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CFD Analysis on the 2nd Cylinder Discharge line in Hydrogen Reciprocating Compressor

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Abstract : Numerical analysis information will be very useful to improve fluid system. General information about an internal gas flow is presented by numerical analysis approach. Relating with hydrogen compressing system, which have an important role in hydrogen energy utilization, this should be a useful tool to observe the flow quickly and clearly. Flow characteristic analysis, including pressure and turbulence kinetic energy distribution of hydrogen gas coming to the cylinder of a reciprocating compressor are presented in this paper. Suction-passage model is designed based on real model of hydrogen compressor. Pressure boundary conditions are applied considering the real condition of operating system. The result shows pressure and turbulence kinetic energy are not distributed uniformly along the passage of the Hydrogen system. Path line or particles tracks help to demonstrate flow characteristics inside the passage. The existence of vortices and flow direction can be precisely predicted. Based on this result, the design improvement, such as reducing the varying flow parameters and flow reorientation should be done. Consequently, development of the better hydrogen compressing system will be achieved.

Key words : Hydrogen compression system, Discharge-path line, Numerical analysis, Flow characteristic analysis

1. Introduction

Hydrogen can be produced from a variety of sources, including fossil fuels; renewable sources such as wind, solar, or biomass; nuclear or solar heat-powered thermo chemical reactions; and solar photolysis or biological method. It is considered to be a prime fuel in supply and security, transition to hydrogen economy, environmental betterment, and social, societal, technological, industrial, economical and governmental sustain abilities in a country. Thus, green energy based hydrogen system can be one of the best solutions for accelerating and ensuring global stability and sustainability. Therefore, the production of hydrogen from non-fossil fuel sources and the development and application of green

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energy technologies become crucial in this century for better transition to hydrogen economy[1].

One of the most important processes in the hydrogen gas handling is the compressing system. This process is essential in all step of hydrogen gas energy utilization: production, storage, distribution until using. In addition since hydrogen will replace the role of fossil fuel, so all approach done in this field should be rewarded. This paper presents the study about gas flow characteristics in suction passage of hydrogen reciprocating compressor.

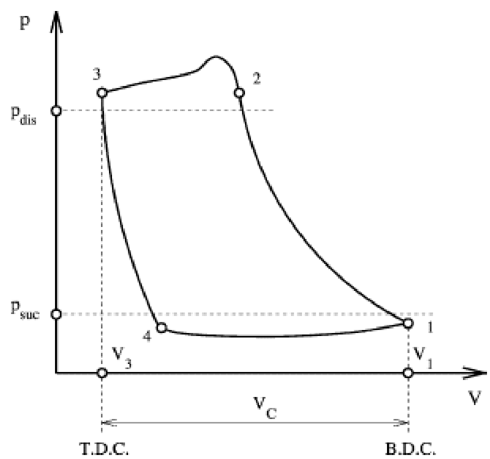

Figure 1: Indicator diagram of a reciprocating compressor.

2. Methodology

2.1 Reciprocating Compressor

Reciprocating compressor is one of the most popular machines which are used in industry. The effective and accurate diagnosis of possible faults which degrade compressor performances are required to help in both reducing maintenance costs and increasing the plant efficiency[2].

Figure 1 presents a schematic view of a reciprocating compressor and the indicator diagram for a typical cycle. When the piston moves downwards, it reaches a position where low pressured vapor is drawn in through the suction valve, which is opened automatically by the pressure difference between the cylinder and the suction chamber. The vapor keeps flowing during the suction stroke as the piston moves towards the bottom dead center (BDC), filling the cylinder volume with vapor at suction pressure, p_{suc}. The suction process is represented by curve 3-1 in the indicator diagram. After reaching the BDC, the piston starts to move in the opposite direction, the suction valve is closed, the vapor is trapped, and its pressure rises as the cylinder volume decreases. Eventually, the pressure reaches the pressure in the discharge chamber, p_{dis}, and the discharge valve is forced to open. After the opening of the discharge valve, the piston keeps moving towards the top dead center (TDC), represented by point A. It should be noted that suction and discharge processes do not take place at constant pressure. This phenomenon is associated with the dynamics of the valves and the restriction imposed by the valve passage areas. This appears on the indicator diagram, with compression continuing after pressure p_{dis} is reached and the same happening for the expansion stroke after pressure p_{suc}[3].

In industrial application, hydrogen gas compressing system is frequently used as the transferring or storing force device. It needs to be in high pressure condition;

therefore high working compressors are required. For this purpose, usually reciprocating type is used. Some aspects affecting performance of the compressor occur in the discharge passage. Since this is the gateway from compressed gas in the cylinder to discharge area.

2.2 Mathematical Model

The necessary reduction in the computational cost is sought here through two approaches. The simulation methodology combines differential and integral formulations for the governing equations. Differential equations are solved to capture flow details during the opening of the discharge valve, which are crucial to correctly predict its dynamics. The flow through the discharge valve could be solved in the same way following Matos et al[4-6].

Eddy viscosity turbulence models are based on the analogy between the molecular gradient-diffusion process and turbulent motion (Boussinesq model). The Reynolds stresses and turbulent scalar fluxes in these models are directly linked to the local gradients of the mean flow field through a turbulent viscosity determined by a characteristic turbulence velocity scale and length scale are very numerous, ranging from prescribed profiles to the popular two-equation models. Special models are also employed to characterize the flow near walls.

k-ε turbulence model comprising transport equations for the turbulence kinetic energy k and its dissipation rate ε. In these models, k and ε are chosen as typical turbulence velocity scale and length scale, respectively. The options differ from each other in one of the following respects:

2.3 The form of the equations

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = s_m \tag{1}$$

Conservation of momentum (Navier-Stokes equation)

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j u_i - \tau_{ij}\right) = -\frac{\partial p}{\partial x_i} + s_i \tag{2}$$

Turbulence kinetic energy

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}\left[\rho u_j k - \left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] = \mu_t (P + P_B) - \rho\varepsilon - \frac{2}{3}\left(\mu_t \frac{\partial u_i}{\partial x_i} + \rho k\right)\frac{\partial u_i}{\partial x_i} + \mu_t P_{NL} \tag{3}$$

Turbulence Dissipation Rate

$$\frac{\partial (\rho\varepsilon)}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_j \varepsilon - \left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] = C_{\varepsilon 1}\frac{\varepsilon}{k}\left[\mu_t P - \frac{2}{3}\left(\mu_t \frac{\partial u_i}{\partial x_i} + \rho k\right)\frac{\partial u_i}{\partial x_i}\right] + C_{\varepsilon 3}\frac{\varepsilon}{k}\mu_t P_B - C_{\varepsilon 2}\frac{\varepsilon^2}{k} + C_{\varepsilon 4}\rho\varepsilon \frac{\partial u_i}{\partial x_i} + C_{\varepsilon 1}\frac{\varepsilon}{k}\mu_t P_{NL} \tag{4}$$

2.4 Model Development

Model for simulation has been performed the fluid passage in the discharge-path line. The Discharge-path line is shown in Figure 2. Then the model was built considering the fluid area only, all dimensions are exactly same with the real compressor used by hydrogen plant.

The model is divided to three areas. First is the cylinder area; actually, this is also varying due to the movement of cylinder. This has circular profile. The second area is support valve. The gas from previous area is distributed to three channels here during pass from the outer to the center area. Then the gas is flow to the valve area. This is a narrow space which connects the support valve and the cylinder area. In the real device, there is a moving part named valve plate which has the function to go or stop the gas flowing. The last area is the outlet channel. Hence the minimum cylinder volume or the top death center (TDC) of the piston was modeled.

The CFD simulation in this study is used "STAR-CCM+". In the present study, the 3D, steady state, finite volume method was applied. Steady state condition was chosen at top death center (TDC) of piston, this happened at the same time with the valve are opened. Then the gas flow through the path-line can be assumed, as a steady state with both inlet and outlet boundary condition. The flow also was assumed as a

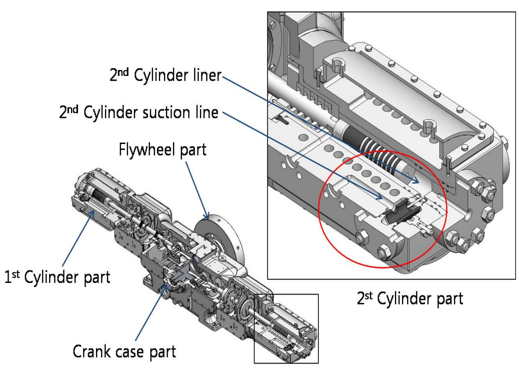

Figure 2: 2nd Discharge-path line in the Hydrogen reciprocating compressor

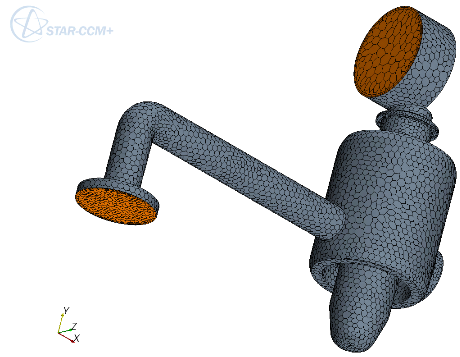

Figure 3: Grid of the 3D CAD model

compressible fluid regarding it is an expansion phase. Material applied is H2 gas according to the real application. For turbulence modeling, standard k – ε turbulence model was used.

3. Results and Discussion

CFD simulation gives numerical result that can be shown by vector and scalar. Parameters studied are velocity vector, absolute pressure and turbulent kinetic energy. From the series of plotted picture, the general phenomena can be interpreted clearly and precisely.

Figure 4 shows distribution of velocity magnitude. The highest velocity is seen in the valve area. Because that valve line space is become narrow suddenly.

The pressure distribution can be seen in Figure 5. The information about it is useful to analyze the passage structure stress load. The highest pressure is seen in the piston area. Then the pressure is decreased rapidly when it is passing through a valve. And the pressure is decreased at the horizontal outlet channel. Finally, the minimum pressure is reached in the discharge-path line.

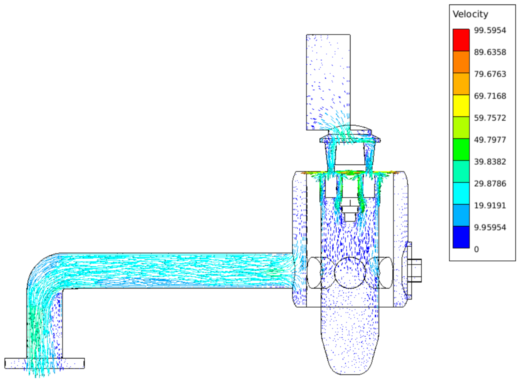

Figure 4: Velocity magnitude at middle plane section

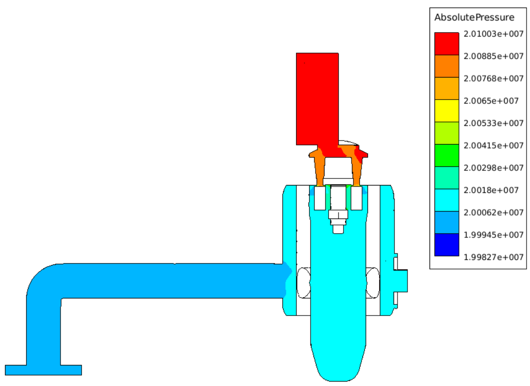

Figure 5: Absolute pressure at middle plane section

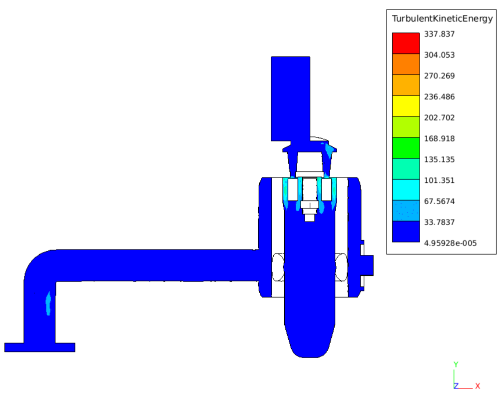

Figure 6: Turbulence kinetic energy at middle plane section

The turbulent kinetic energy is a dependent variable regarding the existence of turbulence in fluid flow. Consequently, the areas with high turbulent kinetic energy contain unstable flow. The distribution of it in the discharge-path area is presented in fig. 6. The highest quantity of turbulent energy is occurred at the passing through a valve area.

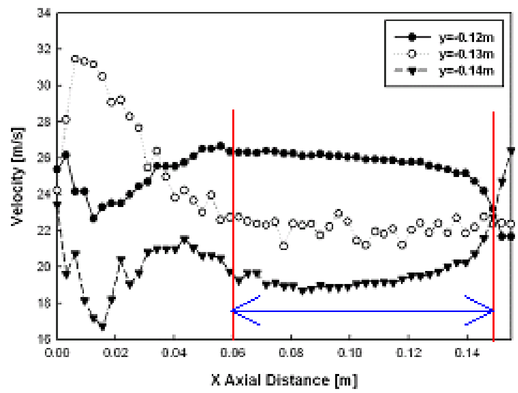

Figure 7: Velocity of different Y axial values at the horizontal inlet channel

Figure 7 shows velocity distribution at y= -0.12m, -0.13 and -0.14m in the horizontal outlet channel. In case of y= -0.12m, velocity is gradually increased until x=0.06m which is reached at 26m/s. then, it is decreased gradually to 23m/s until x=0.15m. Velocity at center of the passage i.e. at y= -0.13m is shown by line with empty circle symbol. At the beginning velocity is 24m/s and is increased sharply to 32m/s within 0.003m horizontal distance. Then, the velocity is sharply decreased to 23m/s and continued almost same value until end of the horizontal outlet path. The line probe 3 is at y= -0.14m i.e. bottom of the passage near wall, which shows suddenly decrease of initial velocity from 24m/s to 16m/s and then again change its direction to upward to a velocity 21m/s and gradually increased up to horizontal outlet channel for x=0.15m.

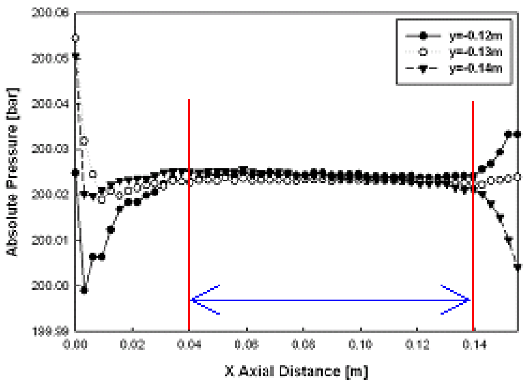

Figure 8: Absolute pressure of different Y axial values at the horizontal inlet channel

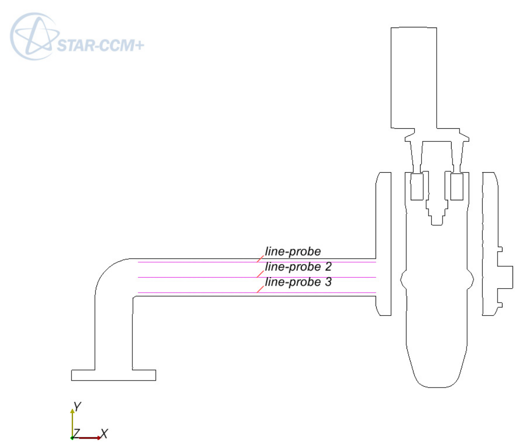

Figure 9: Line-probes of different Y axial values at the horizontal inlet channel

Figure 8 shows pressure distribution when y= -0.12m, -0.13 and -0.14m in the horizontal outlet channel. The pressure at the line near bottom wall starts from 200.05 bar and is rapidly drop to 200.02bar and it has a gradually increasing trend to 200.024 bar for x=0.04m. The center line and top line pressures have same suddenly decrease but different in amount. The center line pressure has more initial pressure than near top wall pressure and are reached the same pressure (200.024 bar) value at x=0.04m. The pressure has similar pattern from x=0.04m till x=0.14m for all. It maintains same value for central probe but lower wall probe and upper wall probe follow sharply decrease and increase pressure pattern, respectively, from x=0.14 to end of the passage.

4. Conclusion

It has seen clearly from above discussion that hydrogen gas flow in the discharge-path line has interesting special characteristics. Based on these CFD simulation results for discharge-path line, the design improvement will be done.

1. At y=-0.12m(line-probe), velocity is initially maintained the same value (26m/s) and then it is gradually decreased. At y=-0.13m(line-probe2), Velocity is continuously maintained the same value about 22m/s with little variation. At y=-0.14m(line-probe3), the initial velocity value is maintained the almost same value about 19m/s and then it is gradually increased up to the end. Finally, all values are equalized at x=0.15m. The velocity of this point is 23m/s.

2. Each of the values is presented similar pattern and same values from 0.04m to 0.14m x-axial distance with 200.023 bar and 200.024 bar.

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