

# THE EFFECT OF ADDITIONAL COMPRESSIVE STRESS ON THE SEAL OF BOTTLE VALVE TO REDUCE THE LEAKAGE RATES OF LPG SUPPLY SYSTEM

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## ABSTRAK

Kebocoran sistem LPG memang tidak dapat dihindari dalam penggunaannya sebagai bahan bakar di rumah tangga, mengingat kebocoran yang terjadi pada sistem ini adalah salah satunya disebabkan oleh aliran difusi. Kebocoran akibat aliran difusi melalui karet perapat pada tabung LPG 3 kg sebagian besar disebabkan oleh aliran difusi laminar atau bila diketahui perbandingan compressive stress dengan gasket seating stress yang bernilai kurang dari satu, dan karakteristiknya berupa persamaan eksponensial. Penambahan compressive stress terbukti memperkecil aliran difusi yang menyebabkan pengurangan tingkat kebocoran mencapai 33,18 % untuk karet perapat NBR dan sebesar 36,43 % untuk karet perapat karet Vulkanisir. Pengurangan Laju kebocoran akibat penambahan compressive stress sangat dipengaruhi oleh material penyusun karet perapat (Rubber seal) yang direpresentasikan melalui nilai parameter AL dan nL. Analisa numerik memperlihatkan bahwa von mises stress yang diterima oleh karet perapat masih dibawah nilai yield strength dari material jenis karet dengan nilai Factor of Safety (FOS) mencapai 7,08 yang menegaskan bahwa defleksi yang terjadi pada karet perapat berada pada daerah elastisnya dengan nilai maksimum sebesar 0,326 mm. Selain itu, analisa numerik juga memperlihatkan bahwa aliran difusi yang terjadi pada karet perapat membentuk gradasi konsentrasi sesuai kedekatan dengan permukaan kontak difusinya.

**Kata kunci:** Laju kebocoran LPG, tegangan kompresif, aliran difusi, aliran laminar, karet perapat.

## ABSTRACT

*The leak of LPG system can not be avoided in its uses as domestic fuel which considering it is one of the result from diffusion flow. The leak because of diffusion flow in 3 kg LPG tube is mostly caused by Laminar diffusion flow known by comparing compressive stress with gasket seating stress which value less than 1 with characteristic in exponential equations. Augmentation of compressive stress is proved in minimizing diffusion flow which cause subtraction in leak until 33.18% for NBR seal and 36.43% for vulcanized seal. Minimizing leak caused by increasing compressive stress is very affected by seal material composed represented by AL and nL. Numerical analysis founded that von mises stress received by seal is still under yield strength from rubber material with Factor of Safety (FOS) achieve at 7.08, this condition affirms that deflection happened in Seal in its elastic area with maximum value about 1.326 mm. Beside that, numerical analysis show that diffusion flow is occurred in seal creating gradation concentration based on the imminent of diffusion contact.*

*Keywords:* leakage rate of LPG, compressive stress, diffusion flow, laminar flow, rubber-seal

## I. INTRODUCTION

Indonesian government policy which converts LPG to kerosene is followed by the number of accidental explosion of LPG cylinders when used by

public. Accident is often occurred started from a gas leak (leakage) in the fuel gas channel system which then can lead to a bolt of flame (flame flash back) that potential to create fires and even explosions. These

phenomenons are followed in case of blockage of fuel vapor (liquid-vapor lock) both on line and on LPG storage.

A rubber seal often a problem for user of LPG gas because this part is the main source of LPG gas leak causes<sup>[1]</sup>. Various attempts were made to improve the performance of the rubber seals, for example by the selection of materials and the addition of pressure on the regulator style with a variety model. But, in fact, this suppressor does not have a clear standard usage, especially the large force that must be given to obtain the optimal leakage reduction results.

This research focused on the effect of adding compressive stress on the rubber seals on the characteristics of the rate of leakage by using a laminar flow model of Hagen-Poiseuille and Knudsen molecular flow model. Leakage flow model refers to theories had been carried out by Gu Boqin<sup>[2,3]</sup> but it was not focused on LPG fuel system. This study uses two variants of seal that is widely available at the market with different material properties in order to know the performance characteristics of each seal against the addition of compressive stress<sup>[4]</sup>

**II. ANALYTICAL CALCULATION OF THE GAS LEAKAGE RATE THROUGH RUBBER-SEALING**

Rubber-seal LPG is one of the non-metallic seal which can be assumed as a porous media flow of gas through this medium with the approach of molecular and convective flow. The following equations are used in this research model:

**• Hagen-Poiseuille flow theory**

According to Hagen-Poiseuille flows theory, the equation of laminar flow through porous media is formulate as:

$$L_L = \sum_{i=1}^k \frac{\pi r_i^4}{16 \eta c l_m} (p_1^2 - p_2^2) \dots\dots\dots (1)$$

where LL is the stream flow rates (Pa m3/s), k is the number of pores, c is the coefficient of bending capillaries, p1 and p2 is the pressure at the inlet and the outlet (Pa), η is the dynamic viscosity (Ns/m<sup>2</sup>), l<sub>m</sub> is the average length of capillary holes (m), and r is the radius of the capillary (m). This laminar flow is the flow through the pores in which collisions occur only in molecules with pore walls, while collisions between molecules are ignored because the speed of the molecules is lower than the viscous flow with a larger pore diameter.

**• Knudsen law**

Formulations for molecular flow is as follows

$$L_M = \sum_{i=1}^k \frac{4r_i^3}{3cl_m} \sqrt{\frac{2\pi r t}{M}} (p_1^2 - p_2^2) \dots\dots\dots (2)$$

where L<sub>m</sub> is the stream flow rate (Pa m<sup>3</sup> / s), R is the gas constant (J / kg K), M is the molecular mass and r is the radius of the capillary (m). Molecular flow



**Figure 1**  
Installation of instrument at gas leak research



**Figure 2**  
Regulator for connecting to the LPG storage

is a flow through the pores in which collisions occur between molecules and molecules with the wall so resembles viscous flow.

• **Total Leakage**

This study uses two types of flow that is *molecular flow and laminar flow* depends on the magnitude of the comparison between the stress given to seal the *gasket seating stress*. *Gasket seating stress* ( $\sigma_0$ ) is the maximum stress experienced by the seal during installation of LPG gas is used. If the ratio  $\sigma/\sigma_0 < 1$  then most of the flow is laminar flow and if the value of  $\sigma/\sigma_0 > 1$  then the flow is the molecular flow<sup>[2]</sup>. Total leakage which is a combination of leakage due to laminar and molecular flow defined in the equation (3).

$$L_M = \sum_{i=1}^k \left( \frac{4\pi r_i^4}{8\eta c l_m} + \frac{4r_i^3}{3c l_m} \sqrt{\frac{2\pi r t}{M}} \right) (p_1^2 - p_2^2) \dots\dots (3)$$

The addition of compressive stress on the rubber-seal of LPG caused changes of the pore properties of both the number of pores and pore radius. Compressive stress has the effect of these parameters into the equation (4)

$$k = f_1 (\sigma^{-m}), r_i = f_2 (\sigma^{-n}) \dots\dots\dots (4)$$

With respect to the addition of compressive stress then the total leakage rate equation becomes (5)

$$L = \left[ A_L \frac{1}{\eta} \left( \frac{\sigma}{\sigma_0} \right)^{-n_L} p_m + A_M \sqrt{\frac{T}{M}} \left( \frac{\sigma}{\sigma_0} \right)^{-n_M} \right] \frac{(p_1 - p_2)}{l} \dots\dots\dots (5)$$

**III. TEST APPARATUS AND PROCEDURE**

This research uses a setup as shown in Figure 1 where 3 kg LPG gas cylinder connected to a pressure meter via a series of connectors that maintained its locked out to avoid any leakage.

To remove the gas from the tube of LPG regulator is used for regulatory function that eliminated with cleaved as shown in Figure 2.

The steps undertaken in this experiment are:

1. The 3 kg LPG storage is placed on the scale (mass counter) with forward-facing position for easy installation of pressure regulators.
2. LPG gas cylinder is connected to a pressure meter using a connector that has a fixed position for each trial for seals and large variations in emphasis.

3. Leak testing for all LPG connections to be proved using bubble soap leakage test.
4. Pressure regulator is installed just above the LPG cylinders with a symmetrical position to obtain a uniform distribution of force.
5. Scales and pressure meter were switched on and waited until the value indicated by scales and pressure meter was stable.
6. Data is taken 150 minutes long with interval every 5 minutes. There was 5 times the retrieval of data for each seal by pressing the spin rate of 0, 0.25, 0.5, 0.75, and 1.

**IV. NUMERICAL METHODS**

This research used numerical method which are the Finite Element Analysis using Solid Works 9 and analysis of flow through a porous media using the software COMSOL 4.1. Finite Element Analysis (FEA) is used to study the response of the construction of the rubber seals when installed on the bottle valve and burdened by a static load. Two things are became the focus of the FEA:

- Strain  
Rubber seals as an elastic materials that can be deformed (deformable body) when subject to the force (force), then the stress – strain deformation will occur, i.e. changes in the shape and size. Measurement involves the changes of size, either length and angle<sup>[5]</sup>.
- Von Mises  
Yield strength of material will be occurred when the energy of distortion or shear strain energy of the material reaches a certain critical value. In simple terms, it can be said that the distortion energy is part of the total strain energy per unit volume involved in the changes in shape. Distorted energy as part of the total strain energy is expressed in the formula<sup>[6]</sup>.

$$ud = \frac{1 + \nu}{6E} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \dots\dots(6)$$

with E is the modulus of elasticity,  $\sigma$  is stress, and  $\nu$  is the poisson ratio.

The numerical analysis used in this study is COMSOL 4.1a CFD software which can simulate double phenomenon (multiphysics). In this study are the influences of static load flow and diffusion.

**V. RESULT AND ANALYSIS**

**A. Flow of mass per time unit**

This research focused on NBR and vulcanized seal that are given compressive stress using stressor regulator screw type.

The Figure 3: and Figure 4: show that the different characteristics shown by each level of emphasis, which saw the declining trend of reduction in mass ( $\Delta m$ ) with increasing rotation. According GU Boqin, CHEN Ye and Zhu Dasheng in their research entitled *Prediction of Leakage Rates Through Sealing Connections with Nonmetcallic Gaskets*<sup>[2]</sup> stated that with the addition of compressive stress on the seal with a non-metal material will result in a large reduction in the number and radius of the pore (leakage path) of the seal.

The addition of compressive stress on the second graph shows that there is a reduction in the rate of

leakage. Reduction that occurred in this study can reach to 36.43% for volcanic seal and 33.18% for seal NBR.

**B. Leakage Rates Equation**

Leakage rate equation is obtained by the approach flow through a porous membrane according to equation 5. Due to the value of  $\sigma$  (the addition of compressive stress)  $< \sigma_0$  (gasket seating stress), the leakage flow can be assumed as laminar flow by eliminating components flow rate leakage derived from molecular flow. Gasket seating stress values for the rubber seals of LPG based on ISO 7655:2010 is 1.85 MPa. Equation 5 can be further written into the equation (7).

$$L = \left[ A_L \frac{1}{\mu} \left( \frac{\sigma}{\sigma_0} \right)^{-n_L} P_m \right] \frac{P_1 - P_2}{l} \dots\dots\dots (7)$$

Linearization of equation (7) is done to have a simple linear equation.

$$y = ax + b$$

by using a natural logarithmic, so equation (7) become

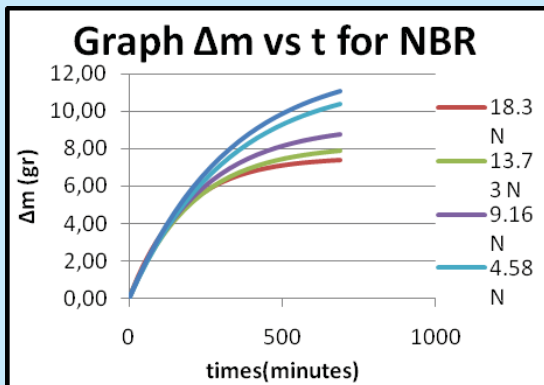
$$\ln L = \ln \left[ \left[ A_L \frac{1}{\mu} \left( \frac{\sigma}{\sigma_0} \right)^{-n_L} P_m \right] \frac{P_1 - P_2}{l} \right]$$

$$\ln L = nL \ln \left( \frac{\sigma}{\sigma_0} \right) + \ln \left( \frac{A_L \cdot P_m}{\mu} \cdot \frac{P_1 - P_2}{l} \right)$$

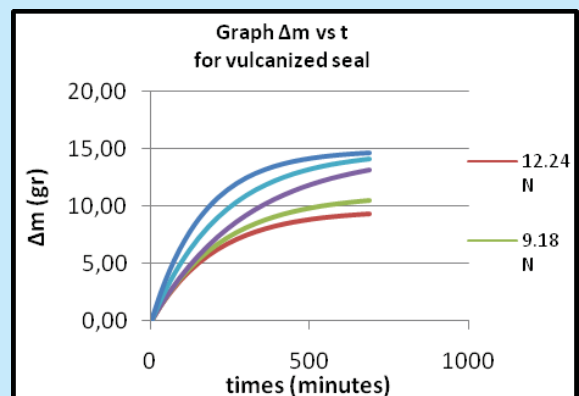
The coefficient  $A_L$  and  $-nL$  can be found by plotting graph  $\ln L$  vs  $\ln (\sigma/\sigma_0)$

**Table 1**  
**Force versus rotation to seal**

Rotation	Length of rotation (mm)	Force (N)	
		NBR	Vulcanized
0	0	0.00	0.00
0.25	0.305	4.58	3.06
0.5	0.61	9.16	6.12
0.75	0.915	13.74	9.18
1	1.22	18.31	12.24



**Figure 3**  
**Graphic  $\Delta m$  versus time for NBR seal**



**Figure 4**  
**Graphic  $\Delta m$  versus time for vulcanized seal**

$$\ln L = y$$

$$-nL \ln\left(\frac{\sigma}{\sigma_0}\right) + \ln\left(\frac{A_L \cdot P_M}{\mu} \cdot \frac{P_1 - P_2}{l}\right) = -0.248x - 7.856$$

$$-0.248 = -nL$$

$$nL = 0.248$$

$$-7.856 = \ln\left(\frac{A_L \cdot P_M}{\mu} \cdot \frac{P_1 - P_2}{l}\right)$$

$$3.8 \times 10^{-4} = \frac{A_L \cdot P_M}{\mu} \cdot \frac{P_1 - P_2}{l}$$

$$3.8 \times 10^{-4} = \frac{A_L \cdot 3.482 \times 10^5}{0.00022} \cdot 2001.691 \times 10^5$$

$$A_L = 1.19 \times 10^{-21}$$

$$L = \left[ 1.19 \times 10^{-21} \frac{1}{\mu} \left(\frac{\sigma}{\sigma_0}\right)^{-0.248} P_M \right] \frac{P_1 - P_2}{l} \quad \dots\dots (8)$$

The leakage rates of Vulcanized Seal by the similar way to NBR seal is

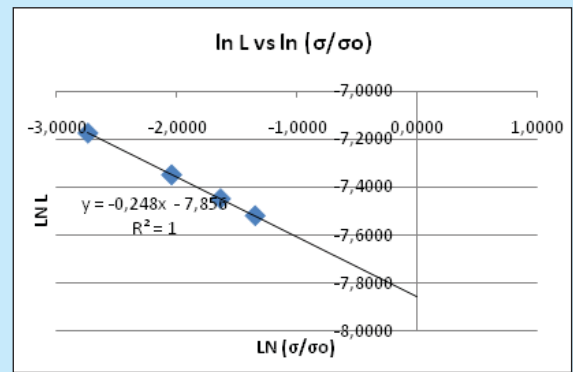


Figure 5  
Graph ln L vs ln (σ/σ₀) for NBR

So the leakage rates equation of NBR is

Table 2  
Value of ln L vs ln (σ/σ₀) for linearization Leakage Rates Equation of NBR

Rotation	L (Pa m3/s)	σ/σ₀	ln L	ln (σ/σ₀)	pm (bar)	p1-p2/l (bar/m)	x (mm)	F (N)	σ (N/m²)	
0	0.00081		-7.11		3.51	2025.88	0	0	0	
0.25	0.00077	0.065	-7.17	-2.73	3.51	2030.69	0.30	4.57	119508.6	
0.5	0.00064	0.129	-7.34	-2.04	3.50	2017.95	0.61	9.15	239017.2	
0.75	0.00058	0.194	-7.44	-1.64	3.45	1979.44	0.915	13.73	358525.8	
1	0.00054	0.258	-7.51	-1.35	3.42	1954.47	1.22	18.31	478034.4	
average					<b>3.48</b>	<b>2001.69</b>				

Table 3  
Value of ln L vs ln (σ/σ₀) for linearization Leakage Rates Equation of Vulcanized seal

Rotation	L (Pa m3/s)	σ/σ₀	ln L	ln (σ/σ₀)	pm (bar)	p1-p2/l (bar/m)	X (mm)	F (N)	σ (N/m²)	
0	0.00108	0	-6.83	0	3.55	2147.03	0	0	0	
0.25	0.00104	0.04	-6.86	-3.08	3.55	2143.68	0.30	3.06	84361.67	
0.5	0.00097	0.09	-6.94	-2.39	3.42	2037.42	0.61	6.12	168723.3	
0.75	0.00077	0.14	-7.17	-1.98	3.40	2020.12	0.91	9.18	253085	
1	0.00069	0.18	-7.28	-1.70	3.47	2079.70	1.22	12.24	337446.7	
average					<b>3.48</b>	<b>2085.59</b>				

$$A_L = 1.28 \times 10^{-21}$$

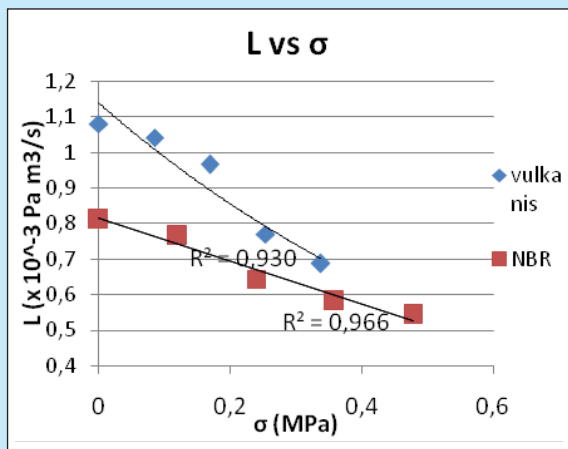
$$nL = 0.305$$

$$L = \left[ 1.28 \times 10^{-21} \frac{1}{\mu} \left( \frac{\sigma}{\sigma_0} \right)^{-0.305} P_m \right] \frac{P_1 - P_2}{l} \dots\dots\dots (9)$$

The thing to be observed is the value  $A_L$  and  $nL$  from two equations that show the characteristics of the leakage rate, where the greater value  $nL$  and  $A_L$  are the greater the leakage rate. These cases will be occurred the compressive stress smaller than the gasket seating stress.

**C. Leakage Rates Against the addition of Compressive Stress**

The Figure 6. show the compressive stress in general more sensitive or has greater influence to volcanic seal in compared with NBR seals for the values of  $\sigma$  at 0-3.5 kPa as seen from the slope of the graph. This phenomenon is caused by the tendency of different properties for the NBR seal in accordance with equation 4 in which  $f_1$  and  $f_2$  are functions that depend on the type and geometry of the material given stress  $\sigma$ . The difference function which is the tendency of different characteristics of the leakage rate for the second seal when given the stress from the outside. Number of pores ( $k$ ) and pore radius ( $r$ ) is the factor that determines the flow rate of diffusion so that when the functions  $f_1$  and  $f_2$  are different then it will indirectly affect the flow pattern of diffusion which will be reflected from the leakage.



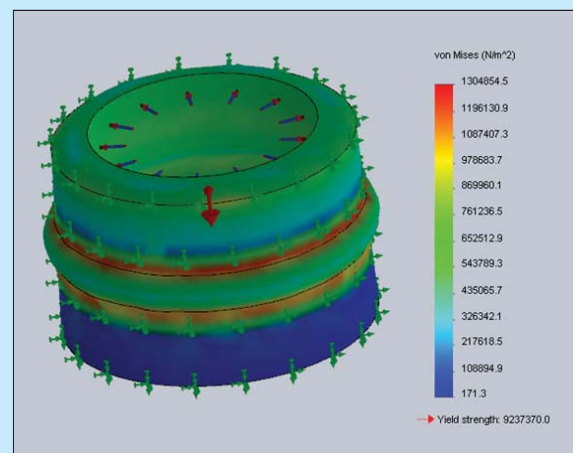
**Figure 6**  
Leakage rates versus addition of compressive stress

Rubber vulcanized seal generally have a greater leakage rate compared with NBR seals. This is especially noticeable at the condition without the addition of compressive stress where there is a difference value is very large leakage rate between the two types of seals.

**D. Analysis of Von Mises Stress Results**

The maximum value of Von Mises stress occurring is equal to 1304854.5 N/m<sup>2</sup> whereas the minimum values ranging from 171.3 N/m<sup>2</sup>. This resulted the seal that actually has an area (section) of work is uneven in every its part. From the figure due to the imposition of the deformation occurs in the middle area which has a thickness which is thinner than other parts of rubber seals, so it is natural that the deformation and von Mises stress occurs in this region of great value. The lowest value of von Mises is at the lower of the seal. It is due at the bottom of this there is a fixed fixture where the presence of fixed contributing to the style of the fixture (in this case is the basis bottle valve) to the lower base resulting in stress reduction received by the rubber. It also resulted in a stress gradient from bottom to top are visible on the outer surface of the rubber.

From the results of von Mises can be seen that the maximum von Mises value is lower than the yield strength of this seal. Comparison of yield strength values of von Mises maximum value known as the Factor of Safety (FOS), which in this case is worth 7.08. FOS value in this case is quite large, which



**Figure 7**  
Von Mises Stress results from FEM

means energy is distorted when loading has not been able to (difficult) to cause the rubber sealing material is plastically deformed so that it can be said of deformation that occurs is still in its elastic region.

### E. Deflection Analysis Result

Deflection which occurred on seal resulted of loading at maximum value as 0.3236 mm and minimum value approaches 0. The maximum deflection is occurred at the center of seal where is indicated by reduction of concave and thickness of seal effected elasticity of seal is higher.

Minimum area of deflection is occurred at under and outside the seal. This condition consist of fixed fixture at this area proceed from wall of valve regulator of LPG until deflection value approaches 0 logically. This deflection also had been gradation along the thickness of seal, which the deflection will decreased from inside diameter to outside diameter. The Von Misses analysis shows that the deflection at this seal is elastic and not plastic that the geometry changes impermanent.

Parameter of deflection at seal of LPG is very important to avoiding leakage. The deflection at above surface is 0.188 mm so that possible to cause gas leakage.

### F. Diffusion Analysis Results

In this simulation, seal was considered as homogeneous porous material which amount and diameter of pore are uniform for whole section.

The pressure and material were used in this simulation are 6 bar and NBR respectively. The composition at input is 60% propane and 40% butane or in concentration about 5 mol/m<sup>3</sup> and 3 mol/m<sup>3</sup> for propane and butane respectively.

In the previous simulation of FEM are known that deflection occurred on seal when loading takes place affected the existence of gap at the center of seal. This gap resulted gas flow through this section. This condition consider as input at contact area of seal using COMSOL 4.1. The concentration travelling is occurred because of difference concentration potential or driving force from high concentrate to low concentrate as movement of LPG flow to seal that also called molecular displacement. In this case, beside of contribution of convective displacement, gas flow can be occurred through diffusion displacement because of its velocity.

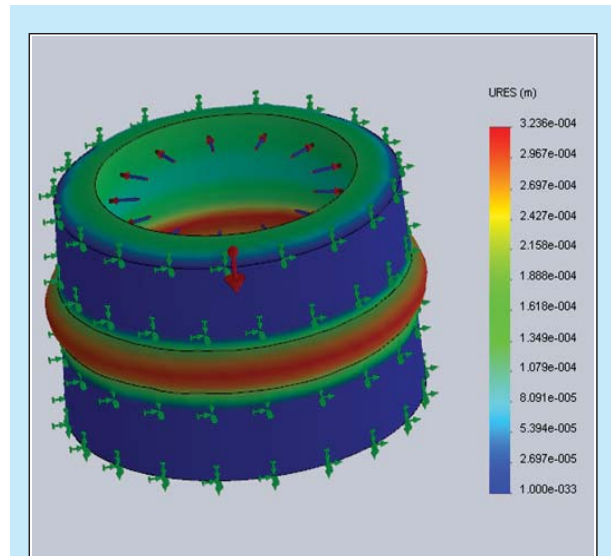


Figure 8  
Deflection result for seal using FEM simulation

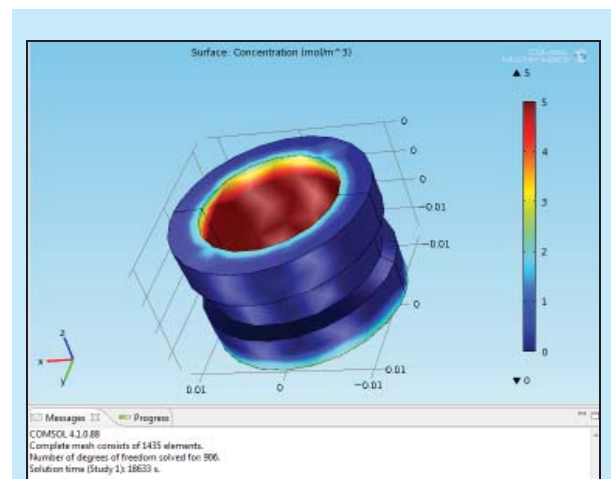


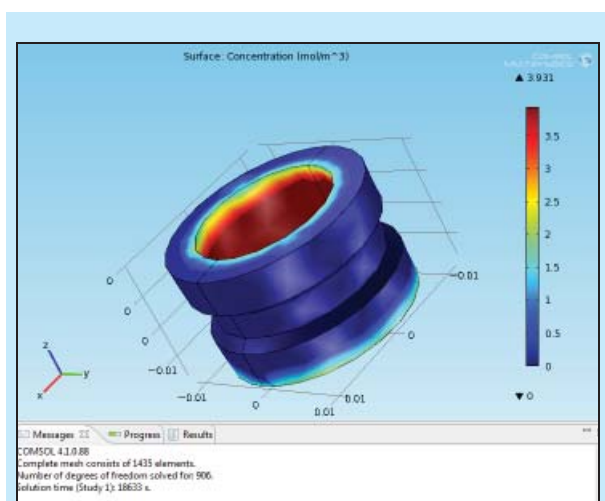
Figure 9  
Propane diffusion flow pattern

Figure 11 shows the diffusion flow along of the thickness of seal. The diffusion of propane and butane gas have concentrate gradation pattern appropriate with diffusion contact area. Closer to diffusion contact area, the diffusion concentration would be higher and conversely.

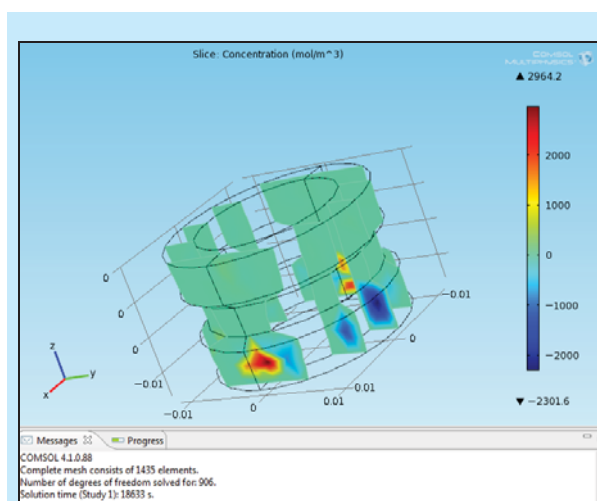
## VI. CONCLUSIONS

In the experiment and numerical analysis of this research can conclude:

1. Characteristics of leakage rate system of LPG fuel with pressure 6 bar are formulated as:



**Figure 10**  
Butane diffusion flow pattern



**Figure 11**  
Propane diffusion flow at cross section

a. *NBR*

$$L = \left[ 1.19 \times 10^{-21} \frac{1}{\mu} \left( \frac{\sigma}{\sigma_0} \right)^{-0.248} P_m \right] \frac{P_1 - P_2}{l}$$

b. *Vulkanis*

$$L = \left[ 1.28 \times 10^{-21} \frac{1}{\mu} \left( \frac{\sigma}{\sigma_0} \right)^{-0.305} P_m \right] \frac{P_1 - P_2}{l}$$

- Increasing of compressive stress at LPG seal is directly proportional to decreasing of leakage rate. This research reports decreasing of leakage rate attained 36.43 % for vulcanized seal and 33.18 % for NBR seal.
- Impact of adding compressive stress to decreasing of leakage rate concludes that vulcanized seal is more sensitive than NBR seal which is presented by value of AL and nL of vulcanized seal are larger than NBR seal.
- Leakage rate of vulcanized seal and NBR seal is directly proportional to difference of pressure inside and outside the LPG storage if the gasket of seating stress seal is larger than the compressive stress given.
- Von mises stress that accepted by seal still under yield strength of material seal type with factor of safety (FOS) attained 7.08 from Finite Element Analysis simulation.

- Deflection that occurred on seal is plastic deformation with maximum deformation consist on concave area at center of seal as 0.326 mm and minimum deformation at area which contact with interior wall.
- Diffusion flow that occurred on seal formed concentration gradation from interior wall through to outer wall as the closeness with contact surface of diffusion.

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