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STRUCTURAL ANALYSIS OF NGVM PRESSURE REGULATOR VIA FEA

R. MOHSIN[1], N. S. NASRI[2], F. KEFLY[3]

ABSTRACT

Rapid expansion of gas industries in Malaysia requires significant efforts towards development of NGV system which will bring about some economic improvements. In this particular project the study will focus upon the finite analysis of a 1st–stage pressure regulator for natural gas vehicle-motorcycle (NGVM). The objective of the study is to optimize design structure using a dedicated finite element analysis (FEA) applied with the most locally suitable available materials. This research is focused upon the development of pressure regulator system for Natural Gas Vehicle-Motorcycle (NGVM). The main objective is to optimize the designed prototype of NGVM pressure regulator via the assistance of finite element analysis (FEA). Only MODENAS KRISS 110cc motorcycle with manual transmission will be used for testing purposes. Optimization of the structural design of the prototype will be carried out using FEA system known as NASTRAN/PATRAN. Through FEA calculation and simulation, analysis conducted could provide structural strength understanding of the prototype. Simulation and analysis of the NGVM body prototype also incorporate various types of body materials including stainless steel, brass and aluminium. Aluminium was found to provide the necessary strength with high strength capability. Further refinements of the structure incorporate the thickness optimization of the overall constructions.

Key Words: NGV, NGVM, ZSM-5, methane, higher hydrocarbons, conversion.

1.0 INTRODUCTION

As the nation looks for ways to reduce air pollution from vehicles, natural gas is the ideal environmental friendly alternative fuel to gasoline, petrol and diesel. Natural gas exists in naturally occurring fossil fuel deposition found by itself the state of settlement near crude oil deposits in deep underground. Natural gas (NG) is a mixture of different gases. One major component of NG is methane, containing typically up to 99 percent of the total volume [1]. The composition of NG is never been constant. Other constituents may include non-methane hydrocarbons such as ethane, propane and butane and in some cases, traces of higher hydrocarbons as well as inert gases like nitrogen, helium, carbon dioxide, hydrogen sulphide and sometimes water [2].

Natural gas runs cleaner than most fuels, producing less pollution. Akansu [1] reported that natural gas vehicle (NGV) developed has been invented and applied around the world and has proven that it emitted at very low pollutants. From this encouraging situation a new application of NG fuel to fire small engine (motorcycle) is currently investigated. The idea of having motorcycles powered by compressed natural gas, (CNG) as a fuel is driven by a high number of small transportation system in Malaysia uses motorcycle as a primary vehicle as mode of transportation. In common, two stroke engines are employed, thus contributing to spectacular amount of pollution emitted by this type of engine as explained by Yaacob *et al.* [3].

Natural gas is compressed to 200 bars and is stored on board the vehicle in cylinders tank. When natural gas is required by the engine, it leaves the cylinders

[1,2,3]Department of Gas Engineering, Faculty of Chemical and Natural Resources Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia.
Correspondence to : Rahmat Mohsin (rahmat@fkkksa.utm.my)

travelling through a high pressure pipe to a high pressure regulator which is located in the engine compartment, where the pressure is reduced. This component is a main controller of the flow and pressure of CNG. Successful implementation of a natural gas fuel management system requires complete understanding of the component requirements and capabilities.

The fuel pressure reducing regulator in these systems is a very sensitive control element. The system, when configured correctly, can provide safe, reliable and predictable service for the life of the motorcycle. If the fuel dynamics and system component interactions are not completely understood by the system designer, the interaction of the system and the pressure regulator may cause the regulator to respond in an undesirable manner, leading to unsatisfactory performance and life as described by Suzuki [4]. It is one of the problems in operating the natural gas engine system.

This project is set out to verify a NGVM pressure regulator design using finite element analysis, or FEA. While finite element analysis offers another way to analyze structures, it requires an understanding of the program and subject being modelled. If the operator does not use the correct model, time is very much wasted with useless data.

Finite element analysis is a powerful tool in the field of engineering. Initially, finite element analysis was used in aerospace structural engineering. The technique has since been applied to nearly every engineering discipline from fluid dynamics to electromagnetic. The difficulty in analysis of stress and strain in structural engineering depends on the structure involved [5]. As the structure grows in complexity, so does the analysis. Many of the more commonly used structures in engineering have simplified calculations to approximate stress and strain. However, these calculations often provide solutions only for the maximum stress and strain at certain points in the structure [6].

1.1 Natural Gas Vehicle (NGV) System

Natural gas is compressed to 3,000 pounds per square inch (psi), and is stored on board the vehicle in cylinders installed in the trunk. Sturdy and heavy tanks are used for safe high-pressure storage. They are built to much more rigorous standards than are gasoline tanks. Figure 1 shows the schematic of basic concept on natural gas vehicle (NGV) operation and it conversion kits. When natural gas powers the engine, it leaves the storage cylinders, passes through a master manual shut-off valve and travels through stainless steel lines which are also connected to the refuelling system to a high-pressure fuel regulator located in the engine compartment.

The pressure regulator is safely reduce the pressure of compressed natural gas (CNG) form the vehicle storage tank to a present level which allowed an engine fuel metering system to properly control the gas. A model of three stages of NGV regulator is shown in the Figure 2.2. This is accomplished by a large pressure sensing element and controlled force moving a control valve to regulate gas flow in response to down stream pressure level. The control valve provides sufficient flow for all vehicles operating condition, while the diaphragm provides precise pressure sensing. From the regulator the natural gas goes to the air/fuel mixer which, located on the intake manifold, meters the flow of gas according to the requirement of the engine which represented by vacuum generated in the mixing devices, so as to ensure optimum carburetion in terms of driving, consumption and emissions.

1.2 NGV Pressure Regulator

A pressure regulator controls the gas flow from a higher to a lower pressure system, while attempting to maintain a constant system pressure as described by Rick [7].

The primary function of a NGV pressure regulator is to reduce high pressure gas 3000 psig in a cylinder tank to a lower usable level as it passes from the cylinder to a combustion chamber NGV engine [8]. It reduces the pressure to as low as 5 psig. It has to place near to the carburettor to ensure the connection tube between the regulator and the gas mixer is at its shortest distance. It also should be positioned lower than the radiator in order to avoid the formation of air bubbles or stagnation. All the connection to and from the regulator must be fasted securely.

1.3 Finite Element Analysis (FEA)

1.3.1 Basic Concept of FEA

The first step of any finite element analysis is to divide the actual geometry of the structure using a collection of discrete portions called finite elements. The elements are joined together by shared nodes. The collection of nodes and finite elements is knows as the mesh as shown in Figure 1. It consists of process of discrimination. It is used a number of terms to process the scheme of discretization such as subdivision, continuity, compatibility, convergence, upper and lower bounds, stationary potential, minimum residual and error.

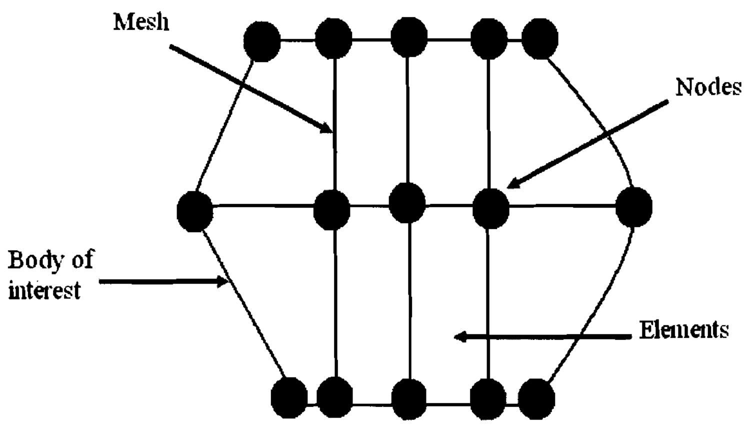

Figure 1 View Concept of Finite Element

The finite element method works by breaking a real object down into a large number of elements. The variable to be determined in the analysis is assumed to act over each element, chosen to ensure that the variable distribution over the whole body is adequately approximated by the combined elemental representations. After the problem has been divided into the discrete units, the governing equations for each element are calculated and then assembled to give system equations that describe the behaviours of the body as a whole.

In a stress analysis problem, the finite element method can calculates the displacements of the nodes and from the information, the stresses and strains in the elements are determined in order to prevent unlimited rigid body motion boundary condition. Today it is a computerized method for predicting on how a component will react to environmental factor such as forces, heat and vibration. It is used as a visual prototyping tool to predict what is going to happen when the product is used [6].

1.3.2 Finite Element Numerical Method

The finite element method is another technique frequently used to obtain approximate solutions of problems governed by differential equations as illustrated by David [9]. Some basic concept related to finite difference method for purposes of comparison is shown as followed.

The finite difference method is based on the definition of the derivative of a function $f(x)$;

$$\frac{df(x)}{dx} = \lim_{\Delta x \to 0} \frac{f(x = \Delta x) - f(x)}{\Delta x} \tag{1}$$

where, x is the independent variable. In the finite difference method, as implied by its name, derivatives are calculated via Equation 1.1 using small, but finite, values of Δx to obtain,

$$\frac{df(x)}{dx} \approx \frac{f(x = \Delta x) - f(x)}{\Delta x} \tag{2}$$

A differential equation such as:

$$\frac{df}{dx} + x = 0 \qquad 0 \le x \le 1 \tag{3}$$

is expressed as

$$\frac{f(x = \Delta x) - f(x)}{\Delta x} + x = 0 \tag{4}$$

in the finite difference method. Equation 1.4 can be rewritten as

$$f(x + x\Delta) = f(x) - x(\Delta x) \tag{5}$$

where we have note that the equality must be taken as approximately equals. David [9] highlighted that, from differential equation theory, the solution is of the first-order differential equation constant of integration. The constant of integration must be determined such that one giving condition (a boundary condition or initial condition) is satisfied. In the current example, we assume that the specified condition is $x(0) = A$ = constant. If we choose an integration step Δx to be a small, constant value (the integration step is not required to be constant), then we can write;

$$x_{i=1} = x_i + \Delta x \qquad i = 0, N \tag{6}$$

where N is the total number of steps required over the domain. Equation 5 is then expressed as;

$$f_{i=1} = f_i - x_i(\Delta x) \quad f_0 = A \quad i = 0, N \tag{1.7}$$

Equation 1.7 is known as a recurrence relation and provides an approximation to the value of the unknown function $f(x)$ at a number of discrete points in the domain of the problem.

David [9] proved that by illustration, Figure 2 shows the exact solution $f(x) = 1-x^2/2$ and a finite difference solution obtained with $\Delta x = 0.1$. The finite difference solution is shown at the discrete points of function evaluation only. The miner variation of the function between the calculated points is not known in the finite deference method. One can, of course, linearly interpolate the values to produce an approximation to the curve of the exact solution but the manner of interpolation is not an a priori determination in the finite difference method.

To contrast the finite element difference method with finite element method, David [9] note that, in the finite element method, the variation of the field variable in the physical domain is an integral part of the procedure. That is, based on the selected interpolation functions, the variable of the field variable throughout a finite element is specified as an integral part of the problem formulation. In the finite element method, this is not the case: The field variable is computed at specified points only.

The major ramification of this contrast is the derivatives (to a certain level) can be computed in the finite element approach, whereas the finite difference method provides data only on the variable itself. In the structural problem statement, for example, both methods provide displacement solutions, but the finite element solution can be used to directly compute strain components (first derivatives). To obtain strain data in the finite difference method requires additional considerations not inherent to the mathematical model.

2.0 METHODOLOGY

Finite element analysis of the modeling single step pressure reduction of NGVM is an important part in this research. Serious studies of solid and contact element have to be conducted and analyzed prior to process modeling. Modeling is completed in 3 type of view: that is three dimensions, symmetric and asymmetric by using AUTOCAD (V2004) and SOLIDWORK (V2005) computer programs. The model develops then exported to the MSC.PATRAN (V2004r2) to process the model of prototype regulator in term of evaluation and iteration. Pressure produced by flow rate, stress and deformation are analyzed to verify the NGVM pressure regulator structural body strength. Figure 2 shows the process flow of this particular research work.

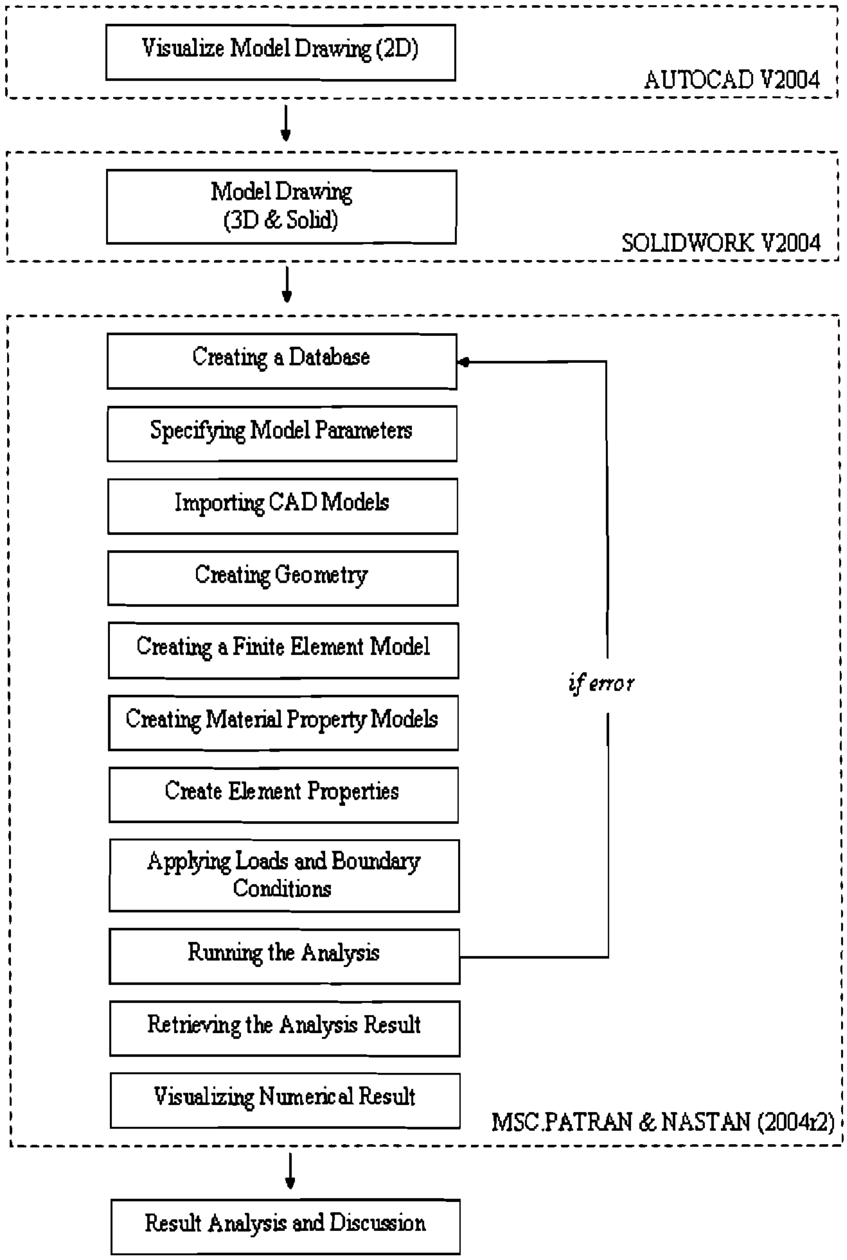

Figure 2 Process Flow Methodology

3.0 RESULT& DISCUSSION

3.1 Two Dimensional Modeling

Two dimensional model of regulator base is successfully drawn using AUTOCAD Version 2004 computer code as shown in Figure 3. The model is drawn to provide the conceptual idea of three dimensional drawing. It will be transformed to solid views to enabling analysis. This model is drawn base on work conducted by Rahmat et. al. [10] in his development of NGVM pressure regulation system.

Part A and B are drawn separately form different view of each other to ensure that the conceptual idea in shape and dimension that will be used in future design can be closely observed. Part A is drawn with elevation that reflects the regulator base from the upper view. Overall observations from this view indicate that Part A regulator base has a breadth of 98 mm length and 80 mm wide with one hollow cylinder for fuel injection. Part B is drawn with elevation that reflects the regulator cap base from the bottom view. The base regulator cap with 70 mm largest diameter has 4 units hole in each of its diagonal dimension to fix the cap to the base (Part A) by means of bolting with 7 mm diameter screw. Accordingly, this has been found to be having a suitable and functional dimensions of the NGVM to the overall dimension regulator base design.

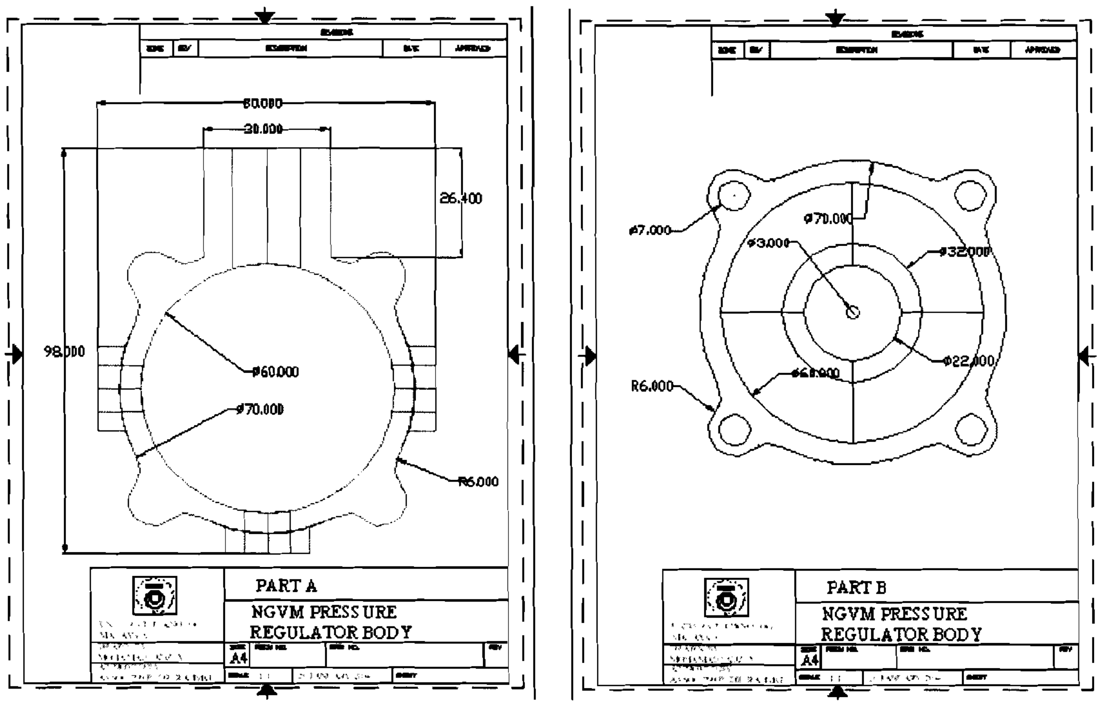

Figure 3 Two Dimensional Model Drawing

3.2 Solidified Modeling

Solid model regulator prototype base has been successfully drawn to enabling deformation and stress analysis. The prototype model has been developed using SOLIDWORK software, based on the original conceptual ideal of two dimensional drawing. The solid prototype base regulator; Part A and B are subsequently combined and shown in Figure 4. However the discussion of the results obtained, will still be based on its individual strength analysis. Solid model has to be drawn and saved by using IGES format file before exporting it to MSC.PATRAN program. This step has been proven successful in this particular work.

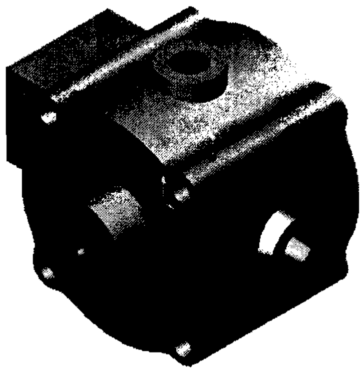

Figure 4 Solid Drawing for Regulator Base via SOLIDWORK

Initially, regulator base prototype is analyzed via strength analysis using various types of body materials prior to performing advance analysis when the load and pressure are applied. Materials selected for this analysis are Standard Steel (S-304), Brass (RED; 80%Cu 20%Zn) and Aluminium. These materials have been selected for such analysis due to their availability and suitability of body strength to fabrication capability. Analysis conducted is focusing on the prediction of weight and body mass of the prototype for different types of materials and changes of moment of inertia. Surface area, solid volume and the center point of both prototypes are also being calculated.

Part A regulator base prototype indicates the total surface area for both inside and outside section is 31,785.088 mm^2 while Part B is 16,621.917mm^2 which is 47.7% less than Part A. If both parts are using similar material, theoretically Part A will provide more mass than Part B. Mass analysis based on three types of material shows that Aluminium offers less weight compared to other material with total mass 418.308 grams. It is 181% and 226% less weight comparing to result given by SS-304 and Brass. This mainly contributed to the fact of density. However decision on selecting specific material could not be completed without further analysis on consideration of advance analysis when pressure is applied.

Fluctuations on the material market price are one of the influence factors that have to be considered. Current latest market price of material used, Aluminium provides the lowest price per kilogram of material, followed by Brass and SS-304. The same patent occurs when the calculation for material mass used is multiplied with its price per kilogram. It shows that the gross costing to fabricate regulator base using Aluminium material is considerably cheap at a rate of RM 7.11, while Brass and SS-304 are estimated at a cost of approximately RM 26.66 and RM 42.04 respectively, at 275% and 497% respectively higher than Aluminium.

James [11] in his book explains that comparison of SS-304, Brass and Aluminum capability to face corrosion problem are not showing too much of differences. These materials are capable to withstand against oxidation. Oxidation represents the direct chemical reaction between metal and oxygen that leads to corrosion problem.

3.3 MSC.Patran/Nastran Analysis

MCS.PATRAN/NASTRAN in terms of finite element analysis, performs an analysis of deformation and stress of the regulator structure base when it is pressurize to 3000 psi (2.07E+7 Pascal) from CNG storage gas supply. The pressure is applied at the inner surface of base regulator. It must be tied to the vehicle body to bind the prototype and prevent movement from its original position. The applied pressure will force the elements to move from its original location. Analysis will indicate how far the displacements of these element nodes are being experienced and allocate where the modification is necessarily required at the critical region (red color contour) of the prototype design. Analysis will be focused on the maximum tensor stress caused by the applied pressure.

Figure 5 shows the result of node element displacement for Part A where its material of construction is SS-304. Maximum displacement of node element is 3.58E-02 mm and occurs on node number 1092 as shown in detail in Figure 6. However the displacement is not critical due to the small distance of node displacement which is 96.42% lower then 1 mm. Thus, the prototype is safe to operate at the pressure.

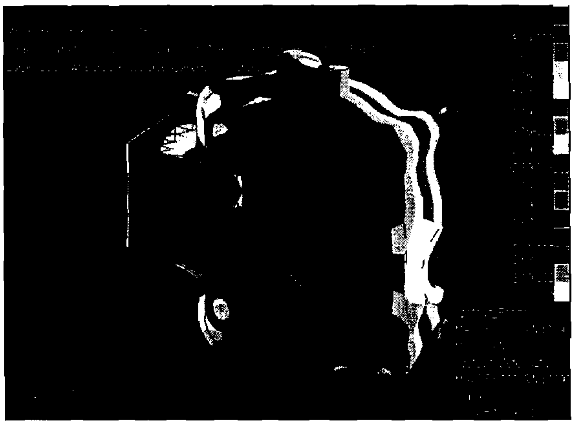

Figure 5 Part A: Displacement Result

Figure 6 Maximum Displacement: Region on Node 1092

Comparing to SS-304, Brass and Aluminium give 6.87E-02 and 9.85E-02 mm node displacement which are 47.89% and 63.65% more than SS-304 node displacement. Both displacement of Brass and Aluminum occurs at the same node as for SS-304. Though the results show the variation values of node displacement, but the displacement occur at the same node for each of material used. This situation explains that the node will receive the maximum force when pressure is supplied and modification is necessary. However, the analysis shows that the displacement values is less than 1mm; indicating that the design of the base regulator body is sufficient to support maximum operating pressure of 3000 psi.

Figure 7 below shows the result for analysis on stress tensor for Part A. The result shows that maximum stress tensor value is 4.04E+08 Pa when the base regulator is pressurized at a maximum pressure of 3000 psi and it occurs at node 98. At the same time, the minimum stress tensor for Part A is 2.21E+06 Pa which occurs at node 998. Even though the maximum stress tensor occurs at node 98 but maximum displacement does not occur at the same node. From the above result, it occurs at node 1092.

Figure 7 Part A: Stress Tensor Result

Comparison made between both Brass and Aluminium material shows that the maximum stress tensors are 4.00E+08 Pa and 3.99E+08 Pa, which are 0.99% and 1.24% less than stress tensor for SS-304.

As discussed on Part A, the analysis will also gives the result of maximum displacement and stress tensor for Part B (cap of regulator base). As for Part A, too high displacement and stress tensor which exceeded the allowable value that can cause regulator base to crack, if continuous pressure at long period of time is applied. Modification to the cap is necessary for the regulator base in order to safely operate at maximum pressure of 3000 psi. Analysis will also discuss on the result for each different material for the prototype construction.

Figure 8 below shows the displacement value for Part B at pressure of 3000 psi in the inner surface. The result shows the node displacement for Part B using SS-304 as its material of construction. From the figure, the maximum value of displacement is 7.64E-03mm and occurs at node 88 in the red contour. Figure 9 shows the detail of node 88 location. This node displacement is 99.24% below the allowable value of 1mm. Therefore, it is safe to be operated at pressure of 3000 psi. Maximum displacement for Brass material is 1.46E-2mm while for aluminum is 2.10E-2mm. Comparison of maximum node displacement between Brass and Aluminium to the SS-304 material gives higher displacement differential of 47.67% and 63.62%. This result occurs at the same node for each material though the values differ from each other.

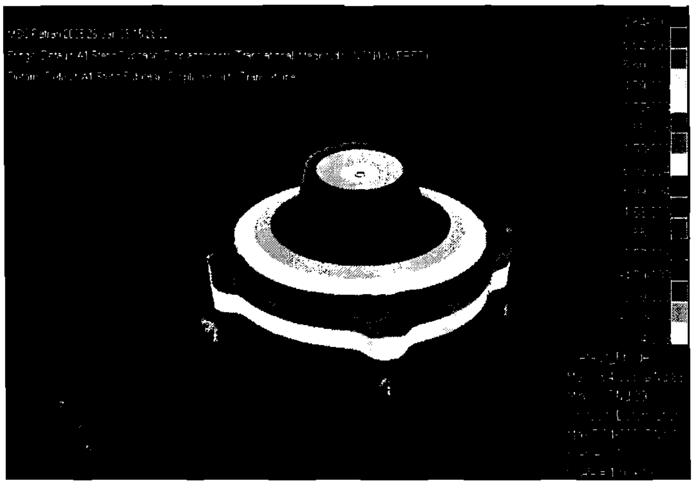

Figure 8 Part B: Displacement Result

Figure 9 Maximum Displacement: Region on Node 88

The result for stress tensor analysis for Part B using SS-304 material is shown in Figure 10 below. From the results recorded, the maximum stress tensor resulted from 3000 psi of pressure is 1.36E+08 Pa which occur at node number 9988, while for the minimum stress tensor is 5.86E+05 Pa and it occurs at node number 8937. As same as above discussion, though the maximum stress tensor occurs at node 9988, the maximum displacement does not occur at the same node, but at the node 88.

Comparison for different material prototype is made. From the result obtained, Brass and aluminum give different values of maximum stress tensor, which are 1.32E+08 Pa and 1.32E+08 Pa. Comparatively, the value for Brass is 2.94 % and aluminum is 2.21 % lower than maximum stress tensor of SS-304.

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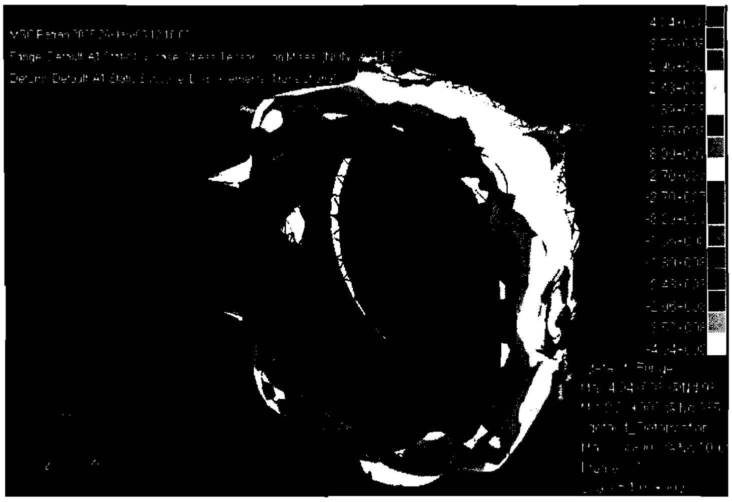

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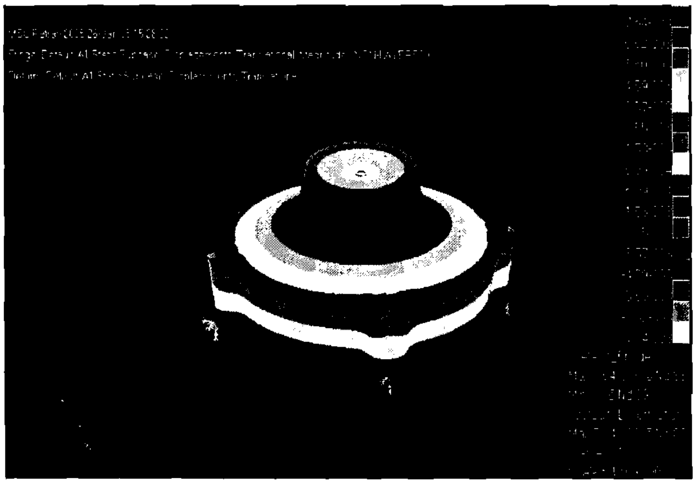

Figure 8 Part B: Displacement Result

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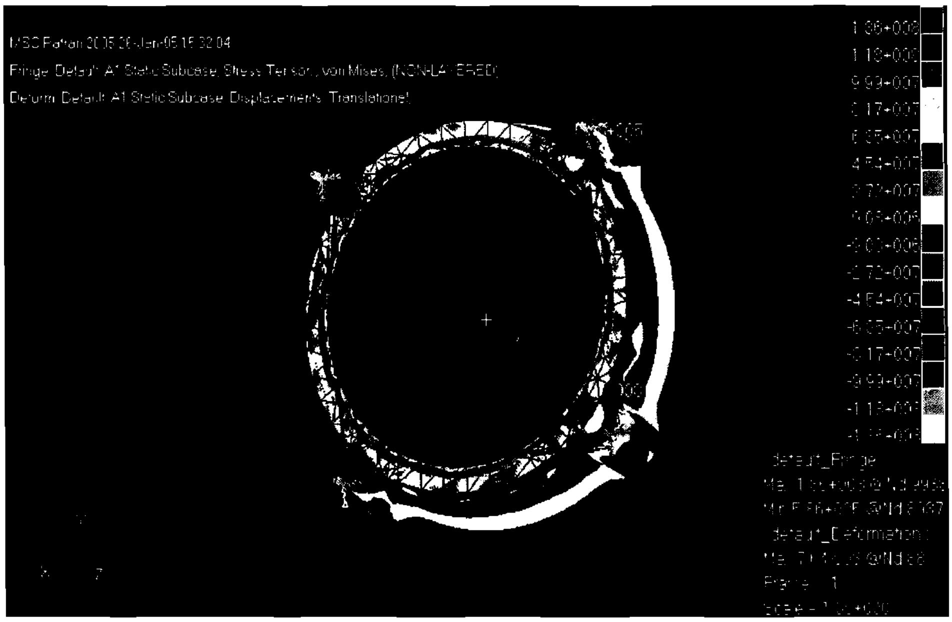

Figure 10 Part B: Stress Tensor Result

4.0 CONCLUSION AND RECOMMENDATION

4.1 Conclusion

A computer model of regulator base prototype is successfully developed to perform an analysis via FEA simulation. Conceptual ideal drawing via AUTOCAD (V2004) in two dimensional viewed was initially introduced based on the work by [10] on the project of Development of Regulator Base Solid model then developed using SOLIDWORK (V2005) program to build analysis prototype. The analysis concluded that stress tensor deformations of the developed prototype model were too small when a maximum pressure of 3000 psi is supplied. Optimization to the design of regulator base structure is still available where reduction of its size and mass should be considered. Analysis also showed that other than SS-304, Brass and Aluminium are considered to be good material for regulator base construction as they comply with the design specification requirements. Besides, Aluminium gives the minimum requirement of mass and cost, in addition it is corrosion resistance.

4.2 Recommendation

Though the results of analysis were satisfying, improvements are necessary in considered order to perform better analysis. Structure vibration, effect of temperature increase caused by temperature change in inlet and outlet gas flow, and gas stream condition must be included into analysis to achieve better results. This research is considered for evaluation purpose, as the analysis results are the bottom line. Verification of the results must be compared to the actual results of mechanical test in order to obtain the percentage of overall results accuracy.

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