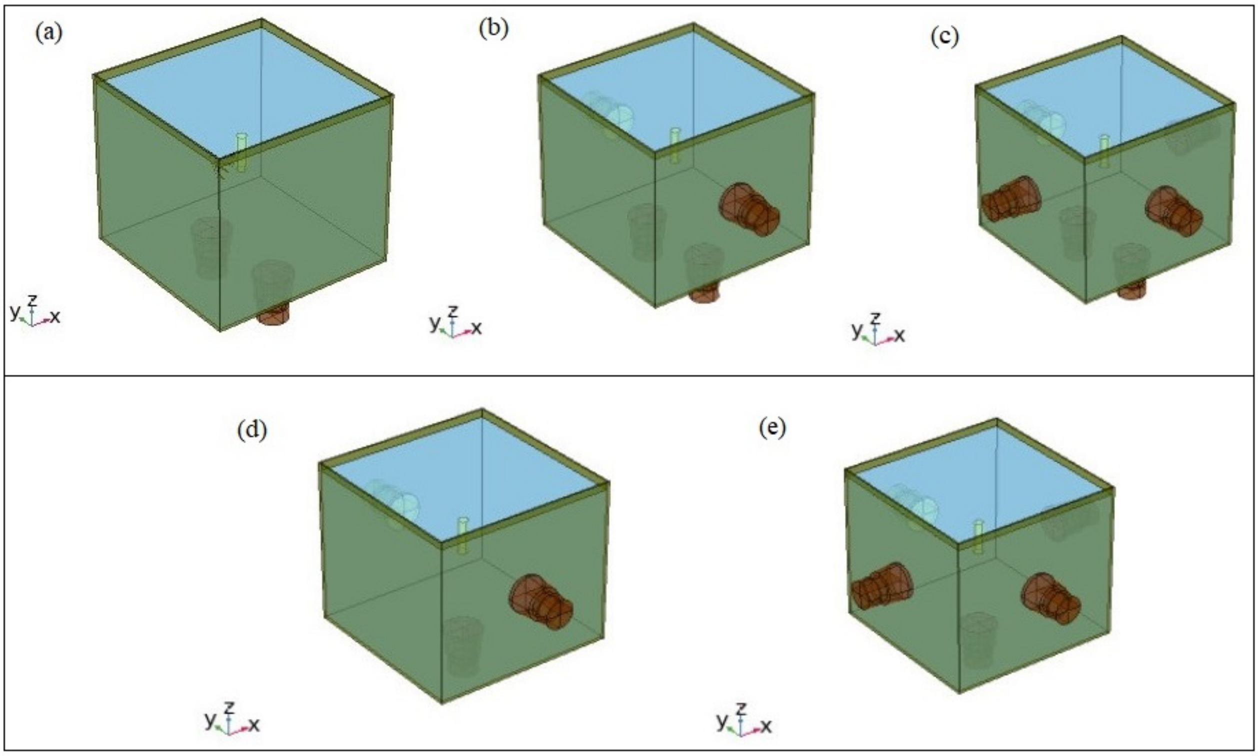

Figure 2. 3D Geometric Models: (a) Model-1:2B; (b) Model-2:2B-1-2OS; (c) Model-3:2B-1-4ES; (d) Model-4:1B-1-2OS; (e) Model-5:1B-1-4ES

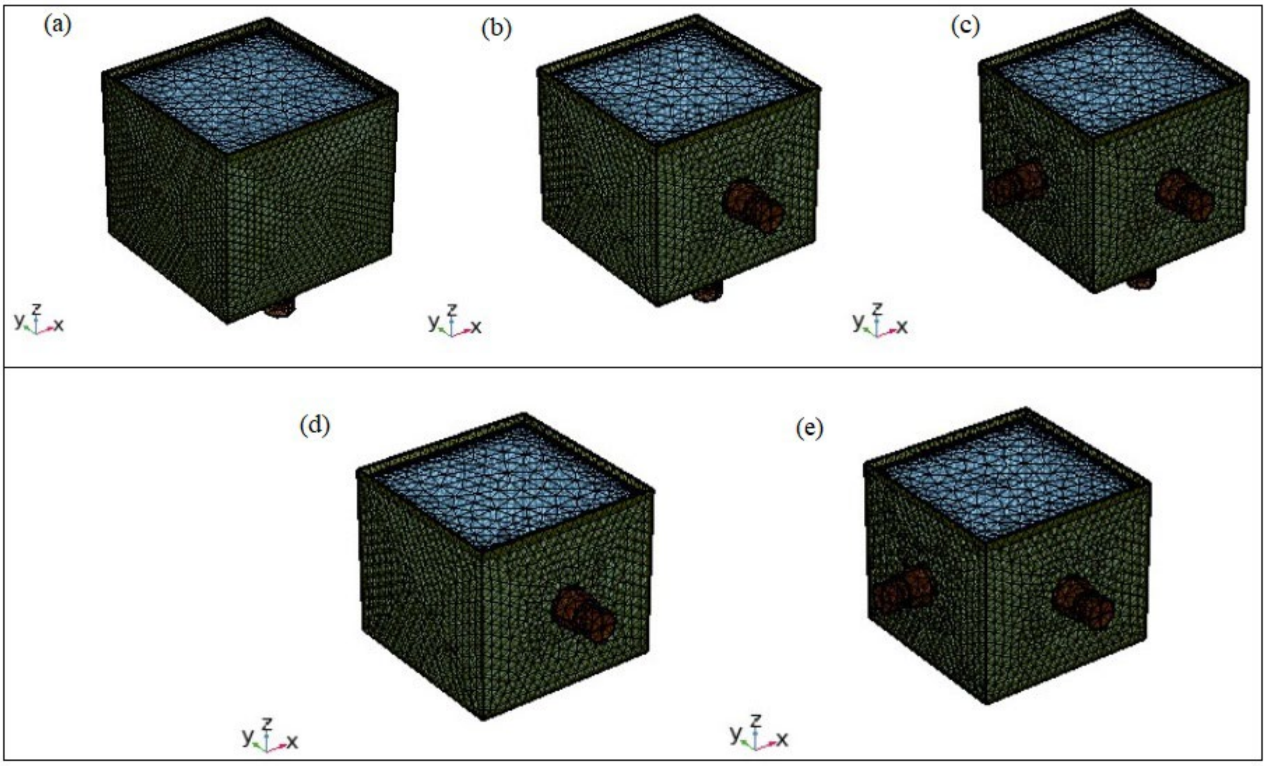

Figure 3. Mesh Models: (a) Model-1:2B; (b) Model-2:2B-1-2OS; (c) Model-3:2B-1-4ES; (d) Model-4:1B-1-2OS; (e) Model-5:1B-1-4ES

Table 1. Properties of Materials

Properties	**Stainless Steel**	**Mild Steel**
Density (kg/m^3)	8000	7840
Young's modulus (Pa)	20.3 x 10^{10}	21 x 10^{10}
Poisson's Ratio	0.27	0.30
Bulk modulus (Pa)	15.1 x 10^{10}	14 x 10^{10}
Shear modulus (Pa)	8.1 x 10^{10}	7.0 x 10^{10}

Table 2. Properties of Piezoelectric Transducer

Properties	PZT-4 Transducer
Frequency (kHz)	40
Power (W)	60
Radiating Surface (mm)	45
Length (mm)	55
Density (kg/m^3)	7500
Permittivity Constant (F/m)	8.854 x 10^{-12}
Relative Permittivity	ƐT11 = 1475, ƐT12 = 1475, ƐT13 = 1300

4. RESULT AND DISCUSSION

In this investigation, COMSOL Multiphysics software has been used by clubbing two different modules like acoustic and CFD and conceptual fundamentals have been found out. Also, 3D model has been investigated the effect of multiple transducers over the erosion rate to improve the efficiency of cleaning process. Acoustic module has been applied to examine sound pressure level and CFD is for turbulence fluid flow, particle trajectories and erosion rate. It is obvious that the used of multiple transduces give better results than single one. But position of transducers is also an important factor for increasing cleaning rate.

Simulation results show that by using multiple transduces of 40 kHz frequency, the acoustic pressure 4.05 x 10^4 Pa, 3.36 x 10^5 Pa, 6.87 x 10^5 Pa, 1.07 x 10^{10} Pa, 1.73 x 10^{11} Pa and sound pressure level 184 dB, 203 dB, 208 dB, 272 dB and 317 dB for model 1-5 respectively has been achieved which are higher side compared to previous results of reference [1,3]. Sound pressure level is directly affecting to the acoustic pressure. It has been observed that acoustic pressure and sound pressure level are lower in cases of 2 transducers at bottom surface in model 1 to 3 while it is higher in model 4 and 5 which have 1 transducer at bottom face. In acoustic cleaning lower pressure waves are more dangerous than higher pressure waves. They have better intensity to remove the contamination material from the base metal. The same effects have been seen in von mises stresses too. Von mises stresses 1.96 x 10^6 Pa, 1.28 x 10^7 Pa, 2.22 x 10^7 Pa, 3.18 x 10^{10} Pa and 2.99 x 10^{14} Pa have been achieved in models 1 to 5 respectively. In addition, when 1-1 transducers attached on two opposite sides with 2 transducers at bottom (model-2), the vibration effect of the transducer side have been absorbed by non-transducer sides. So final result got little improvement. But when 1-1 transducers attached. On each four sides with 2 transducers at bottom (model-3), the vibration effects exploded in liquid to produce rich energy than other two models-1 and 2. Same has been observed in 1 transducer at bottom with 1-1 transducers on two opposite sides (model-4) with compare to 1 transducer at bottom with 1-1 transducers on each four sides (model-5).

Particle trajectories indicates the acoustic streaming of fluid flow with movement and distribution of bubbles in liquid media. The impacting motion of bubbles over the surface of object is responsible for removal of contamination The use of multiple transducers produces the momentum of bubbles in liquid media which boost the erosion rate and also uniform vibration effects have been achieved

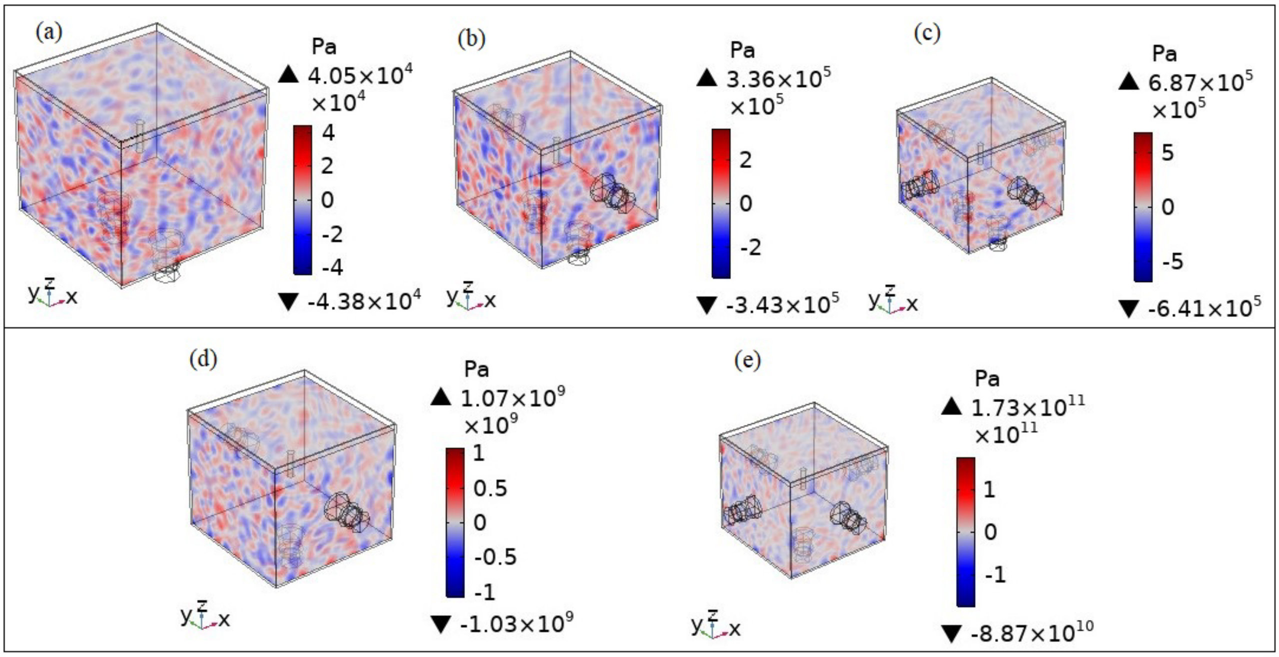

Figure 4. Acoustic Pressure, Pa: (a) Model-1:2B; (b) Model-2:2B-1-2OS; (c) Model-3:2B-1-4ES; (d) Model-4:1B-1-2OS; (e) Model-5:1B-1-4ES

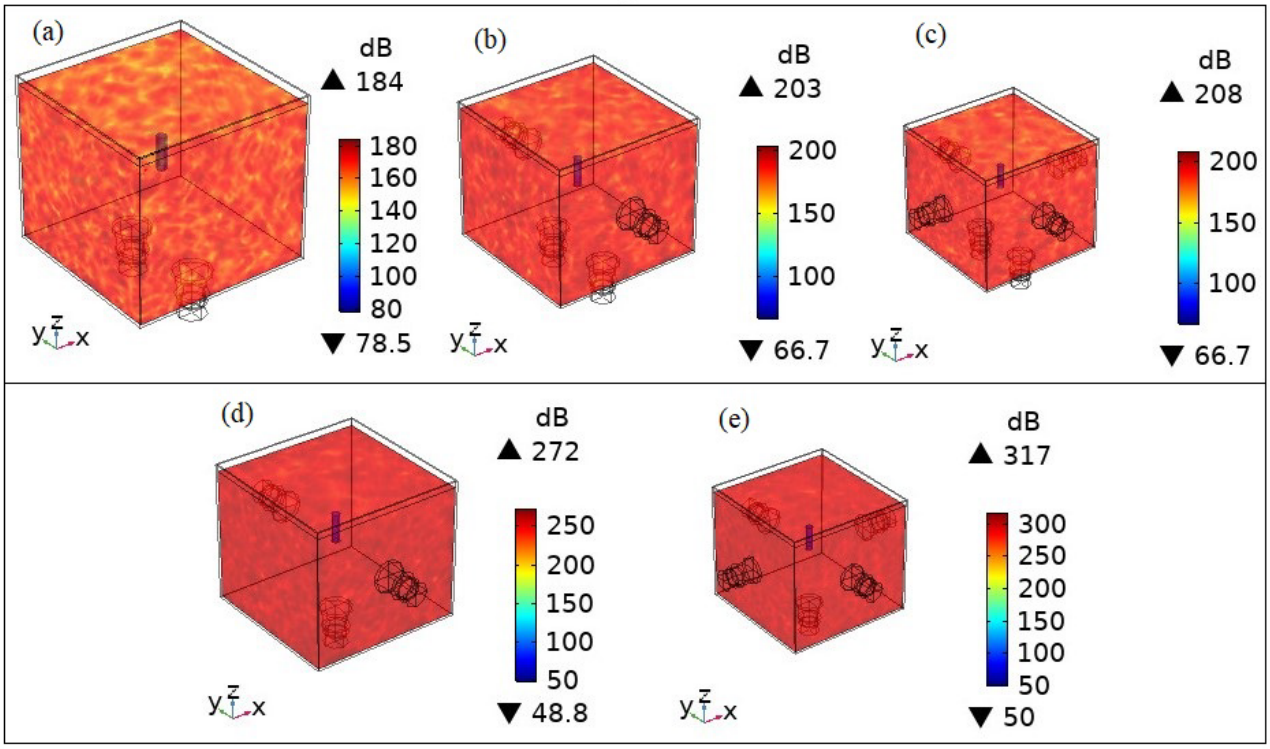

Figure 5. Sound Pressure Level, dB: (a) Model-1:2B; (b) Model-2:2B-1-2OS; (c) Model-3:2B-1-4ES; (d) Model-4:1B-1-2OS; (e) Model-5:1B-1-4ES

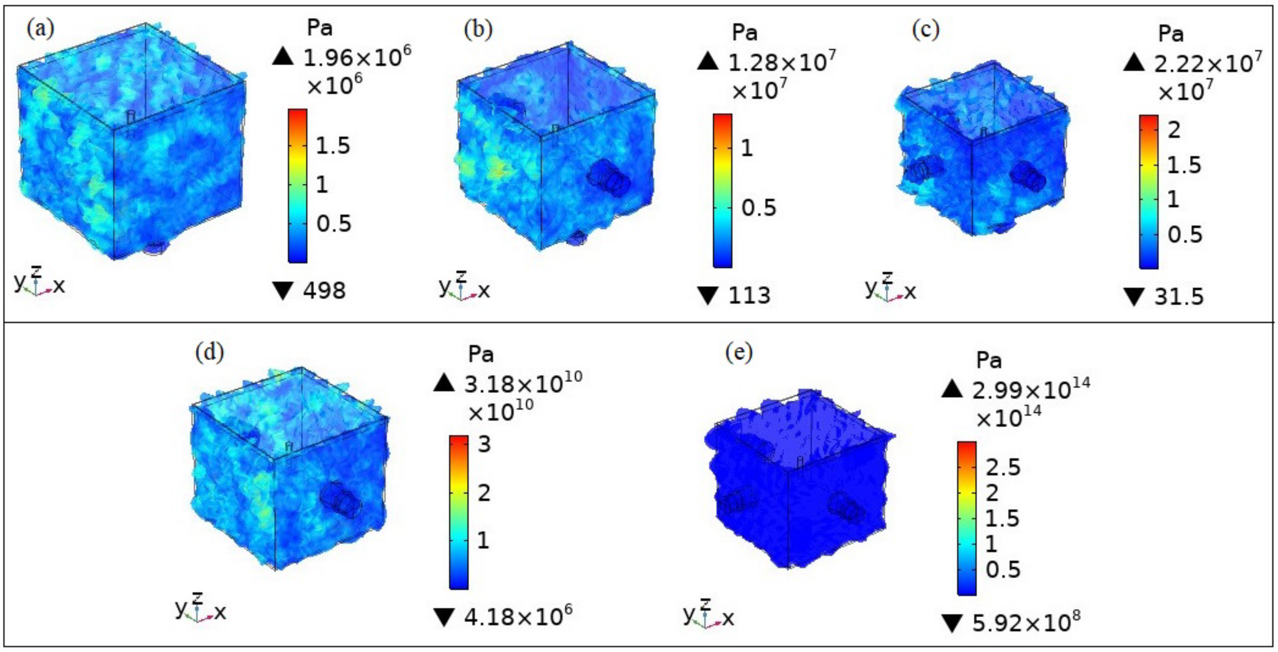

Figure 6. Von Mises Stresses, Pa: (a) Model-1:2B; (b) Model-2:2B-1-2OS; (c) Model-3:2B-1-4ES; (d) Model-4:1B-1-2OS; (e) Model-5:1B-1-4ES

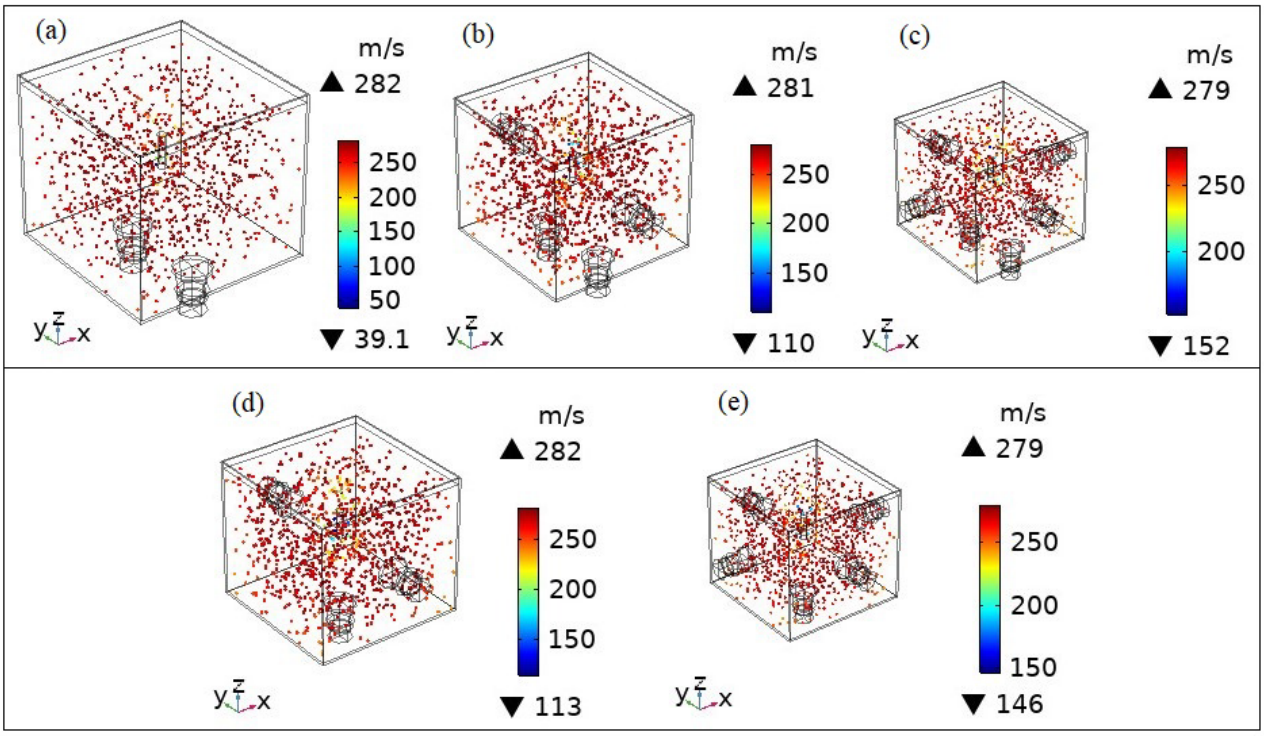

Figure 7. Particle Tracing: (a) Model-1:2B; (b) Model-2:2B-1-2OS; (c) Model-3:2B-1-4ES; (d) Model-4:1B-1-2OS; (e) Model-5:1B-1-4ES

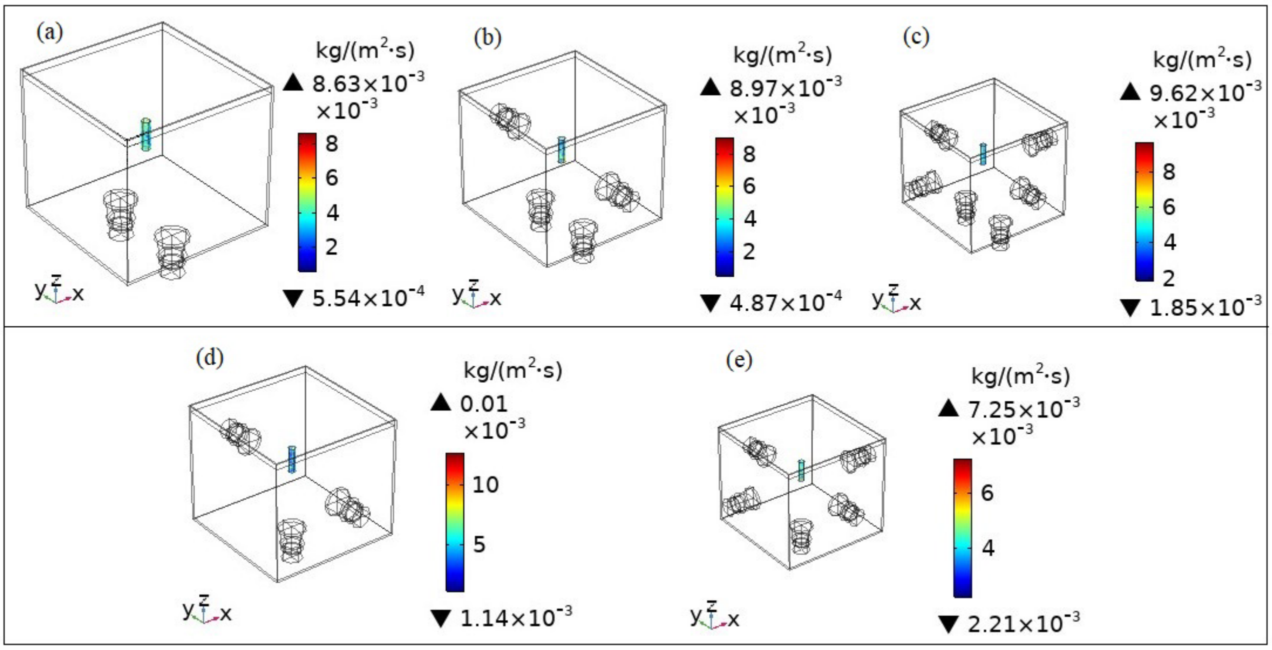

Figure 8. Erosion Rate, kg/m^{2}s: (a) Model-1:2B; (b) Model-2:2B-1-2OS; (c) Model-3:2B-1-4ES; (d) Model-4:1B-1-2OS; (e) Model-5:1B-1-4ES

So, the problem of unclean portion, while using for critical object has been resolved.

Erosion is the combined effect of drag force and acoustophoretic radiation due to rapid vibrating movement of fluid particles around the object surfaces. Here, Finnie model gives the erosion rates like 8.63 x 10^{-3} kg/m^{2}s, 8.97 x 10^{-3} kg/m^{2}s, 9.62 x 10^{-3} kg/m^{2}s, 0.01 x 10^{-3} kg/m^{2}s and 7.25 x 10^{-3} kg/m^{2}s for model 1 to 5 respectively. Here, 2 transducers at bottom and 1-1 on other sides (model- 1 to 3) give significant results than 1 transducer at bottom and 1-1 on other sides (model – 4 and 5). Among all, Model-3 with 2 transducers at bottom and 1-1 on each four sides gives efficient results of erosion rate 9.62 x 10^{-3} kg/m^{2}s. than other models.

Table 3. Summary of Results

Sr No	Model No	Acoustic Pressure (Pa)	Sound Pressure Level (dB)	Erosion rate (kg/m²s)
1	Model-1: 2B	4.05×10^{4}	184	8.63×10^{-3}
2	Model-2: 2B-1-2OS	3.36×10^{5}	203	8.97×10^{-3}
3	Model-3: 2B-1-4ES	6.87×10^{5}	208	9.62×10^{-3}
4	Model-4: 1B-1-2OS	9.07×10^{9}	272	0.01×10^{-3}
5	Model-5: 1B-1-4ES	1.73×10^{11}	317	7.25×10^{-3}

Based on cleaning requirement of components like critical shape or various mass objects, quantities of transducers and its placement may vary.

5. CONCLUSIONS

It has been concluded that multi-transducer models give efficient result in vibro cleaning. But position of transducer sticked an important factor for improvement in cleaning rate. From the study, square type cleaning tank has been used with different combinations of multi-transducer models. From them, 2 transducers at bottom gives suitable result than single transducer. Also, 2 transducers at bottom with other more on side walls make results more significant than others. Here, 2 transducers at bottom with 1-1 on each four sides (model-3) gives highest erosion rate 9.62×10^{-3} kg/m^2s than others.

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