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Numerical analysis on centrifugal compressor with membrane type dryer

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Abstract. Moisture content is a common phenomenon in industrial processes especially in oil and gas industries. This contaminant has a lot of disadvantages which can lead to mechanical failure DEC (Deposition, Erosion & Corrosion) problems. To overcome DEC problem, this study proposed to design a centrifugal compressor with a membrane type dryer to reduce moisture content of a gas. The effectiveness of such design has been analyzed in this study using Computational Fluid Dynamics (CFD) approach. Numerical scheme based on multiphase flow technique is used in ANSYS Fluent software to evaluate the moisture content of the gas. Through this technique, two kind of centrifugal compressor, with and without membrane type dryer has been tested. The results show that the effects of pressure on dew point temperature of the gas change the composition of its moisture content, where high value lead more condensation to occur. However, with the injection of cool dry gas through membrane type dryer in the centrifugal compressor, the pressure and temperature of moisture content as well as mass fraction of H_2O in centrifugal compressor show significant reduction.

1. Introduction

Centrifugal compressors have numerous applications ranging from aircraft and process industries to oil and gas industries. This type of compressor is widely used due to high single stage pressure ratio, simple structure, long life and other favourable characteristics [1]. Centrifugal compressors are often required to maintain or increase gas flow into the pipeline system, since well flow and reservoir pressure tend to decrease over time. These happen due to depletion occur at reservoir. Thus, this type of compressor works as re-injection for the purpose of reservoir pressure maintenance. Generally, the gas extracted from the oil wells composed of many moisture contents including water vapour. However, water vapour or moisture content in gas is one of the reasons why performance of centrifugal compressor drops. Most common contaminants which lead to mechanical failure are carbon dioxide (CO_2) and hydrogen sulphide (H_2S), especially for parts that manufactured in low alloy steel. These carbon dioxide (CO2) become a dangerous contaminants when is associated with water vapour or and high pressure. Combination of carbon dioxide (CO_2), liquid water and high pressure leads to the formation of carbonic acid (H_2CO_3), which can heavily corrode the compressor component [2]. Besides, the effect of hydrates formation can lead to the compressor's leading edge blocking, can reduce the pipeline flow capacities and has potential to damage other process equipment such as filter and valves [3].

In order to control or prevent these problems, moisture content measurement in natural gas is important. The amount of moisture content in the gas can be measured by indicating the temperature of gas, called dew point temperature, where higher dew point temperature indicates high level of water vapour. Dew point temperature is the temperature where air or any gas is saturated with water and moisture content will begin to condense. All atmospheric air contains some water vapour which will begin to condense into liquid water when the gas is cooled past the saturation point, where it can hold no more water vapour. When the dew point temperature and gas temperature are same, the air is said as saturated [4]. Another factor that sensitive to dew point temperature is pressure of gas. As the gas pressure increase, the dew point temperature also increases. This happen due to the molecular of gas that compressed in compressor becomes turbulent flow. This is called dew point pressure. At this stage, the dew point pressure is higher than atmospheric pressure but the temperature of dew point always lower (or equal to) to gas temperature. These phenomenon affect the efficiency of compressor as volume production of natural gas per cycle decrease [4].

Designation of impeller is one of the solutions for DEC problem. For example, improving the blade angles of impeller [5], choosing different blade inlet and backward sweep of the impeller [6] and modification of impeller geometry in term of skew angle [7]. Another approach is to dry the gas itself. There are various methods to dry compressed air or gas such as refrigerated dryers, chemical dryers, desiccant dryers and membrane type dryers. In this study, we choose membrane type dryer as the mechanism to remove moisture content from the gas. Addition membrane type dryer on centrifugal compressor is chosen due to composition of water vapour trough continuous gas moving can be modelled numerically. In the real application, the mechanism of this kind of dryer is when the compressed air is moving through a bundle of polymer hollow fibres, the polymer hollow fibres attract the water vapour inside before it diffuse into thin selective layer until it reach outside of membrane layer [8].

2. Methodology

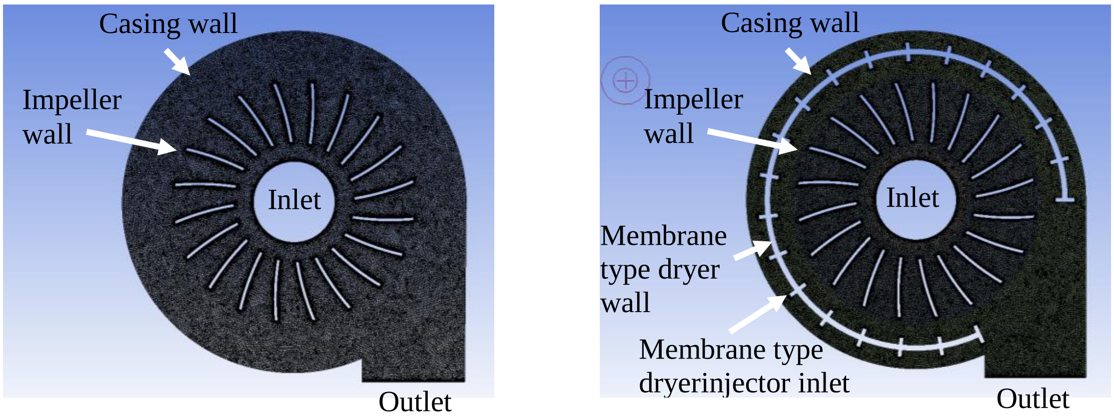
2.1. Multiphase flow

Multiphase flow model [9] is implemented in this work to numerically simulate the behavior of the moisture content around the compressor. Multiphase flow can be classified into four categories, gas-liquid or liquid-liquid flows, gas-solid flows, liquid-solid flows and three-phase flows. Existing moisture content or water vapor in gas indicates that this case as gas-liquid flows (presence of discrete fluid droplets in a continuous gas). There are two approaches in modelling multiphase flow; Euler-Lagrange approach and Euler-Euler approach [10]. In the Euler-Lagrange approach, fluid phase is treated as a continuum by solving the Navier-Stokes equations while Euler-Euler approach use concept of physic volume fraction which assume to be continuous functions of space and time. For the Euler-Euler approach, there are three multiphase models: volume of fluid (VOF), mixture model and Eulerian model [11]. In this study, analysis of moisture content behavior in centrifugal compressor is conducted using ANSYS Fluent with multiphase species transport model. Composition of moisture content in gas is analyzed based on pressure and temperature distribution.

2.2. Centrifugal compressor model

In order to compare the reduction of moisture content, two cases of centrifugal compressor are considered. Case 1 is the typical centrifugal compressor model and Case 2 is centrifugal compressor model with the addition of membrane type dryer. Both models were designed using SolidWorks 2014, which begins with 2D sketch, then follow with creating features and lastly combination of parts to create a complete model. The models are then saved in IGES format before imported into the ANSYS DesignModeler.

After importing geometry into the ANSYS, meshing step is required to solve the multiphase flow equations at discrete locations of the compressor's fluid domain. In this work, the author applied triangle elements to discretize the fluid domain with the addition of boundary layer mesh around the impeller walls. Meshing model for fluid region of centrifugal compressor without and with membrane type dryer is shown in Figure 1(a) and Figure 1(b), respectively.



(a) Without membrane type dryer. **(b)**With membrane type dryer.

Figure 1. Mesh of Centrifugal Compressor

2.3. Solver setup

Pressure-based solver is used in this research to solve the viscous flow and species transport of mixture content of water vapor and gas. The flow mixture content is assumed as viscous flow and k-epsilon is chosen as a turbulent model, which is considered appropriate for a flow in centrifugal compressor. As explained in the previous section, multiphase transport species is selected to obtain the changes of mixture content. The mixture-template is used to select the materials which involve mixture flow, which existing of water vapor along continuous gas.

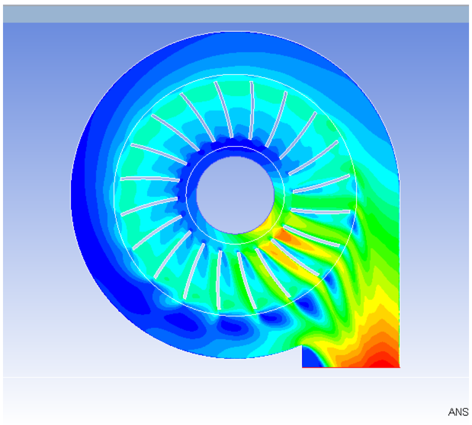
Other than that, in order to simulate the effect of impeller rotation to the gas in the compressor, multiple rotating frames technique is used in the ANSYS Fluent. Instead of using deforming mesh to make the impeller rotate, this technique allow the impeller to be fixed while the gas rotates around it, which has the same effect as rotating impeller. The boundary conditions, as shown in figure 1(a) and 1(b), are mainly consists of Wall, Inlet and Outlet. Casing wall and membrane type dryer wall are considered as non-slip, adiabatic and stationary wall, while impeller wall is set as non-slip, adiabatic moving wall with a rotational velocity of 523.6 rad/s in anti-clockwise direction. At the compressor Inlet, gas pressure is set manually and at the Outlet, static pressure is assumed to be equal to the standard sea level atmospheric pressure. In this study, 3 cases of gas pressure is set at the compressor inlet, which is 200 kPa, 300 kPa and 400 kPa. The 40 injectors around the membrane type dryer are assumed as Inlet, where each of them inject cool gas at the speed of 30 m/s into the compressor.

3. Result and discussion

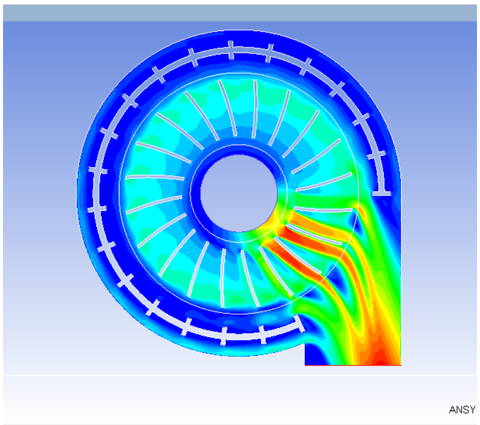
3.1. Velocity distribution

As the impeller rotating in anti-clockwise direction, Figure 2(a) and 2(b) show the mixture material moves together along the impeller before leave through the outlet. Those contour velocity magnitude indicate the mixture gas experiences highest velocity (yellow color background) at impeller region that close to the outlet. Thus, the casing region at the outlet has highest velocity compare to other region as the movement of impeller react as a re-injection to the mixture gas leaving the centrifugal compressor.

Besides that, addition of membrane type dryer into centrifugal compressor also affects the velocity of the mixture. In Figure 2(b) the mixture gas experiences high velocity at flow path from impeller region to casing region due to injection of cool gas into centrifugal compressor. Besides that, injection of cool gas through membrane type dryer forced the mixture gas moved toward the outlet region and reduces the velocity around casing region (blue color). The changes of light blue color to red color in impeller region towards outlet show the high velocity region where the water vapor is swept away. This high velocity of mixture indicates high pressure, hence in other word, injection of gas through membrane type dryer can help to increase gas pressure when the depletion of gas occurs.



(a) Without membrane type dryer.



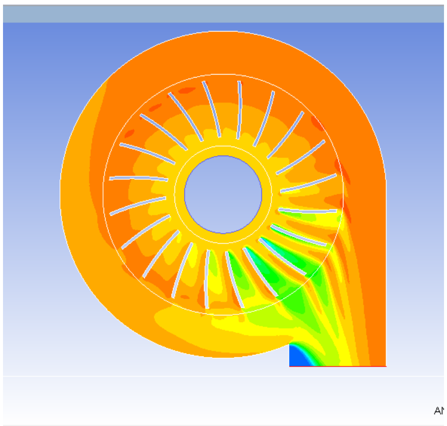
(b) With membrane type dryer.

Figure 2. Contours of velocity magnitude (compressor inlet pressure 200 kPa).

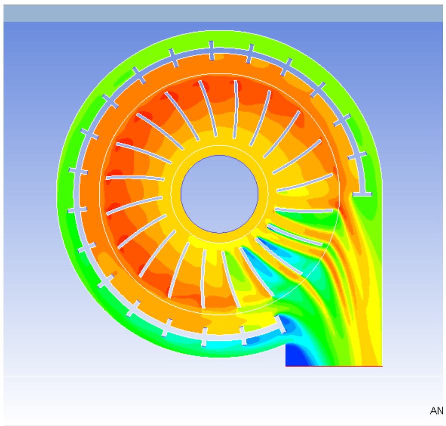
3.2. Pressure distribution

The kinetic energy of the water vapor and gas molecule increased as pressure increased in impeller region. These molecule collide each other and also cause friction to occur around impeller wall. This situation can be seen in Figure 3(a) and 3(b) where the leading edges experience high pressure compared to the trailing edge. High values of pressure indicate the gas more easily to condense and increase dew point temperature. At this stage, the dew point pressure is higher than atmospheric pressure but the temperature of dew point always lowers to gas temperature. Thus, membrane type dryer is proposed to be installed in the centrifugal compressor to control dew point temperature and pressure of the gas.

Based on Figure 3(b), there is different distribution color background for pressure of mixture. Injection of cool gas towards fluid region reduces the pressure of mixture content. The cool gas (green color) is injected with ratio of 1/10 of inlet centrifugal compressor into the fluid region act to cool the high pressure (reddish orange color) inside the centrifugal compressor. Decreasing the pressure of continuous gas with water vapor reduced the kinetic energy of molecules to collide with each other. This can be proved by the measurement of total pressure for each fluid region in the centrifugal compressor as stated in Table 1.Including the case where Inlet pressure is 200 kPa, the different value total pressure distribution for cases where Inlet pressure is 300 kPa and 400 kPa are also stated in the same table. Figure 4 illustrates the centrifugal compressor's fluid regions mentioned in the table.



(a) Without membrane type dryer.



(b) With membrane type dryer.

Figure 3. Contours of total pressure distribution (compressor inlet pressure 200 kPa).

Table 1. Total distribution pressure for each region for two different type centrifugal compressors with different pressure at inlet of centrifugal compressor.

Pressure (kPa)	Type of centrifugal compressor	Total pressure distribution (Pa)			
		Inlet region	Impeller region	Casing region	Average
200	Case 1	200534.80	223861.89	215789.92	213099.77
	Case 2	199746.63	210154.09	171141.39	191905.44
300	Case 1	300407.32	317841.42	310803.44	308486.12
	Case 2	299644.28	305793.13	234618.04	267709.21
400	Case 1	400314.84	411525.75	405800.78	403786.28
	Case 2	399547.79	401181.74	304120.59	347240.93

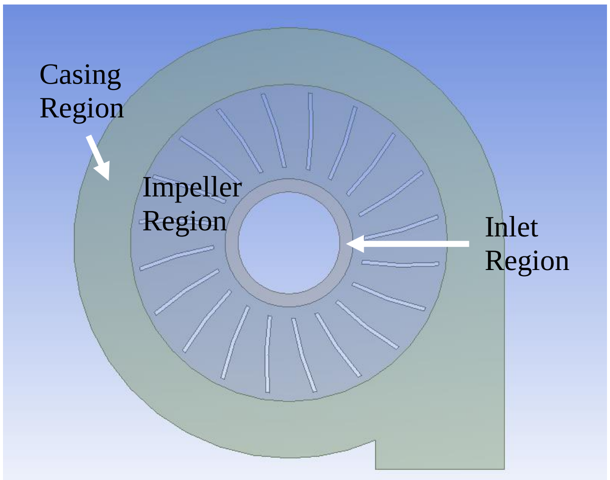


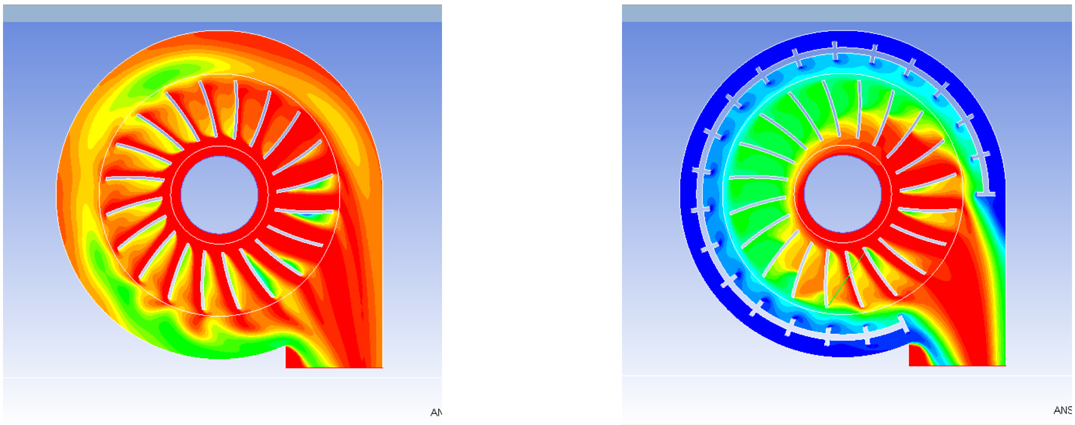
Figure 4. Fluid region of centrifugal compressor

3.3. Temperature distribution

Based on the theory of dew point temperature, the air cannot longer hold the water vapor as the temperature of air is raised to the dew point. At this point, the relative humidity is 100% if the water vapor begins to condense. Besides, higher dew point temperature indicates high level of water vapor. Thus, it is important to make the sure that the temperature of mixture content lower than dew point temperature.

The mixture content moves together along the blade of impeller when the blade is rotating. As a result, the temperature of mixture content slightly increases. The changes of green color into red color at impeller region in Figure 5(a) shows the temperature of mixture approach the dew point temperature where the water vapor inside the gas start to condensed. Furthermore, casing region near to the outlet show more in red color indicates higher temperature than other regions. This is because at this region more condensation of gas occurs to become liquid droplet. The temperature of leading edge experience high temperature compared to the trailing edge. Thus, as the temperature increase, the pressure also increases. This will lead more condensation of water vapor occur.

The contour of total temperature in centrifugal compressor for Case 1 and Case 2 show big difference value. For Case 2, the cool gas with temperature of 1/2 of inlet gas temperature is injected through membrane type dryer into centrifugal compressor to reduce the mixture temperature. Figure 5(b) shows that the cool (blue color) gas is diffused into casing region and impeller region which has high temperature initially. As a result, the continuous gas with composition of water vapor (high temperature gas) is push away to the outlet. This technique helps to cool down high temperature regions especially at impeller region and casing region. This reduction of temperature distribution help the water vapor from condense.



(a) Without membrane type dryer. **(b)**With membrane type dryer.

Figure 5. Contour of total temperature (compressor inlet pressure 200 kPa).

3.4. Mass fraction of $H_2 0$

Instead showing concentration water vapor in centrifugal compressor by using pressure and temperature distribution, simulation CFD software also provides multiphase species transport that can calculate mass fraction of water vapor or H_2O in centrifugal compressor. In this research, the gas extracted from the reservoir into centrifugal compressor is assumed to be composing with 50:50 ratio of water vapor to gas. Thus, the species transport model created in ANSYS Fluent has 50% air and 50% water vapor at inlet region. The composition of water vapor can be seen based on mass fraction of H_2O data inside centrifugal compressor for each region in Table 2.

Table 2. Mass fraction of H_2O for centrifugal compressor without membrane type dryer.

Pressure (kPa)	Inlet region		Impeller region		Casing region		Average	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
200	0.500	0.405	0.389	0.164	0.169	0.065	0.265	0.110
300	0.500	0.428	0.409	0.180	0.204	0.071	0.294	0.120
400	0.500	0.429	0.410	0.187	0.208	0.075	0.297	0.125

As shown in the table, the mass fraction of H_2O inside the centrifugal compressor slightly increase with increasing pressure. Mass fraction of H_2O represents the dew point pressure. This result prove as the pressure increase, the dew point pressure also increase. Thus, this condition leads to the increasing of dew point of temperature. Combination of water vapor with high pressure and carbon dioxide can lead the formation of carbonic acid which can corrode the centrifugal component especially impeller part. Therefore, the result is consistent with the theory. Besides proving the theory, the results of Case 2 show that mass fraction of H_2O, i.e. concentration of water vapor reduced in all compressor regions. This is due to the cool gas injected into centrifugal compressor to cool the impeller region from condensation occur and sweep the water vapor excess (extrude from reservoir) direct to the outlet

4. Conclusion

The results from the CFD were very effective and have the ability to show the behavior of multiphase flow of mixture content inside centrifugal compressor. The simulation result shows that the moisture content increase as the pressure increase. However, the addition of membrane type dryer in centrifugal compressor shows improvement in term of pressure, velocity, temperature and mass fraction of H_2O. The results show the water vapor can be reduced inside centrifugal compressor through the addition of membrane type dryer. The injection of cool gas from the membrane type dryer with moderate velocity helps to force the water vapor to exit through the outlet of the centrifugal compressor.

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Reference

[1] Sivaji Ganesh C, NagpurwalaCh and Bhaskar Dixit Q H 2010 Effect of leading edge sweep on the performance of a centrifugal compressor impeller *SAS Tech J.* **9** pp 55–62
[2] Guedes AV, de Carvalho Ferreira R, et d'Audenhov F D N and da Silva Marques B 2013 CO_2 corrosion on natural gas compressors: criteria and guidelines *Proc. of the 42nd Turbomachinery Symp.*
[3] Chung D D L 2001 Materials for thermal conduction *Appl Therm Eng* **21** pp 1593–1605
[4] Kolass R and Parker C n.d.Moisture measurement in natural gas accessed 11 Nov 2016 Retrieved from: http://www.iceweb.com.au/
[5] Röyttä P, Grönman A, Jaatinen A, Turunen-Saaresti T and Backman J 2010 Effects of different blade angle distributions on centrifugal compressor performance *Int. J. Rotating Machinery* **2009** pp 1–9
[6] Tough R A, Tousi A M and Ghaffari J 2010 Improving of the micro-turbine's centrifugal impeller performance by changing the blade angles *Int. Conf. on Computational & Experimental Engineering and Sciences* **14** pp 1–22
[7] Arunachalam V C, Nagpurwala Q H, Deshpande M D and Shankapal S R 2008 Numerical studies on the effect of impeller blade skew on centrifugal compressor performance *SASTECH J.* **7** pp 33–40

[8] Fish A 2017 The importance of drying compressed air *Parker Hannifin* accessed 28 June 2017 Retrieved from: http://blog.parker.com/facts-you-need-to-know-about-drying-compressed-air
[9] Brennen C E 2005 Fundamentals of multiphase flow *Cambridge university press*
[10] Sokolichin A, Eigenberger G, Lapin A and Lübert A 1997 Dynamic numerical simulation of gas-liquid two-phase flows Euler/Euler versus Euler/Lagrange *Chemical engineering science* **52** pp 611–626
[11] Fluent Inc. 2003 Fluent 6.1 user's guide p 1093