Design of a Small and Low Cost Thermal Cycling Chamber for Testing Thermostats

Mohammad Hossain*[1], *Jonathan Rocha*[1], *Shawn Jackson*[1], *Robert Carson*[1], *Md Mahmudur Chowdhury*[1], *Chris Jensenius*[2]

Abstract–A chamber for testing thermostats was designed by students as a part of the capstone design class using the NX7.5 software. The project was sponsored by John Deere Company. Operational temperature and pressure of the chamber rangefrom -40°C to 120°C and -40kPa to 280 kPa, respectively. The chamber is designed to be ergonomic by not requiring anyone to lift the chamber using hoist rings and having handles for the lid. It also consisted of a window to monitor the thermostat operation and a metering glass for nitrogen level determination. The chamber can go from -40°C to 120°C in about 17 minwithout any heat loss and 18 min with heat loss, respectively.Afinite element analysis (FEA)using the NX Nastran software at621 kPa revealed a maximum stress of 67,800 kPa for the chamber.

*Keywords:*Thermal Cycling Chamber; Thermostat; John Deere; NX 7.5; FEA.

INTRODUCTION

Engines operate at high temperatures. However, it may be started at low temperatures. Thermostats regulate the temperature throughout the operation. They also control the rate of cooling and heating of an engine. Hence,first it is important to test thermostats at both low and high temperatures during engine operation. Therefore, an effective thermal cycling chamber that can simulate engine cooling, start up, and operation is vital to engine performance.Students are tasked to design a small and low cost thermal cycling chamber for testing thermostats for John Deere Company. It has to be capable of cooling to -40 °C and heating to 120 °C creating a pressure of 280 kPa during heating and a vacuum of -40 kPa during cooling. The unit needs to have at least 2 gallon capacity with a removable lid for putting test components in and have a viewing window. Moreover, pressure and temperature must be monitored over time and the operator should not be required for operation.

DESIGN PROCESS

First, background research was conducted to define the scope of the project. Next, surveys of the potential customer (John Deere) were taken to establish customer needs. These customer needs then led to the design specifications of the device. The customer needs and design specifications were then embedded into two quality-function-deployment (QFD) houses, which provided further insight in the design process. The substitute quality characteristics (SQCs) and functional requirements of the subsystem were determined through the QFD analyses. Next, students generated several product concepts using brainstorming. Sketches based on these initial concepts were then converted into an initial collection of CAD concept models using NX 7.5 software. After these initial models had been generated, students performed concept selection using a Pugh matrix to obtain the design most consistent with the specifications those had been developed. The final design was then selected for the thermal cycling chamber for thermostats, and a more detailed conceptual model of the winning design was then refined and detailed still further using NX 7.5 software.

[1] Tuskegee University, 238 Luther Foster Hall, Tuskegee, AL 36088, hossainm@mytu.tuskegee.edu.

[2] John Deere Power Systems, PO Box 8000, Waterloo, IA 50701, JenseniusChristopherD@johndeere.com.

Quality Function Deployment (QFD)

In order to ensure a successful design, a survey was generated to receive customer feedback to determine the important parameters for the device. The survey was taken by John Deere and its customers. They were asked to rate the parameters from the most important to the least important. Based on the customer needs the substitute quality characteristics (SQCs) were developed in terms of engineering needs through the House1 (Table 1). The relationship based on this scale is: 0 - no correlation, 1 - low correlation, 3 - moderate correlation, and 9 - high correlation. The priority based on this scale is: 0 - no priority, 1 - low priority, 3 - moderate priority, and 5 - high priority.

Table 1: Quality Function Deployment (QFD): House 1

Substitute Quality Characteristics (SQCs)

Customer Needs	Priority	Pressure (psi)	Volume (gallons)	Temperature (°C)	Rate of change of Temperature (°C/Min)	Transparent Window	Automatic operation	Force to close lid (N)	Chemically inert material with glycol and water	Depth of Thermostat from surface (in)	Weight (lbs)	Rate of pressure change	Boiling point	Cost ($)
1. Chamber Safety	5	9		9	9	3	9	3	9			9		9
2. Chamber Size	1	3	9	3	9					9	9	9		3
3. ChamberThermal Cycling	5	9	9	9	9	3	9		9		9	9	9	9
4. Heat Rate	5	9	9	9	9	3	9		9		9	9	9	9
5. System Pressure	5	9	3	9	3	3	9	9				9	9	9
6. Slight Vacuum System	5	9	3	9	3	3	9	9				9	9	9
7. Removable Lid	3	3		3	3	3		9			3	3	3	9
8. Viewing Window	3	3		3	3	9				9	3	3		9
9. Automatic operation	5						9							9
10. Chamber Leak	3	9		9	3	3		9				9	3	9
11. Ease of temperature monitoring	5	3		9	9		9			9				3
12. Ease of pressure monitoring	5	9		3			9					9	9	3
13. Connection capability to the shop pressure supply	5	9		9			9					9	9	3
14. Thermostat Cooling	5		9						9	9	3		9	9
15. Thermostat Location	5		9		9	9				9	9			3
16. Chamber Portability	1		9								9			9
Importance		**378**	**228**	**378**	**291**	**165**	**405**	**159**	**180**	**171**	**186**	**369**	**333**	**468**

Using the SQCs from House1, functional requirements were generated through the House2 to help us develop three possible design concepts. The ratings of each functional requirement were taken from the previous SQCs' importance values dividingby 10 and rounding up the number. The relationship based on this scale is: 0 - no correlation, 1 - low correlation, 3 - moderate correlation, and 9 - high correlation (Table 2).

Customer needs, business needs, SQCs, and functional requirements are obtained through the QFD analysis. The customer needs are: chamber safety, chamber size, chamber thermal cycling, heat rate, systempressure, slight vacuum system, removable lid, viewing window, automatic operation, chamber leak, ease of temperature monitoring, ease of pressure monitoring, connection capability to the shop pressure supply, thermostat cooling, thermostat location, and chamber portability.The business needs are: low production cost, minimum custom parts, minimum machining, avoiding injury and liability, low maintenance to provide warranty, and targeting more customers. Our SQCs are: Pressure (psi), volume (gallons), temperature (°C), rate of change of temperature (°C/Min), transparent window, automatic operation, force to close lid (N), chemically inert material with glycol and water, depth of thermostat from surface (in), weight (lb), rate of pressure change (psi/min), pressure monitoring system, boiling point (°C), and cost($).

Table 2: Quality Function Deployment: House 2:

Functional Requirements

Substitute Quality Characteristics	Rating	Increase in temperature	Decreaase in temperature	Increase in pressure	Decrease in pressure	Maintain pressure	Monitor pressure	Monitor temperature	Maintain constant vacuum	Safe	Efficiency	Visibility through the window
1. Pressure (psi)	38	9	9	9	9	9	9	9	9	9	9	3
2. Volume (Gallons)	23	3	3	9	9	9	9	3	9	3	3	3
3. Temperature (°C)	38	9	9	9	3	9	9	9	9	9	9	9
4. Rate of change of temperature (°C/Min)	29	9	9	9	9	9	9	9	9	3	3	3
5. Transparent window	17	0	0	0	0	0	0	0	0	0	0	9
6. Automatic operation	41	3	3	3	3	3	3	3	3	3	3	3
7. Force to close lid (N)	16	3	3	9	9	9	3	3	9	9	9	0
8. Chemically inert materials	18	9	9	9	9	9	3	9	9	9	3	0
9. Depth of thermostat from suface (in)	17	3	3	3	3	3	3	3	3	3	3	9
10. Weight (lbs)	19	3	3	3	3	3	3	3	3	3	3	0
11. Rate of pressure change	37	3	3	9	9	9	3	9	9	3	9	3
12. Boiling point	33	9	9	3	3	3	3	3	3	3	3	3
13. Cost ($)	47	3	3	3	3	3	3	3	3	3	3	0
	Importance	**2004**	**2004**	**2262**	**2034**	**2262**	**1836**	**2028**	**2262**	**1728**	**1842**	**1251**

Product Design Specification: (PDS)

Performance:

- 8 hours to go from 120 °C to -40 °C and 15 min to go from -40 °C to 120 °C.
- -40 kPa vacuum pressure during cooling and 280 kPaduring heating.
- Temperature and pressure monitored as a function of time.
- Viewing glass to see within the chamber.
- Operator not required during testing.

Environment:Manufacturing area.
Target product cost:Less than $10,000.
Competition: None
Quantity: 1 prototype for John Deere then possibly for others.
Aesthetics:Compact.
Market constraints: Customizing the chamber to fit in John Deere's shop.
Size: 2 gallons minimum.
Weight: As light as possible.
Durability: Corrosion resistant and resistant to impacts from other machines and mishandlings.
Lifespan: At least 10 years.
Testing: To be pressure tested beyond operating conditions.
Maintenance: Seals and gaskets replaced as necessary.
Ergonomics: The chamber should be portable to avoid lifting and have hoist rings.
Safety: A pressure relief valve is necessary and chamber should withstand 90 psi.
Disposal: As many recyclable parts as possible and if refrigerant is used, no CFCs.

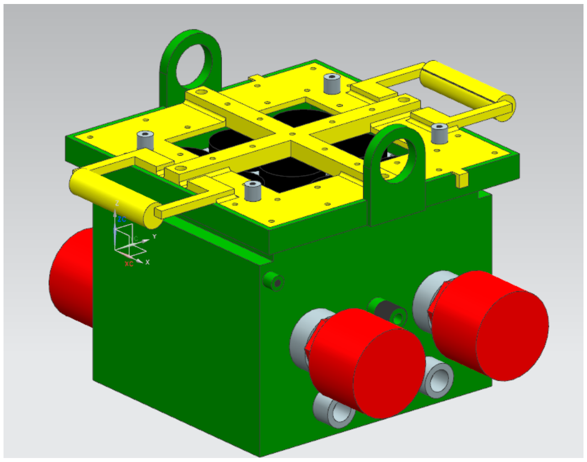
Selection Pugh Matrix

The design concepts were generated based on SQCs, functional requirements, and PDSs. In order to help make the best selection of the three design concepts: C1, C2, and C3, a Selection Pugh Matrix was developed to comparepros and cons of each design with an existing device(B1) at John Deere.The Selection Pugh Matrix is shown in Table 3.

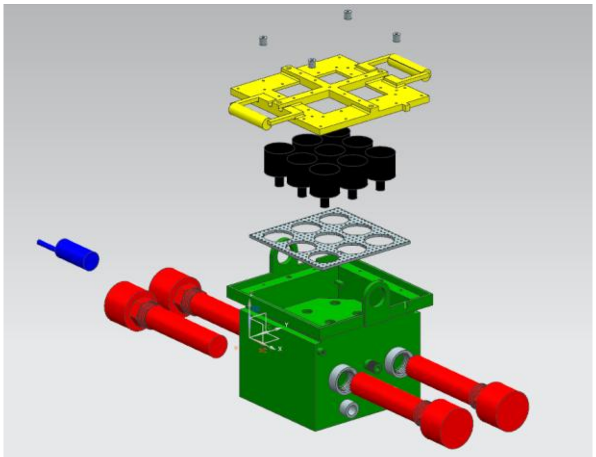
Table 3: Selection Pugh Matrix

Concept Selection Pugh Matrix Variable Chamber						
			Options			
Category	**Evaluation Criteria**	**Importance**	C1	C2	C3	B1
Quality	Safety	1	1	1	1	0
	Operator required	3	1	1	1	0
	Possible failures	3	-1	-1	-1	0
	Visibility through chamber	2	1	1	1	0
	Amount of liquid	1	-1	-1	-1	0
	Size	1	1	1	1	0
	Transportability	3	0	0	1	0
	Ease of assembly	1	-1	-1	-1	0
Functionality	Positive pressure	3	1	1	1	0
	Vacuum pressure	3	1	1	1	0
	Control pressure	3	1	1	1	0
	Temperature control	3	1	1	1	0
	Rate of temperature increase	3	1	1	1	0
	Testing adaptability	2	0	1	0	0
	Rate of temperature decrease	3	1	1	1	0
Cost	Cost of components	3	-1	-1	1	0
	Amount of machining	1	-1	-1	-1	0
	Amount of fabrication	1	-1	-1	-1	0
	Sum of +'s		10	11	12	0
	Sum of -'s		6	6	5	0
	Concept Rating (sum of +'s and -'s)		4	5	7	0
	Weighted Concept Rating		15	17	24	0

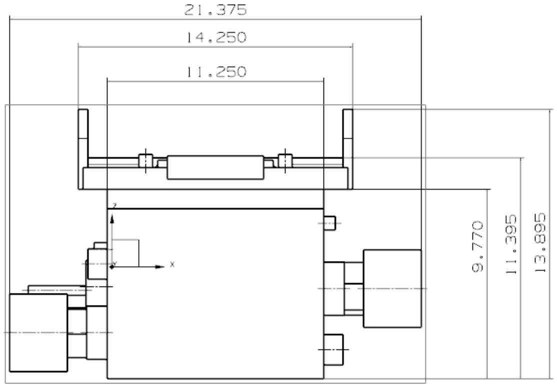
DesignC1 received the maximum 4 and 15 for concept and weighted concept rating, respectively. The concept and weighted concept rating for DesignsC2 and C3 are5 and 17, and 7 and 24, respectively. Hence, DesignC3 was selected as the final concept design to refine and perform the engineering analysis. The final design including assembly, exploded view, drafting, and various features is shown in Figure 1.



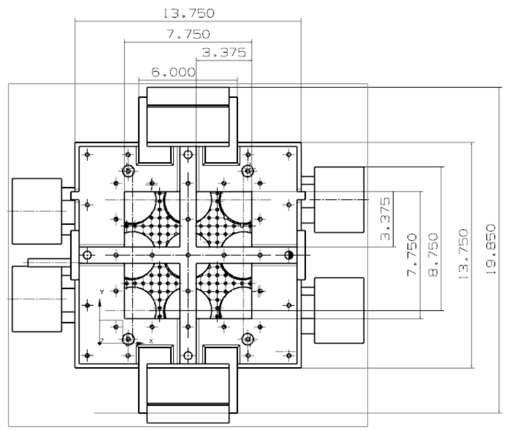
a. Final Design Assembly



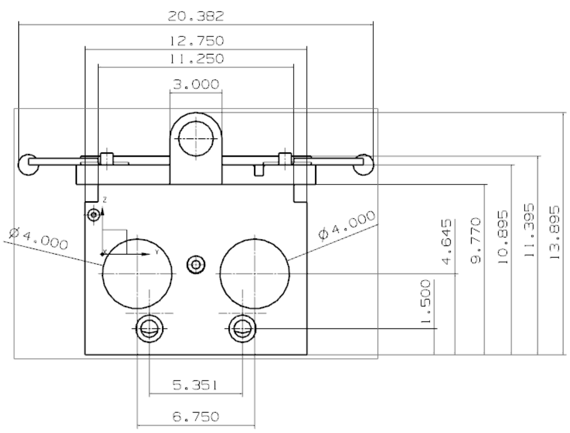
b. Final Design Exploded View



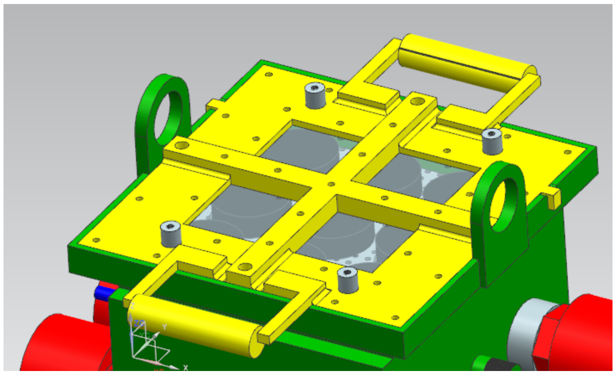
c. Front View



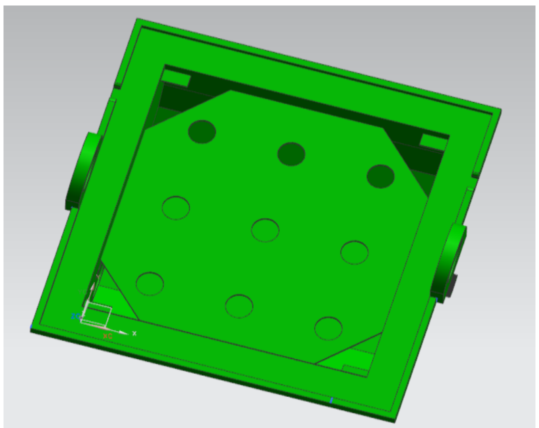
d. Top View



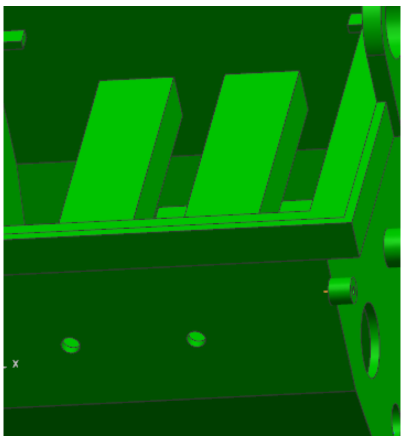
e. Right View



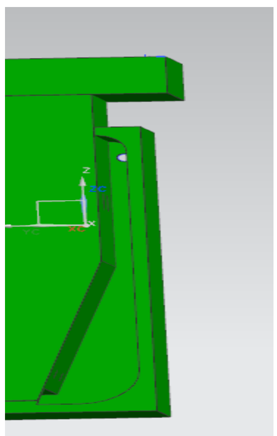
f. Viewing Window, Handles, Hoist Rings, and Positioning Tabs



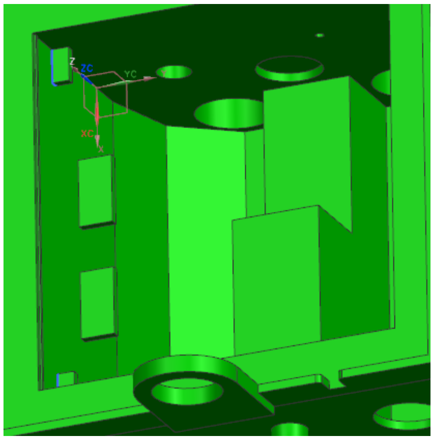
g. Holding Tray



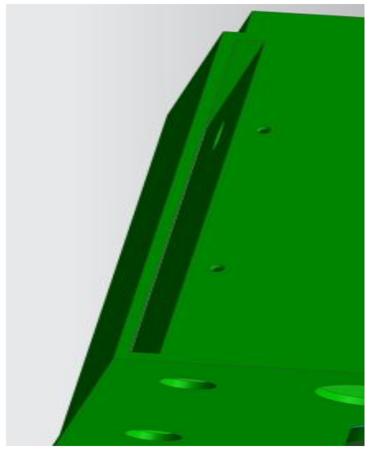
h. Nitrogen Passage



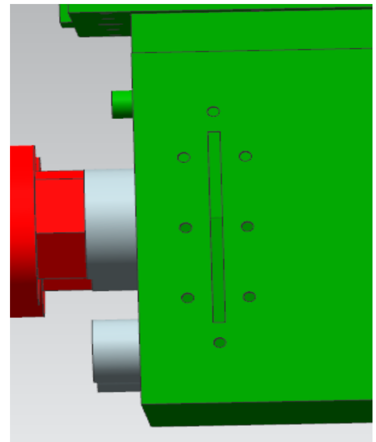
i. Nitrogen Reservoir and Thermal Cooling Jacket



j. Bottom inner chamber nitrogen passage



k. Bottom Reservoir and Thermal Jacket



l. Nitrogen level meter

Figure 1: Final Design with various Components

Working Principle

The process begins at room temperature. The thermostats are put into the chamber and then the positioning tray is placed on top of the tabs in order to ensure proper position of the thermostats. Glycol is then poured into the chamber to about 1/4 in. from the top. The filling point is indicated by a line near the rim of the chamber. Then the chamber is sealed using the lid, bolts, and nuts. During the operation the inside of the chamber may be seen using the viewing window on the top. It has hoist rings so that it does not need to be carried. Furthermore, the lid has handles so that the operator can pick up and move the lid comfortably. When putting the lid on, there are positioning tabs that allow the lid to be put correctly. This ensures that any modification to the chamber that requires a specific orientation of the lid will not have any problem due to improper lid installation. Once the chamber has been sealed, it would be cooled using the chiller probe to -20 °C and a vacuum would be created using a vacuum pump (-40 kPa gauge). The vacuum pump has a built in regulator and in the case of the regulator malfunctioning, there is a vacuum relief valve that would allow atmospheric air in. The vacuum in the chamber is turned on and off using a vacuum solenoid valve. After achieving -20 °C, liquid nitrogen would be let into the chamber using a cryogenic solenoid valve connected to the pressurized nitrogen tank. Then, the inner and outer chambers would fill with nitrogen. As the liquid nitrogen absorbs the heat, it will become a gas and pressurize the chamber. This nitrogen would then be bled off using a cryogenic relief valve. The chamber will reach -40 °C and maintain that temperature.Subsequently, heaters would be used to heat the chamber up to 120 °C. The vacuum solenoid valve would switch off and the vacuum pump would be turned off. A general use solenoid valve would switch on, allowing compressed regulated air from the compressor into chamber at 280 kPa gauge. There is a safety relief valve on the chamber to remove excess pressure above 280 kPa. Once at 120 °C, the heaters would be turned off and then the pump would take glycol from the chamber to the heat exchanger. Simultaneously, the hot water solenoid valves (one for the input and one for the exit to avoid freezing up the heat exchanger) would open allowing the glycol to flow and a general solenoid valve would open allowing water through to the other side of the heat exchanger. To avoid any over pressurization of the lines, the heat exchanger has a pressure relief valve to let off glycol, if glycol becomes too hot and expands causing a rupture due to the closed volume created by the two solenoid valves. Heat will then be exchanged between the 120 °C glycol and the running water coming from the cooling towers which are attached to the chamber. When the temperature is reached to 30 °C, the pressure is cut off by the solenoid valve and the vacuum is kicked in once again while the chiller probe cools the chamber down to -20 °C. Thus, a cycle is completed. The process can be repeated as needed.

ENGINEERING ANALYSIS

Sample Analytical Results

Detailed engineering analytical calculation has been performed to design the chamber. However, only important ones are presented in this article where heat loss has been neglected.

Calculation of energy required for heating between the temperatures of -40 °C to 120 °C is shown in Equation 1:

$$q_{-40\ to\ 120\ no\ heat\ loss} = q_{chamber} + q_{glycol} + q_{plexiglass} \tag{1}$$

$$= m_{chamber}C_{steel}\Delta T + m_{glycol}C_{glycol}\Delta T + m_{plexiglass}C_{plexiglass}\Delta T$$

$$= \Delta T\left[m_{chamber}C_{steel} + m_{glycol}C_{glycol} + m_{plexiglass}C_{plexiglass}\right]$$

$$= (120 + 40)(°\text{C})\left[33.26\ kg \times 0.42\frac{kJ}{kgK} + 15.5\ \text{kg} \times 3.13\ {}^{\text{kJ}}/_{\text{kg K}} + 0.693\ \text{kg} \times 1.4651\ {}^{\text{kJ}}/_{\text{kg K}}\right] = 10159.9\ kJ$$

The time required for the immersion heaters to increase the temperature from -40 °C to 120°C is presented below in using Equation 2:

$$t_{-40\ to\ 120\ no\ heat\ loss} = \frac{q_{required}}{4 \times Power_{heater}} \tag{2}$$

$$= \frac{10159.9\ kJ}{4 \times 2.5\ kW} = 1016s = 16.93\ min$$

Calculation of energy required for cooling between the temperatures of 30 °C to 0°C is shown in Equation 3:

$$q_{30\ to\ 0\ no\ heat\ loss} = \Delta T\left[m_{chamber}C_{steel} + m_{glycol}C_{glycol} + m_{plexiglass}C_{plexiglass}\right] \tag{3}$$

$$= (30 + 0)(°\text{C})\left[33.26\ kg \times 0.42\frac{kJ}{kgK} + 16.08\ \text{kg} \times 3.13\ {}^{\text{kJ}}/_{\text{kg K}} + 0.693\ \text{kg} \times 1.4651\ {}^{\text{kJ}}/_{\text{kg K}}\right] = 1959.45\ kJ$$

Calculation of energy required for cooling between the temperatures of 0 °C to -40°C is shown in Equation 4:

$$q_{0\ to -20\ no\ heat\ loss} = \Delta T\left[m_{chamber}C_{steel} + m_{glycol}C_{glycol} + m_{plexiglass}C_{plexiglass}\right] \tag{4}$$

$$= (0 + 20)(°\text{C})\left[33.26\ kg \times 0.42\frac{kJ}{kgK} + 15.5\ \text{kg} \times 3.13\ {}^{\text{kJ}}/_{\text{kg K}} + 0.693\ \text{kg} \times 1.4651\ {}^{\text{kJ}}/_{\text{kg K}}\right]$$

$$= 1270\ kJ$$

Calculation of energy required for cooling between the temperatures of -20 °C to -40°C is shown in Equation 5:

$$q_{-20\ to -40\ no\ heat\ loss} = \Delta T\left[m_{chamber}C_{steel} + m_{glycol}C_{glycol} + m_{plexiglass}C_{plexiglass}\right] \tag{5}$$

$$= (-20 + 40)(°\text{C})\left[33.26\ kg \times 0.42\frac{kJ}{kgK} + 15.5\ \text{kg} \times 3.13\ {}^{\text{kJ}}/_{\text{kg K}} + 0.693\ \text{kg} \times 1.4651\ {}^{\text{kJ}}/_{\text{kg K}}\right] = 1270\ kJ$$

The power capability assumed for the chiller in the range from 30 °C to 0 °C, 0°C to -20°C, -20 °C to -40 is 480 W,360 W, and 200 W, respectively.

Calculation of the time required for the chamber to go from 30 °C to -40 °C without heat loss and nitrogen being used is shown in Equation 6:

$$Time_{30\ to-40\ no\ heat\ loss,\ \ no\ nitrogen} = Time_{30\ to\ 0} + Time_{0\ to-20} + Time_{-20\ to-40} \tag{6}$$
$$= \frac{q_{30\ to\ 0\ no\ heat\ loss}}{Power_{30\ to\ 0}} + \frac{q_{0\ to-20\ no\ heat\ loss}}{Power_{0\ to-20}} + \frac{q_{-20\ to-40\ no\ heat\ loss}}{Power_{-20\ to-40}}$$
$$= \left[\frac{1959.45\ kJ \times 1000 \,{}^{J}/_{kJ}}{480 \,{}^{J}/_{s}} + \frac{1270\ kJ \times 1000 \,{}^{J}/_{kJ}}{360\ {}^{J}/_{s}} + \frac{1270\ kJ \times 1000 \,{}^{J}/_{kJ}}{200\ {}^{J}/_{s}}\right]$$
$$= 13960s \times \frac{1\ hr}{3600\ s} = 3.88hr = 232.67\ min$$

However, this time assumes that there is no heat loss occurring which is not realistic. This estimation uses the lower power for each range. Furthermore, this time does not include the use of nitrogen within the system. Thus, the time could be decreased as desired by using more nitrogen to cool.

Structural Finite Element Analysis (FEA)

Pressure of 90 psiwas applied throughout the inside of the chamber and constrained at the bottom to simulate the real life condition(Figure 2). Yield Strengths of 129,566, 235,000, and 65,000 kPa for the default steel, rolled steel, and polycarbonate, respectively, wereused in the FEA. The stress, displacement, and reaction contours of various parts of the chamber are presented in Figures 3.

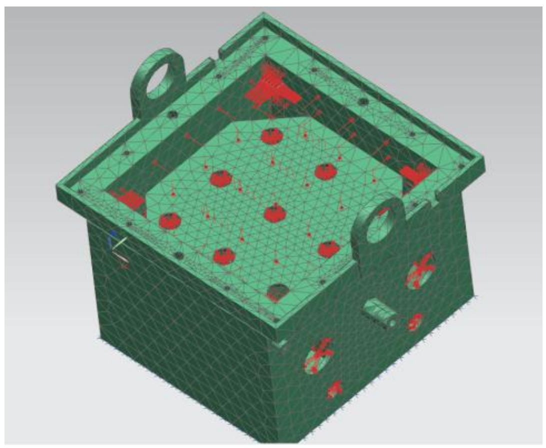
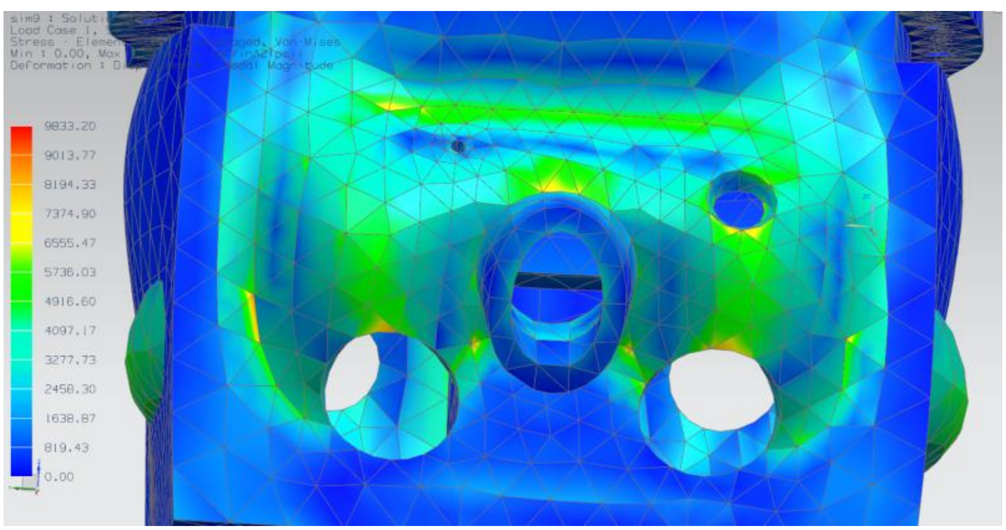
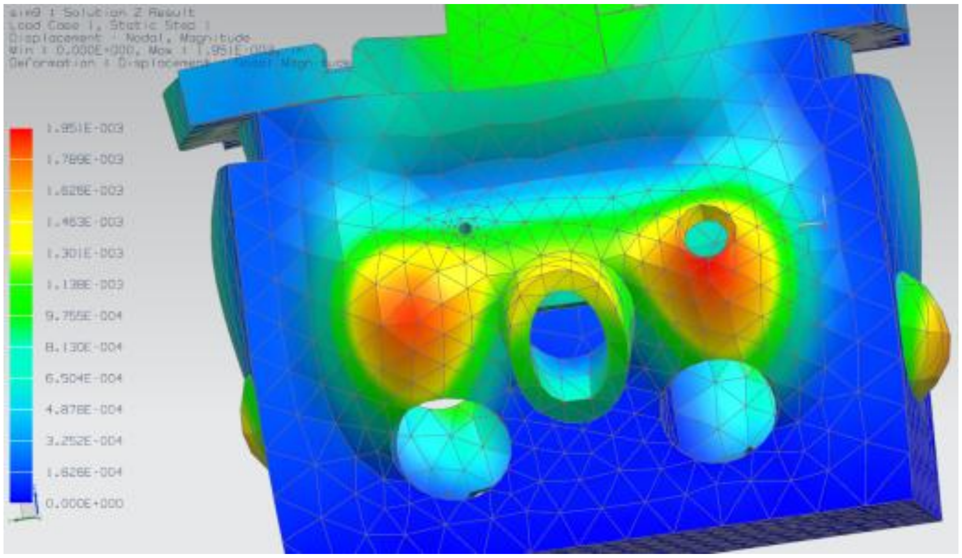


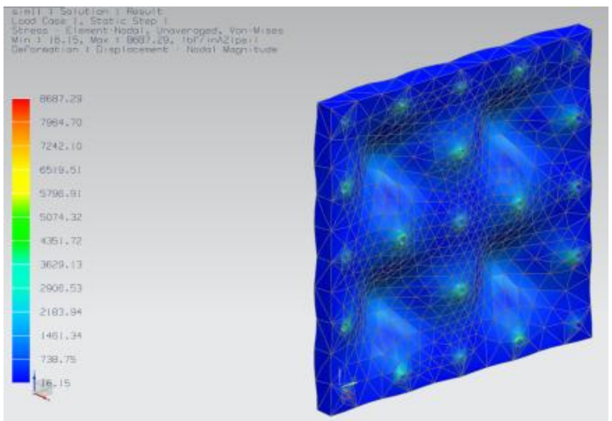
Figure 2: Applied Pressure and Constraints



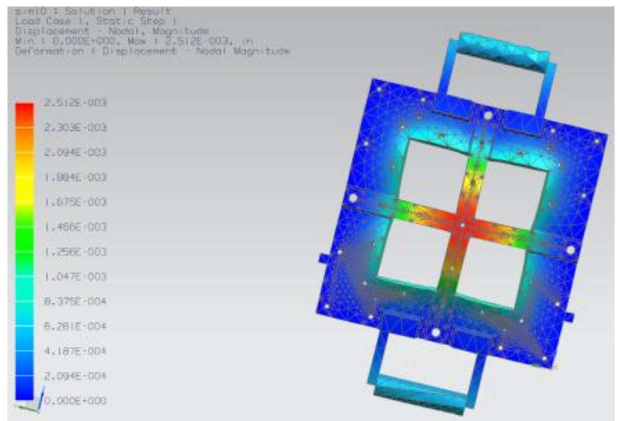
3 (a) Right side of Chamber Stress Contour



3(b) Right Side of Chamber Displacement Contour



3(c) Plexi glass bottom Stress Contour



3(d) Top Lid Displacement Contour

DISCUSSIONS

The heaters can go from - 40 °C to 120 °C in about 17 min and 18 min without and with heat loss, respectively. The heat loss does not affect time significantly because the heaters produce a power of 10 kW that is small compared to the heat loss. The heat gain estimated at -40 °C is 263 W. The chiller probe can only put out 200 W. Hence, the probe will not be able to drop the system to -40 °C without assistance from another source. However, the chillers could reduce the temperature to -40 °C in 3 hours and 53 min with no heat loss. The reason is that probes lose efficiency as they decrease in temperature and the heat gain increases at lower temperatures. Therefore, there is an exponential decrease in the amount of temperature change per unit time. This problem is not detrimental in the heating cycle because the heaters do not lose efficiency. Hence, staying within the 20 min mark is a tradeoff that still simulates approximately what occurs in an engine.

A 0.25 in. thick steel chamber was observed to fail in the FEA analysis under 90 psi pressure. Hence, the thickness of the chamber was gradually increased until it could withstand the pressure. However, this resulted in a bulky, heavy, and costly chamber. To solve this problem, material was added efficiently only to places where the stress concentrations were observed. This revealed the maximum stress to 67,800 kPa. Steel with yield strength of 129,566 kPa can thus be employed to maintain a factor of safety of 1.91. Perhaps the thickness of the walls could be reduced from 0.25 to 0.125 in. and the stress concentrations can be taken into an account. The FEA done on a solid lid without any window revealed maximum stress of 127,600 kPa which is just below the yield strength. A separate FEA shows that the combination of the window and lid would be much stronger than the lid alone. Finally, the polycarbonate used for the window experienced a maximum stress of 59,000 kPa which gave a factor of safety of 1.1.

PROJECT BENEFITS

From this project students learned the followings:

- how to tackle an engineering problem
- how to use six sigma method to find out and correlate the customer, engineering, and business needs to develop a commercial product
- how to incorporate existing commercial products in the design
- how to select the best design
- how to design the final product
- how to usecomputer-aided design(CAD)for assembly
- How to complete the analytical engineering calculation for the design
- How to perform the computer-aided engineering (CAE) analysis on the structure of the design
- how to estimate product costs
- how to interact with professional people

Mohammad Kamal Hossain
Mohammad Kamal Hossain is an Assistant Professor in the Department of Mechanical Engineering at Tuskegee University. He received his Ph.D., M.S., and B. Sc. in Mechanical Engineering from the University of Nevada, Las Vegas (USA), Tuskegee University (USA), and Bangladesh University of Engineering and Technology (Bangladesh), respectively. His specialization is in the areas of materials and design. He has been involved with the capstone design program at Tuskegee University for the last six years.

Jonathan Rocha
Jonathan Rocha was an Undergraduate Student in the Department of Mechanical Engineering at Tuskegee University. He graduated with a BS in Mechanical Engineering and currently pursuing for his MS in Mechanical Engineering at Purdue University, USA.

Shawn Jackson
Shawn Jackson was an Undergraduate Student in the Department of Mechanical Engineering at Tuskegee University. He graduated with a BS in Mechanical Engineering and currently working in the industry, USA.

Robert Carson
Robert Carson is a Senior Undergraduate Student in the Department of Mechanical Engineering at Tuskegee University.

Md Mahmudur Chowdhury
Md Mahmudur Chowdhury is a MS Student in the Department of Mechanical Engineering at Tuskegee University.

Chris Jensenius
Chris Jensenius is the Lead Engineer at the John Deere Power Systems, PO Box 8000, Waterloo, IA, USA.