FAMU-FSU COLLEGE OF ENGINEERING

SENIOR DESIGN I – EML 4551

DELIVERABLE: MID-TERM REPORT

MECHANICAL DUMP VALVE – TEAM 3

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Date of Submission: December 6th, 2013

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i. Abstract & Acknowledgements

With the assist of Cummins Fuel Systems and the FAMU/FSU department of Mechanical Engineering, a mechanical dump valve has been design by team #3 from the Mechanical Engineering Senior Design Project. Three different designs were created by the team and after using various methods for evaluation, a single design was chosen and further work was done to it. Mathematical models were used to analyze the physical system, and with the use of FEM analysis programs like COMSOL the design was simulated to ensure it has the desired performance. As the design was confirmed, appropriate CAD drawings were made that will be submitted to Cummins who will do the manufacturing of the prototype.

We would like to acknowledge Christopher Besore, Dr. Lou Cattafesta, Dr. Kamal Amin, Dr. Cheung Shih, Dr. KunihikoTaira, and Dr. Steven Van Sciver for their advising and aid throughout this semester.

1.0 – Project Overview

1.1 <u>Introduction</u>

Cummins Inc Fuel Systems XPI (extreme pressure injection) department currently has an MDV (mechanical dump valve) operating in all their common rails as a mean of safely relieving the pressure in the rail in case of over pressurization. This valve is dormant while the rail pressure is within the limits desired for the engine and while the pressure sensor is able to regulate the fuel flow into the rail. In case of a failure of the pressure sensor the ECM (engine control module) has no way of telling the IMV (inlet metering valve) how much fuel it needs to allow to get pumped into the common rail, in which case over pressurization could happen. As a safety back up, a purely mechanical valve is installed on the common rail. The function of this valve is to allow the fuel out of the rail and therefore reduce the pressure within it, which ultimately avoids thermal events. The valve would then take over the system and act as a mechanical controller to regulate the amount of fuel in the common rail. The fuel the valve is relieving goes back into the fuel storage through a line to be reused. The common rail can be observed with the injectors in Figure 1.

Figure . Common Rail

This MDV is durable, as well as reusable. The part is designed to reset once the engine is turned off. After the engine is turned back on, if the pressure sensor continues to fail the valve will once again begin to operate until the driver can get to a location where the sensor can be replaced. If the sensor is in working status the valve will be once again dormant until it is needed. The engineers at Cummins FS XPI wish to obtain a valve that continues to do these tasks but it is also more lightweight, more inexpensive, and with improved functions.

1.2 Problem Statement and Objective

There is a need for mechanically controlling the fuel pressure in a highly pressurized common rail diesel engine, as well as relieving the fuel in case of over pressurization. The means of achieving this should be inexpensive and the mechanical component should be lightweight and easy to install on an engine to allow for maintenance as well as easy replacement.

1.3 Non-Disclosure Agreement

A very important portion of this project is the Non-Disclosure Agreement (NDA). This NDA was created by Cummins Inc to prevent damages regarding intellectual property. If the product developed by the students meets the Technical Profile specifications and Cummins decides to manufacture it, the product will be patented. If the product is to be used by Cummins they will have to avoid competitors from using the new product as well. This creates the need for the project to be confidential and for the students to share no calculations results, data, dimensions, or prints with the public; for this reason any figures and data presented by this team are rough drawings and the data has been distorted to prevent confidential information share. Working around the NDA is one of the biggest challenges of this project.

1.4 Product Specification

As explained in the previous section, the exact values for the specifications of the product may not be disclosed in this document. Appendix A shows ranges of values that cover the specific constraints from the technical profile obtained. From these product specifications, the main constraints on the design are size and cost. The MDV will have to be installed in an existing location that has limited space. The cost of the existing valve that is used by Cummins Fuel Systems was given by the sponsors. In order for the new product to be considered it would have to be cheaper so this constraints the complexity and materials that can be used.

Another significant constraint is the way the MDV has to respond to the extreme pressures. As shown in Figure 2, the pressure inside the common rail should follow that behavior in case the pressure builds up. The MDV should start working when the pressure reaches P_1 which is in the range of 2400-2900 Bar. The MDV should regulate the pressure by bringing it down to P_2 which is defined as the Limp Home Pressure. The common rail should keep the P_2 pressure for an unlimited time, so that the engine can be taken to repair.

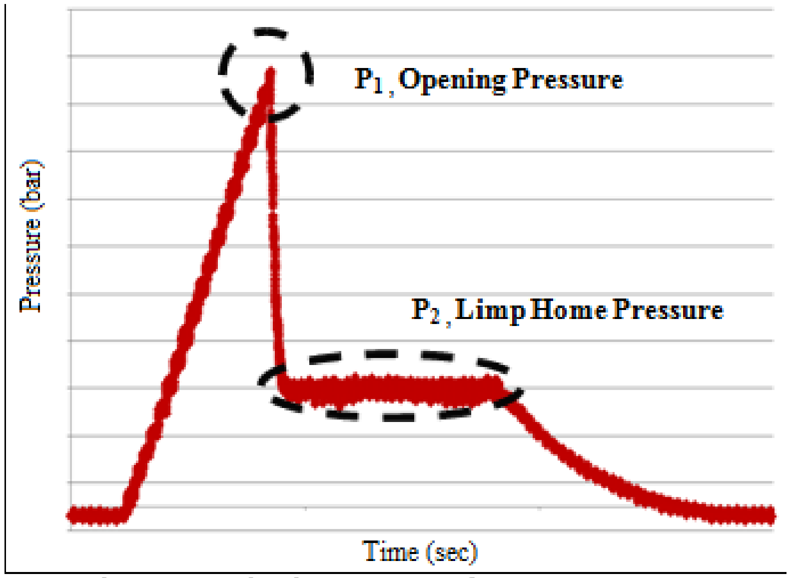


Figure . Desired Response of MDV

2.0 – Design Concepts

2.1 Design Concept D

This design is composed by a plunger and a spring inserted into the high-pressure seat casing. The smaller area A_1 seats on the smaller cone (high-pressure seat) creating a seal as shown in Figure 3. The spring will be keeping the seal until the pressure buildup reaches P_1, which is the opening pressure. Once the opening pressure is reached the plunger will retract, compressing the spring. Once this first stage occurs the pressure will drop to P_2 which is the desired limp home pressure in stage 2 as shown in Figure 3. Also with this change, the area of interest has also changed to a larger A_2, the combination of the new pressure and area will maintain the valve open and in an oscillatory stage to meet and average desired limp home pressure. The flow will go around a small clearance around the cylindrical top area of the plunger. This design has some flaws, which include material restrictions due to high stresses, possible beating on the high-pressure seat due to impact could create a leak, and there could also be issues with the plunger not being centered correctly. Just as there are flaws there are various benefits to this design, since there are few components that are easy to machine and assemble the cost of production is decreased, also this design is relatively simple the mathematical/model analysis is not at difficult as with other designs.

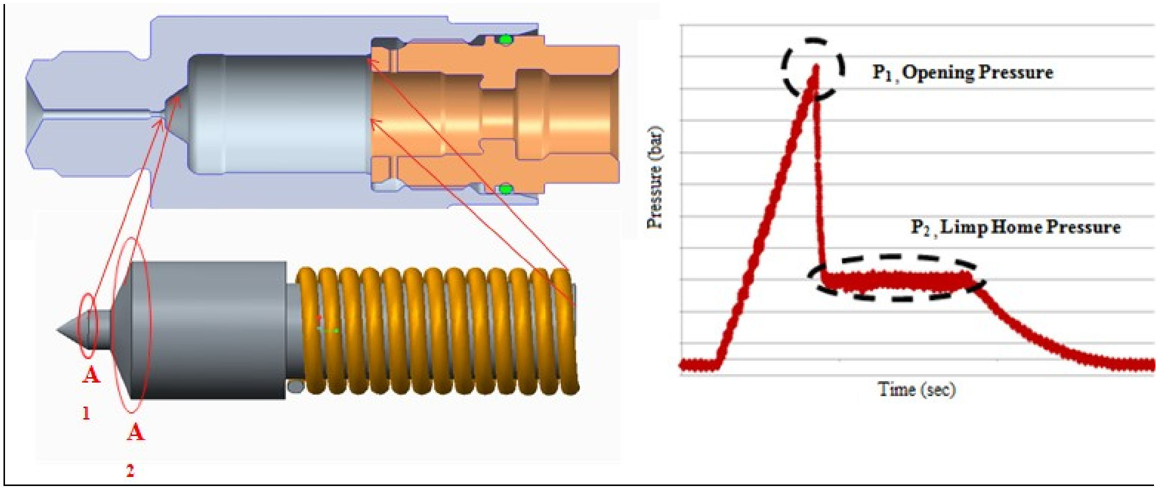


Figure . Design Concept D

After further analysis on this design in conjunction with Christopher Besore (Sponsor at Cummins), this design concept was updated. The updated design can be seen below in Figure 4. The set up for this design is very similar, but the variable geometry of the areas is simplified only one cone which potentially reduces stresses on the surface. Also, the drainage was modified to go through the plunger instead of around it, this allows for a better guiding system, preloading the spring with the inserted guide (seen in blue in the image), as well as providing a more stable way of drainage and reduction of vibrations of the plunger.

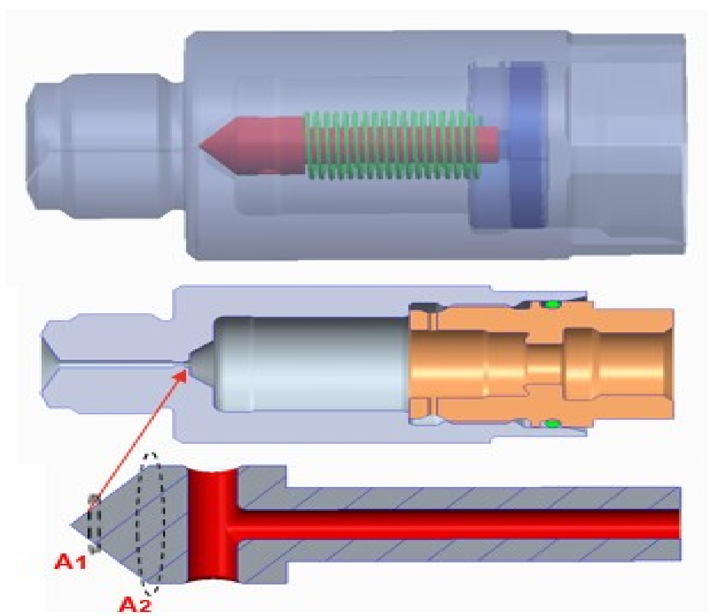
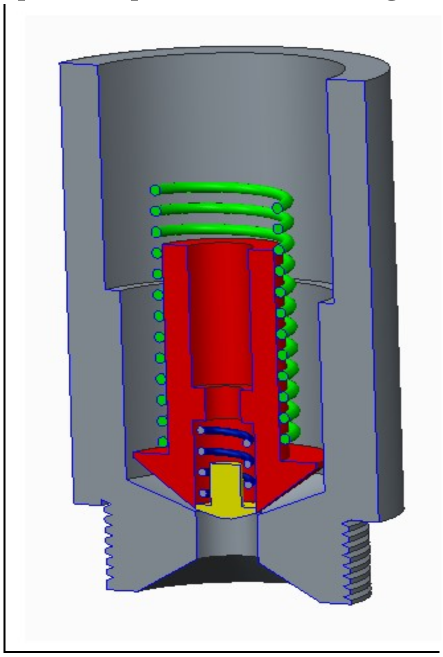


Figure . Updated Design D

2.2 <u>Design Concept A</u>

Design concept A is a combination of both the previous designs. This design is composed by two plungers and two springs that work in conjunction to regulate the pressure within the common rail. The first plunger as shown in Figure 4 in yellow, has a spring that has a high enough spring constant to withstand the force of the fuel until it reaches the desired opening pressure P_1 . Once the pressure has reached the desired value, the pressure will be released by the compression of the spring which will move the first plunger in the upward direction respectively. When this happens the force will decrease since the area has increased therefore decreasing the pressure to P_2 the limp home pressure. Next the second stage will be engaged. The first plunger will return into the second plunger, and this is going to regulate the limp home zone since the area has increased. With the second spring constant lower than the first will stay oscillating at this pressure and stay until the engine has turned off.

This design concept has it pros and cons. The good thing about this design is that



it has two areas and two different spring constants that will make it easier for the mechanical dump valve to reach its desired valve. The spring constants and areas can be changed depending on what the calculations and the data simulation gives us. There are more cons than pros for this design. Since there are more parts it is one going to be more expensive to machine. Two there are going to be more modes of failures since there are more parts. Finally it's a complex design therefore repairs are going to be difficult, and if it is not perfectly machined it will not perform in the desired way it is supposed to.

2.3 <u>Design Concept S</u>

The first design described below consists of two isolated spring systems. The lower spring system as shown in Figure 6 opens up (compresses) when the pressure in the common rail equals the Opening Pressure, as shown in Figure 2. As soon as the spring compresses, liquid will flow inside the lower compartment and the pressure will be acting on the entire surface area of the disk, thus increasing the pressure force, as shown in Equation 1, where P equals pressure and A equals area. Since pressure force is much larger, the spring will remain compressed for the remaining time.

$$F = P * A \quad \text{Equation 1}$$

The top spring is less stiff, however, the stiffness is to be calculated to match the force equivalent at the limp home pressure, so that it will decompress as soon as pressure goes lower than limp home and then compress again as soon as the pressure increases. The design shows advantages in costs and simplicity. Both disks would be the same material and the entire structure has no complicated shapes.

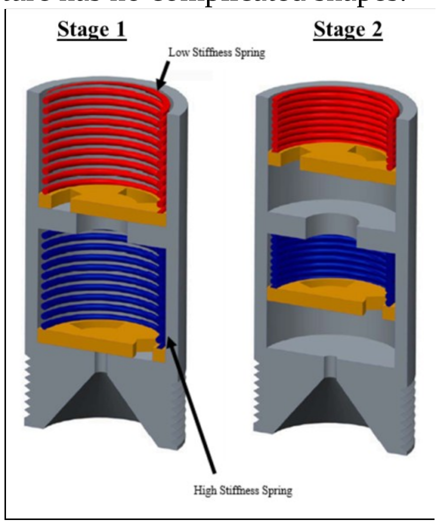


Figure . Two Stages of Design Concept S

After discussing with the fluid systems department in Cummins, it was determined that the design could be further simplified. Instead of using 2 spring systems, only one system would be used. By using only one plunger, the valve can still perform with the desired response.

The final design S can be observed on Figure 7. On the left we can see the plunger compressed and on the right the valve is activated. To solve the issue of making the valve work like the previous design, the plunger has the shape of a cone so the variable area, which provides the same results.

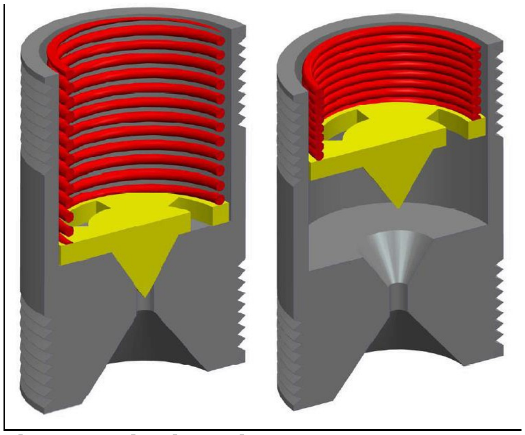


Figure . Final Design S

2.4 Design Selection and Analysis

After further reviews with Cummins Fuel Systems, the third design was chosen as the final design to be submitted to Cummins. The next step was doing analysis on this design to ensure it would follow the desired performance. A control volume approach was used on this design. The assumptions made were that the is conservation of mass, the temperature is around 150 degrees C, and that the outside pressure of the system is atmospheric pressure as well as the pressure of the fluid once it exits the valve and returns to the storage tank. Conservation of mass (Equation 1) and conservation of momentum (Equation 2) were the concepts applied in the problem. The equations can be seen below.

Equation 2

Equation 3

Unfortunately any specific values obtained cannot be shown in this report due to the NDA. The use of the control volume approach allowed for a better mathematical and physical understanding of the system. This also provided some insight on what to expect for spring stiffness requirements. COMSOL was also used as means of analyzing the system, a simulation was done to observe how the fluid would behave inside the valve as well as to corroborate any results acquired previously.

To perform this CFD analysis, the geometry was simplified as shown in Figure 8. An axis-symmetric geometry was used as it makes the study easier and a 3D plot can then be made with COMSOL. The dotted line shows the center axis on which the surface rotates around. The inlet in this design is located in the bottom surface of the geometry. Furthermore, the outlet is located on the top surface of the geometry shown below. The FEM model is the same as the one for the Preliminary model; however, the inlet velocity was changed to 40 m/s.

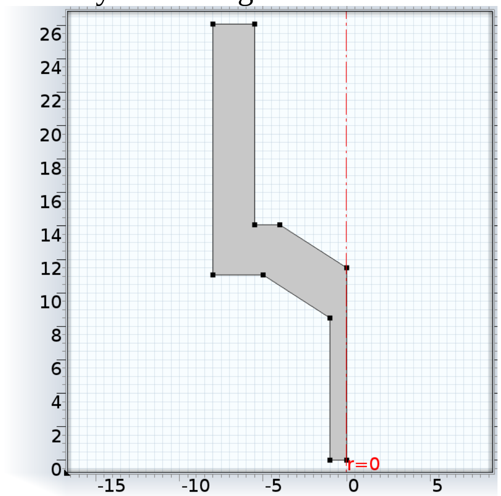


Figure . COMSOL Geometry of the domain

The pressure acting on the plunger was determined by making an integration analysis throughout the surface represented with a red line as shown in Figure 8. Different simulations with COMSOL were done for varying lengths (z_1¿ where the plunger is located. This pressure is of importance because it can be used to determine the force acting on the valve with a constant flow rate in the inlet.

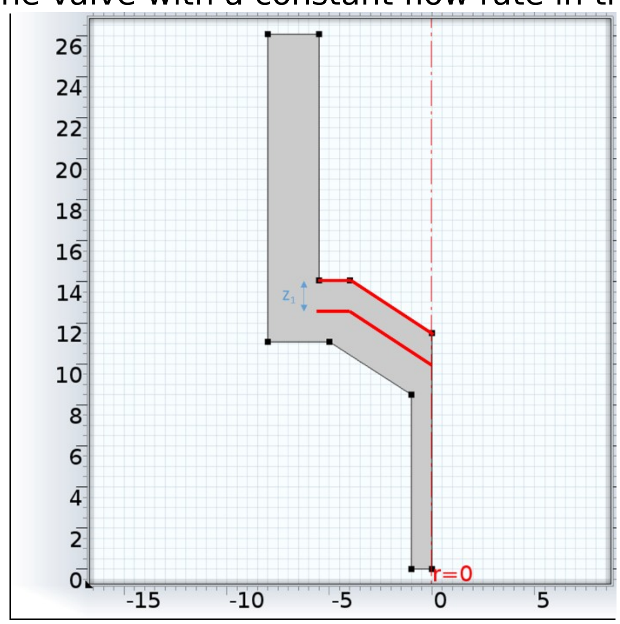


Figure . Geometry showing the change in valve length

The following plot was made showing how this pressure changes as the valve opening length (z_1¿ increases. As expected, the pressure is at its highest when the valve is almost closed. The pressure obtained with COMSOL was multiplied by 2 π to obtain the total pressure in the 3D model. The pressure started to level off at around 0.6 cm.

Figure . Plot showing the Pressure on the bottom surface as the opening increases

A 3D plot of the flow velocity was made by making the geometry revolve around the axis by 200 ° . This makes an easier visualization of the flow inside the valve. As expected, as the flow reaches the outlet it has a very small velocity. The 3D plot can be observed below on Figure 11.

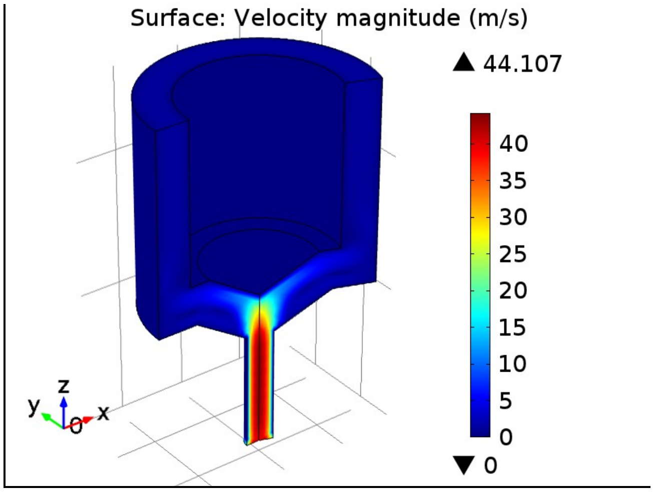


Figure . Velocity plot for the inside of the geometry

With the use of the pressure found with the CFD analysis, the forces acting on the plunger will be used to determine the materials used on the valve.

2.5 Materials Analysis and Selection

The material analysis for the Cummins mechanical dump valve has four different components that need to be analyzed. As a reference, see Figure XXX, this general analysis of this figure applies to all designs including the selected design. There is the body, plunger, retainer, and the spring. The body and the retainer are made from 4140 Steel. The hardness of this steel material is 43 – 47 HRc. This is only really relevant for the body since the body and plunger will impact each other when the valve is opening and closing. If the hardness is not taken into account the material could be damaged which would cause the mechanical dump valve to fail. This could be due to leakage which is definitely not desired for the mechanical dump valve will completely fail not work completely. The plunger will be made out of A2 Tool Steel. The reason behind this type of material is that it is a material that can be machined. With the complexity of shape of the plunger, it needs to be able to be machined to work in the desired way. Tool steel is tough and needs to be tough. It has a hardness value of 58 – 62 HRc. This high hardness is needed as stated above for the high impact between the plunger and the body. Finally the spring's material needs to be addressed. The spring constant needs to be able to withstand the extremely high pressure in the common rail. Stainless steel spring, in this case would be the desired spring to withstand and properly work the mechanical dump valve.

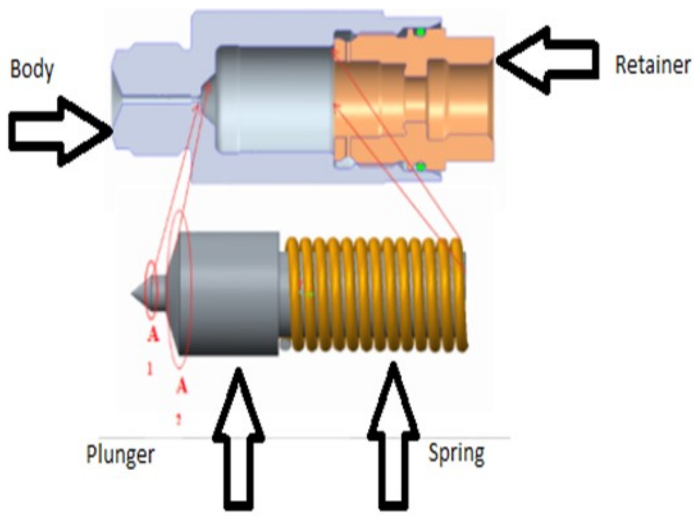
*There are no programming needs or electrical components in this design.

3.0 – Future Work

3.1 Detailed Design

Due to the NDA associated with this project no dimensions, detailed drawings or any specific values are to be shown.

3.2 Prototyping & Manufacturing



Cummins Fuels Systems XPi currently machines it's valves through SCHUMAG (German based company). Once we provide Cummins with our detailed drawings they will then send them to SCHUMAG for prototyping and for a manufacturing quote. Once the prototype is machined it will be sent back for testing at Cummins Fuels Systems. The total cost analysis will be provided by SCHUMAG along with their quote for machining.

3.3 Procurement

As part of the project, the final prints of the final design are going to be sent to both Cummins and SCHUMAG. Both the companies are going to be machining and building the prototype of the mechanical dump valve. Since the budget is $2000 and no money has been used, SCHUMAG is going give a cost analysis of materials and manufacturing in creating the mechanical dump valve. After the MDV is built they are going to be tested at Cummins fuel systems plant in Columbus, Indiana. Once the tests are finished Cummins is going to send our team the results, which will be analyzed. The analysis will then be sent to Cummins and a final decision of whether the product meets the requirements will be sent to the team.

3.4 Risks and Reliability

There are no risks associated with this design, in case of failure the testing device would simply shut down to ensure safety. In addition to that, since testing is to be performed at Cummins Fuel Systems any other emergencies would be approached according to their safety standards and procedures.

3.5 Gantt Chart

The following Table shows the Gantt chart for the Fall semester. All the different tasks are up to date and the project is on track.

Table . Gantt Chart for Fall 2013

3.6 Future Plans

A complete full materials and cost analysis is to be finalized. The complete thermal-fluids analysis and CAD drawings are to be sent to Cummins by the end of this year for their final review. Shortly after, prints will be sent to SCHUMAG so a prototype can be machined. The testing of the MDV will occur on Spring 2014.

4.0 – Internal Resources & Conclusions

4.1 Communication

This team has communicated effectively with the advisor and sponsor as well as within itself. Each member has identified his/her strengths and weaknesses and as a team the work load has been divided to meet those specific skills of each person. Communication has been mainly through meetings, a group messaging system, emails, and phone call conversations as well. Communication with the sponsor and advisor has followed the same manner.

4.2 Conclusions

During this semester this team has achieved the goals proposed at the very beginning of the semester. Three design concepts were created, analyzed and one of them was ultimately selected as the future prototype for testing. The team performed calculations and CFD analysis on the design selected and kept in touch with the sponsor Christopher Besore at Cummins Fuels Systems to update him on any advances made. The team was aided by its adviser Dr. Lou Cattafesta, he performed reviews of presentation materials as well as of calculations, in addition to advising the team with the future work and goals to be achieved. Next semester the work load will continue to be distributed and completed in a timely manner as it has been done this semester and the future work will be completed efficiently until the prototype is finalized.

ii. References

"Cummins Announces New Global Heavy-Duty Engine Platform." *Power Torque Magazine*. 20 Sept. 2013. 10 Oct. 2013. <http://www.motoringmatters.com.au/news/cummins-announces-new-global-heavy-duty-engine-platform>

"DieselNet: Diesel Engine Emissions Online." *DieselNet: Diesel Emissions Online*. N.p., n.d. Web. 10 Oct. 2013. <http://www.dieselnet.com/>.

Cummins Fuel Systems. <http://www.cummins.com/cmi/navigationAction.do?nodeId=7&siteId=1&menuId=1001>.

iii. Appendix

A)

- Design Specifications
  - External Connection: M20 x 1.5-6g threads
  - Internal Drain Connection: M14 x 1.5-6g threads
  - Length: 30 – 60 mm
  - Sealing Pressure: 1.5 times operating pressure
  - Cost: <$26.00 per valve (Including man hours)
- Performance Specifications
  - Opening Pressure: 2400 – 2900 Bar
  - Limp Home Pressure Range: 200 – 1100 Bar between 0.15 L/min – 4.5 L/min flow rates
  - Minimum Limp Home Time: Unlimited.
  - Temperature Fluctuations: 100 – 200 °C