

Study on the Snubber as a Pressure Pulsation Damper in Reciprocating Hydrogen Compressing System

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ABSTRACT: Due to rapid exhaustion of fossil fuel by its diversified and increased uses, its harmful effects on environment, energy capturing politics of different countries, and recent increase in the price of fossil fuels have added impetus to the movement towards alternative energy. The green energy based hydrogen has been becoming popular recently for its renewability and pollutant free properties. In all steps of hydrogen gas energy utilization: production, storage, distribution and end-use, compression is essential because of its low volumetric energy content. Since hydrogen will replace the role of fossil fuel, so all approach done in this field should be efficient and economic. It forms high pulsation waveform after passing through reciprocating compressor. A pulsation damper- “Snubber” is then used to reduce these harmful pulsation waveforms. An experiment has been conducted to investigate the role of snubber in regulating pressure pulsation developed in reciprocating compression. In order to get the detail pressure values at different parts of this snubber system, Computational Fluid Dynamics (CFD) analysis is applied. A comparative study of pressure pulsation by experiment and CFD model are performed. CFD estimates pressure pulsation reductions very close to that of experiment.

Keywords: Snubber, hydrogen compressing system, pressure amplitude, CFD

NOMENCLATURE

1. INTRODUCTION

Despite substantial contribution to today's civilization energy resources create unwanted environmental effects of various kinds- single or in combination. Such effects can be local or widespread and have long provoked concern. The emission of greenhouse gases: carbon dioxide, methane, nitrous oxide, and others is the most

significant environmental effects of energy production and consumption. They alter the earth's climate which is inhospitable to life. The United States, as one of the world's largest producers and consumers of fossil fuels, is responsible for a major portion of global energy-related emissions. A total of 2732.9 and 1,958.6 out of 5945.3 million metric tons of carbon dioxide emissions from energy consumption by industrial and transportation sector in 2005 [1]. Roughly 97% of all energy consumed by our cars,

sport utility vehicles, vans, trucks, and airplanes is still petroleum-based [2]. The increasing demand of energy for increased population and newly developed society, energy capturing politics of different country, and possibility of damage of environment make scientists to search for alternate future fuel and fuel vehicle. The recent hikes in the price of fossil fuel have added impetus to the movement towards hydrogen and other alternative fuels [3]. The physical and chemical properties of hydrogen make its utilization superior to fossil fuels. It is a simple, non-toxic molecule that generates power cleanly and efficiently, even silently and without combustion, if desired. As a versatile and universal carbonless energy carrier, hydrogen is a necessary element for future energy systems aimed at being free of air pollution, CO₂, and other greenhouse gases. If generated from renewable energy, hydrogen becomes the crucial link in an inexhaustible global fuel cycle based on the cleanest, most abundant, natural, and elementary substances: H₂, O₂ and H₂O [4]. In integrating production planning and reactive scheduling for the optimization of a hydrogen supply network, compressor is an essential part [5]. Reciprocating compressor is used in hydrogen compression for its higher pressure increasing capacity. But inherently there develops pressure pulsation resulted from reciprocating back and forth movement of piston inside the cylinder. It gives several various problems for the equipment related to the system and acting gas in it. This may cause inaccurate metering, unwanted vibrations, noises, explosions, shorten life of equipment, poor performance etc. of the hydrogen plant. Therefore, it should be lessened this pressure pulsations. Snubber or damper is linear unit designed to limit this sudden unwanted pressure pulsation [6]. It reduces the pressure fluctuation with restoring high pressure values and also removes the impurities contained in gas [7]. This study was taken to find out the snubber

performance in pressure fluctuation reduction by experiment and CFD during reciprocating hydrogen compression.

2. METHODOLOGY

2.1 Experimental set up

A snubber was constructed by acrylic material. It had one inlet pipe, one outlet pipe with 3 pressure measuring points in each and one tube shaped unit with incline placed 163.97 x 75 x 4.88 mm flat plate inside (Fig. 1). The inlet pipe was connected to the compressor using a small hose pipe and its outlet was exposed to the atmosphere. The experimental setup for its different components was as in Fig. 2. The experiment was conducted by running the compressor by motor setting at 10, 20, 30, 40, 50, and 60 Hz. Pressure value was sensed by pressure sensor at each measuring points, amplified and recorded in a PC using data logger.

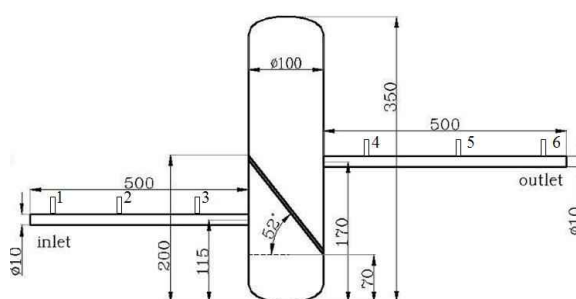


Figure 1: Snubber dimensions with pressure measuring points

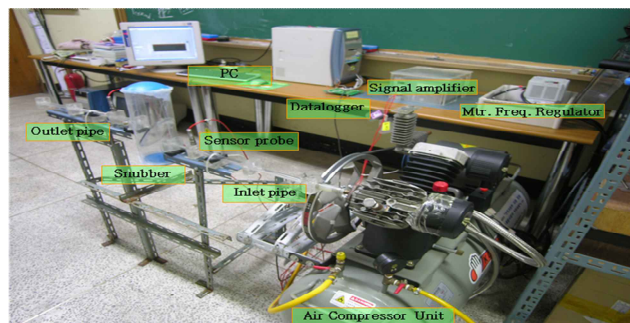


Figure 2: Experimental set up

Hydrogen gas has same character with the atmospheric air by physical approach. Air and hydrogen gas have almost the same

compressibility character. So, air was used in this experiment instead of hydrogen considering safety and availability issues.

2.2 Experimental Methods

Motor driven reciprocating pump controlled by frequency regulator was used in this experiment. The compressor rotation and its frequency were as in eq. (1) and (2).

$$\omega_{\text{comp}} [\text{rpm}] = f_{\text{set}} [\text{Hz}] \times 12.84 [\text{rpm} / \text{Hz}] \quad (1)$$

$$f_{\text{comp}} [\text{Hz}] = f_{\text{set}} [\text{Hz}] \times 0.214 \quad (2)$$

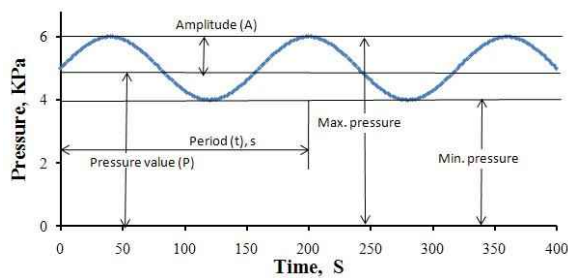


Figure 3: Basic theory of pressure fluctuation

The periodic action of propelling gas through a pipe by the to and fro movement of the piston in the cylinder in reciprocating compressor created pulsation that causes the force of vibration in the whole system. Simple description of fluctuating pressure is shown in Fig. 3 and the pressure and its amplitude can be derived as eq. (3) and (4).

$$P = \frac{P_{\text{max}} + P_{\text{min}}}{2} \quad (3)$$

$$A = \frac{P_{\text{max}} - P_{\text{min}}}{2} \quad (4)$$

Experimental data at every section were collected and analyzed them. Data at point 3 and point 4 were analyzed for pressure loss and amplitude reduction. RMS values of input and output pressure were used for pressure loss. FFT analysis was done to on data to find out amplitude values of the pressure waves. The resultant value was calculated by taking square root of summation of squares of all values [8]. Gas passing through a snubber will be reduced in magnitude of pressure and its fluctuations.

Then, pressure and pressure pulsation reduction were obtained by eq. (5) and (6).

$$P_{\text{red}} (\%) = \frac{P_{\text{in}} - P_{\text{out}}}{P_{\text{in}}} \times 100\% \quad (5)$$

$$A_{\text{red}} (\%) = \frac{A_{\text{in}} - A_{\text{out}}}{A_{\text{in}}} \times 100\% \quad (6)$$

2.3 Computational Methods

Star CD (Version 3.24) computational code is employed, which solve the full 3D time dependent Navier-Stokes, continuity and energy equations using finite volume method. It is widely used in the numerical simulation of different flow conditions in various complex geometries and was chosen in this study for its proven capability and validity. The turbulent flow in this investigation is considered as transient, incompressible, viscous, Newtonian and isotropic. The numerical solution involves splitting the geometry into many sub-volumes and then integrating the differential equations over these volumes to produce a set of coupled algebraic equations for the velocity components, and the pressure at the centre of each volume. The solver guesses the pressure field and then solves the discretised form of the momentum equations to find new values of the pressure and velocity components. This process continues, in iterative manner, until the convergence criterion is satisfied. Turbulent model was using standard k-ε model. SIMPLE algorithm revised pressure and convection term belong to Upwind Scheme. Maximum residual tolerance was set under the 0.001 [9]. The geometry was drawn using the CATIA (V5R15) and then imported to pro-Surf as an Initial Graphics Exchange Specification file (IGES). Inlet and outlet boundary conditions of snubber for CFD were applying the pressure from experiment at inlet (1) and outlet (6). The model was built in a half type for the symmetrical shape of the snubber and the symmetry boundary condition was applied (Fig. 4).

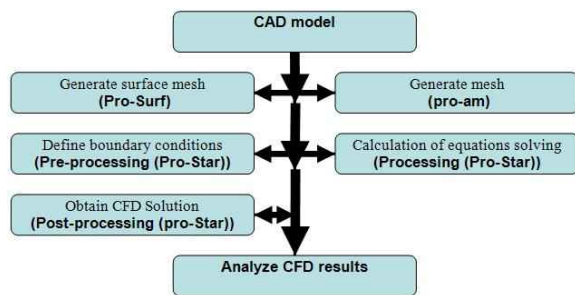


Figure 4: CFD analysis process

3. RESULTS AND DISCUSSION

3.1 Pressure Characteristics analysis

The gas pressures along the snubber system are varied corresponding to distance from the compressor outlet and motor frequency. Data obtained from the experiment show pressure characteristic of gas. The transient characteristic of gas is shown in Fig. 5. This pictorial view shows that higher pressure at inlet (P1) and then the pressure is reduced and reached at outlet (P6), and the distribution of pressure at different points of a snubber for 6 different motor speed. Along the snubber, six measuring points from input and output side are chosen as 1, 2 and 3 are in the inlet pipe at 7.5, 25.0, 45.0 cm; and 4, 5 and 6 are in the outlet pipe of the snubber at 74.0, 94.0 and 111.5 cm, respectively, from compressor outlet. RMS values of pressure are plotted against motor speed for different measuring points located at distant places from the compressor outlet and found these curve form. It shows that pressure drop line for 1, 2, 3 at 7.5 cm, 25.0 cm, 45.0 cm from compressor are similar fashion but different in slope for all the motor frequency setting. At the outlet part of the snubber have also alike fashion of pressure gradient line as inlet parts but with lesser slope for each pressure line for 4, 5 and 6. When motor frequency is set at 30Hz, the pressure at point 1, 2, 3, 4, 5 and 6 are 103.4879, 103.1812, 102.8375, 101.8500, 101.5282 and 101.3259 kPa, respectively. The highest pressure gradient is found for motor frequency 60 Hz and that of the lowest is at

10 Hz. The pressure gradient at point 1 and 6 are the highest and the lowest of all. There is a clear reasonable deviation in pressure line is found between 3 and 4 due to the main body of snubber. For higher motor frequency, the pressure reduction rate is also higher.

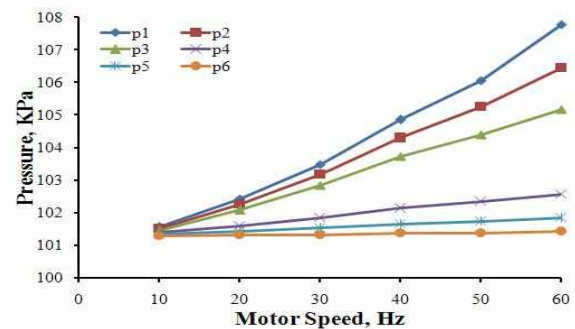


Figure 5: RMS values of pressure at corresponding to motor speed

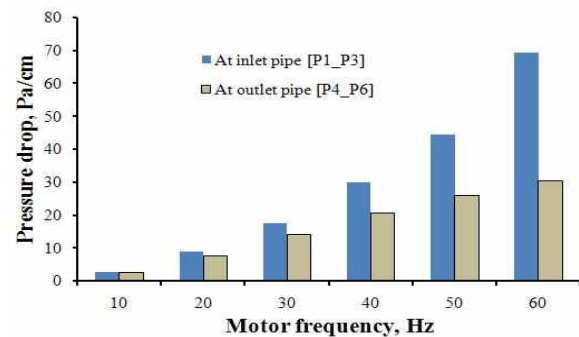


Figure 6: RMS values of pressure drop at inlet and outlet for various motor speed

The compressed gas flow are occurred in the inlet, tube shaped snubber and outlet acrylic pipe. Fig. 6 shows the pressure drop per unit length along the inlet and outlet pipe against specified motor speed. At inlet pipe, the pressure drop increases with the motor frequency. They are 2.6800, 8.9867, 17.3440, 29.9867, 44.4480 and 69.3147 Pa/cm for 10, 20, 30, 40, 50 and 60Hz, respectively. The maximum and the minimum pressure drop are occurred at 60 and 10Hz, respectively for both of the cases. At outlet pipe, pressure drop also varied with motor speed but less in magnitude that of inlet pipe. The 2.3471 Pa/cm and 30.3645 Pa/cm pressure are found as minimum and maximum for 10 and 60Hz at outlet pipe.

The variation of pressure in inlet or outlet does not follow any statistical relationship with the motor frequency.

Table I: Pressure amplitude and its reduction at snubber

Motor speed, Hz	Amplitude at snubber		
	Input, kPa	Output, kPa	% loss
10	0.2282	0.0948	58.4604
20	0.7931	0.3494	55.9466
30	1.3492	0.5633	58.2487
40	1.8810	0.8083	57.0261
50	2.0814	0.8977	56.8709
60	2.0205	0.8631	57.2832

Table II: Pressure magnitude and its reduction at snubber

Motor speed, Hz	Pressure at snubber		
	Input, kPa	Output, kPa	% loss
10	101.4571	101.3883	0.0678
20	102.0846	101.5995	0.4752
30	102.8375	101.8500	0.9603
40	103.7319	102.1418	1.5329
50	104.3943	102.3423	1.9656
60	105.1724	102.5648	2.4794

The pressure amplitude values of the flowing gas through the snubber are reduced different amount for different motor speed of compressor operation. Tube shape buffered snubber reduces its incoming amplitude to a considerable amount. Detail pictures are as in Table I. For motor frequency 10, 20, 30, 40, 50 and 60Hz, input amplitude are varied from 0.2282 kPa to 2.0205 kPa; and the minimum and maximum output amplitudes are 0.0948 kPa and 0.8631 kPa, respectively. Although the compressor operates with different motor speed, it results with almost same percentages of amplitude reduction. The amplitude reductions in the snubber vary from 55.9466% to 58.4604%. The pressure magnitude before and after the snubber, and its loss are determined and recorded for all setting of motor speed in Table II. Increased pressures are decreased here with the motor speed as it increase. The highest and lowest pressure loss are recorded as 2.4794% and 0.0678% for 60Hz and 10Hz. For 40Hz

motor frequency, the input, output pressure and pressure loss are 103.7319 kPa, 102.1418 kPa and 1.5329%, respectively. This indicates the best pressure restoring performance of the snubber.

Detail pressure amplitudes per unit length are shown in Table III. Pressured gas losses its amplitude in flowing through the system. The amplitude drop per centimeter of length in inlet pipe are 2.5733, 6.0899, 10.8360, 20.5243, 38.3142, 63.7240 Pa for the specified motor frequencies. But, at the outlet pipe drop of pressure amplitude are less in magnitude. The maximum 21.0838 Pa amplitude is dropped per centimeter of the outlet pipe for 60 Hz (Table IV).

Table III: Amplitude of pressure in inlet pipe of the snubber

Motor speed, Hz	Amplitude in Inlet pipe		
	At point 1, kPa	At point 3, kPa	Drop/cm, Pa/cm
10	0.3247	0.2282	2.5733
20	1.0215	0.7931	6.0899
30	1.7556	1.3492	10.8360
40	2.6507	1.8810	20.5243
50	3.5182	2.0814	38.3142
60	4.4102	2.0205	63.7240

Table IV: Amplitude of pressure in outlet pipe of the snubber

Motor speed, Hz	Amplitude in outlet pipe		
	At point 4, kPa	At point 6, kPa	Drop/cm, Pa/cm
10	0.0948	0.0088	2.2933
20	0.3494	0.0338	8.4144
30	0.5633	0.0545	13.5690
40	0.8083	0.0749	19.5579
50	0.8977	0.0729	21.9937
60	0.8631	0.0725	21.0838

3.1 CFD simulation of pressure

Fig. 7 shows the transient pressure values along the snubber system at 4 different sections. It gives clear idea about pressure pulsation and its reduction scenarios from point to point. There is more reduction from point 3 to point 4 due to snubber arrangement and then reduction between 3

and 4 is almost similar as 2 and 3. It is presented CFD simulation results for each section in Fig. 8 for 35 Hz. CFD simulated pressures are almost same behaviours that of pressure values find experimentally at these four sections.

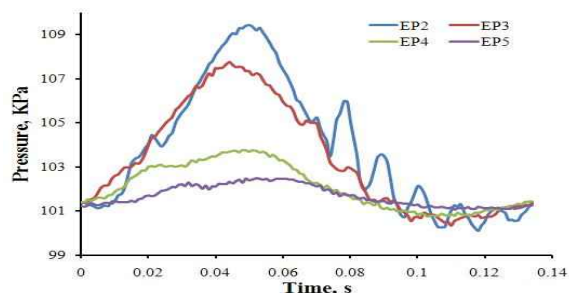


Figure 7: Experimental pressure values against time at snubber

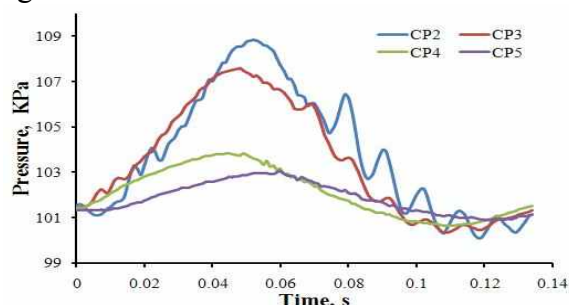


Figure 8: CFD simulated pressure values against time at snubber

RMS values are the best representation of the periodic variables. At different points of the snubber, the pressure are measured experimentally and simulated by CFD. Recorded data of these periodic pressure values are then calculated their respective RMS for both cases and presented in Fig.9. These values for simulation and experiment are very close to each other. It differs from point to point and possesses maximum near compressor and then decreases along the length for pipe friction but abrupt down fall of the pressure due to tube snubber. RMS values of pressure by simulation and experiment are 2(103.8692, 103.8624); 3(103.5051, 103.4031); 4(102.1157, 102.0861); 5(101.8647, 101.6803). The average values at these points are shown in Fig. 10 for both experimental and CFD. They also very close to each other at the

same points. These average of simulated and experimental values are 2(103.8327, 103.8219); 3(103.4759, 103.3748); 4(102.1101, 102.0810); 5(101.8624, 101.67923).

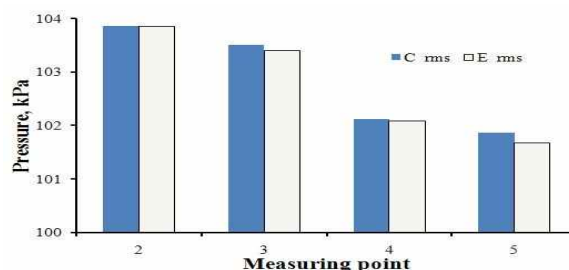


Figure 9: CFD simulated and experimental RMS pressure values at different points

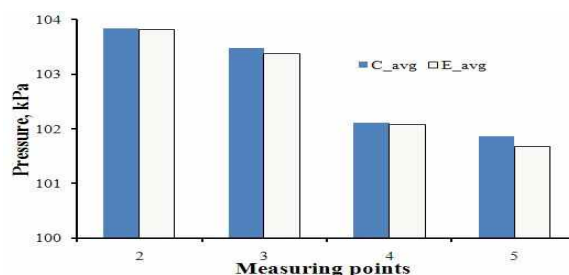


Figure 10: CFD simulated and experimental average pressure values at different points

Analyzing all these CFD calculated pressures at point 2, 3, 4, and 5 are well match with the pressure found in experiment. So, now we can allow the pressure distribution calculation of CFD to describe the pressure in the various points in the snubber system. Fig. 11 explains the pressure values in the snubber system with pictorial, numerical, maximum and minimum values for $t=0.043s$. High pressure is developed at the beginning in the inlet pipe and it dwindles gradually with length of pipe. But there is sudden pressure drop from point 3 to point 4 due to snubber main body. Inside the snubber main unit, the entrance point of snubber, below the buffer parallel to inlet pipe, exit pipe entrance has high pressure zones. At the beginning of time step, there form different pressures at various points but at end of time step it is demolished and then pressure is become well distributed throughout the snubber but some locations. At the time step 0.043s, the

maximum and minimum pressures are $0.1097\text{E}+06$ Pa and $0.8787\text{E}+05$ Pa, respectively at the entrance and exit point in the snubber system. Detail pressure distribution with graphical and numerical values at various time steps, can be obtained by selecting specific zone of the snubber model in CFD.

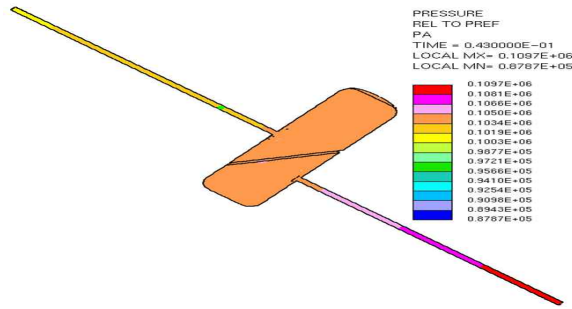


Figure 11: Pressure distribution in the snubber system at 35 Hz for $t = 0.043\text{s}$

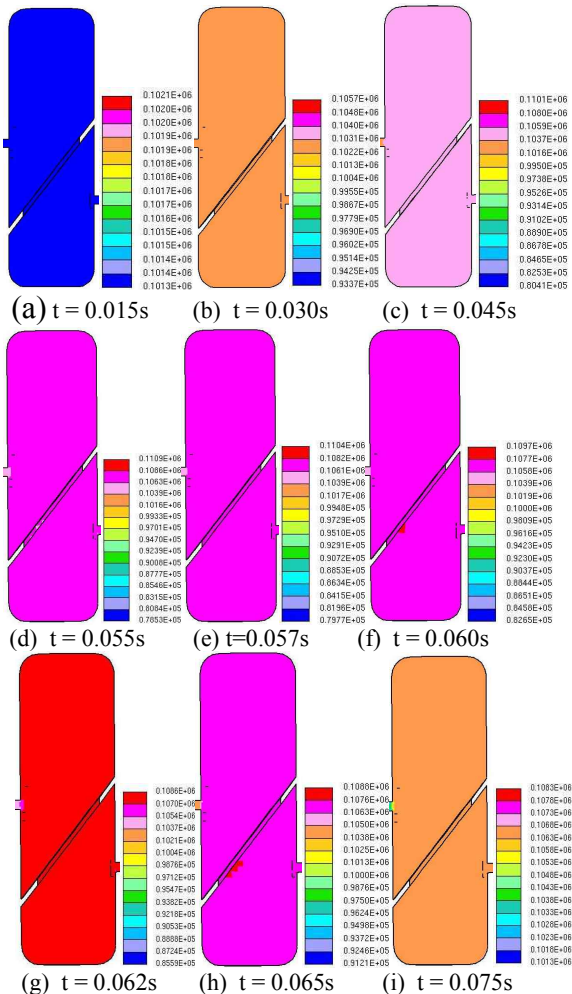


Figure 12: Pressure distribution inside tube shape of snubber for different time steps

For time step $t = 0.015\text{s}$, 0.030s , 0.045s , 0.055s , 0.057s , 0.060s , 0.062s , 0.065s and 0.075s the transient pressure distribution pattern in the tube shape inside buffered snubber are presented in Fig. 12 (a) – (j).

3.1 Comparison of experiment and CFD

Table V shows the comparison of experiment and CFD simulation result for amplitude reduction at the snubber with 35Hz motor frequency. Input amplitudes are found 1.503 kPa and 1.649 kPa from experiment and CFD simulation, respectively. Similarly, they have output amplitude as 0.630, 0.720 kPa by experiment and CFD, respectively. The percentages of amplitude reduction are 58.064% and 56.343% for experiment and CFD simulation. The variation of percentages of amplitude reduction from experiment is 1.721%. It indicates that CFD model credibility and efficacy and it can be applied for calculating pressure amplitude and amplitude reduction for any setting of motor frequency to run reciprocating compressor. Akbar *et al.* (2006) [10] showed that snubber with buffer had better performance than without buffer snubber in reduction of pressure fluctuation with less pressure loss. Experiment with steel snubber of different dimensions was resulted maximum 21.59% pressure pulsation reduction [11]. The input and output pressure by experiment and by CFD are 103.404, 102.077 and 103.508, 102.117 kPa, respectively. The pressure loss for experiment and CFD are 1.283% and 1.344%, respectively. The 0.061% deviation in pressure loss is found from experiment. So, it can be the best tool for calculating pressure pulsation reduction and pressure loss in the snubber by forming such CFD simulation.

Table V: Comparison of experiment and CFD simulation for snubber performance

Test type	Amplitude [P3 P4]			Pressure [P3 P4]		
	Input kPa	Output kPa	% Reduction	Input, kPa	Output, kPa	% Loss
EXP	1.503	0.630	58.064	103.404	102.077	1.283
CFD	1.649	0.720	56.343	103.508	102.117	1.344

5. CONCLUSION

Pressure fluctuation attenuation is essential in hydrogen chain economy. Numerical solution of various equations using CFD is a now-a-days tool to calculate pressure distribution in a system. CFD model can also predict the pressure information from which pressure pulsation and pressure loss can be obtained. In this study, CFD predicts pressure pulsation reduction as 56.343% and by experiment 58.064% pressure pulsation reduction is found. The percentage of pressure losses are estimated as 1.283% and 1.344%, for experiment and CFD simulation, respectively, at 35 Hz of motor speed running the compressor. As CFD facilities detail and specific point pressure in any system, it can be used for fastest and detail calculation of pressure pulsation and pressure loss at the snubber in hydrogen compression system.

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