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## Microfluidics sterilization system

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# **MICROFLUIDICS STERILIZATION SYSTEM**

**ME 1501-1502**

**Technical Design Report**

**Microfluidics Steam Sterilization Cycle  
Optimization  
Project #W01/S01**

**Final Report**

**Design Advisor: Prof. Kowalski**

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**December 4, 2006**

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# **Microfluidics Steam Sterilization Cycle Optimization**

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## **Abstract**

Our solutions to verify the system sterilization temperature field and eliminate seal failure in the Microfluidics M710 Microfluidizer Processor are described in this document. The Microfluidizer is a device that breaks product particles into uniform nanoparticles. The system is modeled using GAMBIT and analyzed using Fluent. This simulation will allow us to predict the pressures and temperatures across the entire system. The temperature and pressure are not able to be measured in many parts of the system because it can not be broken to add thermal couples. A Fluent simulation is one of the only ways to verify temperature in many locations. This data will enable us to alter the inlet temperature to ensure that all parts of the system will reach 121° C as defined by ASME standard BPE-a-2004 but will not become so hot that the seals in the intensifier pump fail.

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## Copyright

“We the team members,

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Gregory Kowalski

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## **Introduction**

The creation of a computational computer model of an advanced micro particle processing machine designed and built by Microfluidics was created to aid in determining the design solution for this project. The purpose of this model was to simulate the steam sterilization cycle of Microfluidics M700 microfluidizer, verifying that appropriate temperatures were being reached throughout the system. Verification of these temperatures would prove that the sterilization process was compliant with ASME standard BPE-a-2004 codes. In addition to this, information could be gained from this analysis which could shed light onto the recurring problem of seal failures within the system due to the sterilization process. The following report documents the efforts by the design team to create a working model of the system and to use this information to solve the design problems.

# CHAPTER 1 DESIGN CHALLENGE

## 1.1 STEAM STERILIZATION

Microfluidizers, such as the one seen in Figure 2 are used by companies to process various products such as makeup, lotion, ink and drugs, and in many cases they are processed by a single machine. Since many of these products are for pharmaceutical, medical, and cosmetic purposes it is highly likely that the resulting product may be ingested by or applied to the bodies of consumers. As a result of this, each apparatus must be cleaned and sterilized after each batch of product is processed. This is necessary so that none of the particles from one batch mix with the next, potentially causing harmful effects. One only has to imagine the consequences of residue from a batch of some sort of toxic material mistakenly getting mixed into any widely used medicine to see the need for this cleaning process.

### 1.1.1 Process

Since the product could potentially be used on or ingested by humans, the sterilization process must comply with extremely strict codes (ASME BPE-a-2004). The most critical part of the code states that all parts of machinery that come into contact with the processed product must be heated up to 121° C or higher, continuously for 20 minutes. Microfluidics currently employs a multistage and complex sterilization procedure to meet the ASME BPE-a-2004 requirements.

After the product has been processed, a Clean in Place (CIP) cycle is run. First, the machine is flushed with USPPW (purified water). This flushes the bulk of the soil from the machine. Second, a base - such as a weak NaOH – is used to clean the piping. Third, the machine is flushed again with USPPW. This removes the base. Fourth, clean with an acid (phosphoric acid is commonly used). This neutralizes the base and removes many soils that don't respond to cleaning with a base. Finally, the machine is flushed with WFI (Water for Injection) - a de-ionized water.

Immediately following the CIP cycle is a Steam in Place (SIP) cycle. The SIP cycle is the most important part of the entire process because it is the heat from the steam which actually sterilizes the piping. Steam is pumped under low pressure (35 psig) throughout the system through three pathways. Valves are opened and closed to change the flow for each path and ensure that all parts of the machine are sterilized. The SIP cycle differs from the CIP cycle, as the intensifier pumps are automatically cycled about once a minute to ensure sterilization of the entire pump portion of the system. In the CIP cycle the intensifier pumps are off. Once the SIP cycle has been completed a cool down cycle commences in which sterile filtered air is pumped through the system to cool it down.

### 1.1.2 Why is sterilization necessary?

Due to the nature of the product and its many uses, an extensive sterilization process is necessary to ensure the purity of the product being processed. Since these machines are used in the processing of

pharmaceutical products, the sterilization must meet industry standards. ASME BPE-a-2004 is the code with which Microfluidics products must comply.

### 1.1.3 What do other companies do?

Currently, the autosiever and high shear dispersers, dissolvers and emulsifiers are incapable of creating particles suitable for use in pharmaceutical, medical or biomedical applications. This causes their sterilization requirements to be must less stringent. Most of these technologies only use a CIP cycle. In this process CIP solution is put into the machine, and the machine is run as if it were filled with processing product.

### 1.1.4 Current ASME BPE-a-2004 Compliance Verification

Microfluidics currently ensures sterilization is compliant with ASME BPE-a-2004 by checking temperature readings taken at the system inlet and outlets used during steam sterilization. Steam at 138° C is pumped through the system. As it exits the system a temperature probe gives the exit temperature. Once the exit temperature is consistently greater than 121° C timing begins. The temperature is checked to ensure that it remains above 121° C for the entirety of the 20 minutes required for sterilization. Unfortunately this technique only gives temperature readings at the inlet and outlet of the system. These temperature readings are taken by temperature probes which must be inserted into the piping system. Without massively overhauling the entire system there is no real way to increase the amount of points where temperature readings can be taken. This makes it impossible to know the actual temperature at all points along the flow path.

## **1.2 SEAL FAILURE**

One of the problems with the current system revolves around the high-pressure seals of each intensifier pump. The location of these seals can seen in Figure 2. These seals are designed to withstand the high pressures required to draw the product into the pump and then force it through the two chambers. These high pressures (20,000 - 30,000 psi) do not affect the durability of the seals. During the steam-in-place sterilization process, they can be exposed to temperatures as high as 138° C. The steam sterilization process will be analyzed to determine actual temperatures and pressures around the seals. This data is required to ensure all surfaces are properly sterilized as well as to investigate the failures and determine possible solutions.

### 1.2.1 Seal Material

The seals are made of TIVAR H.O.T. (High Operating Temperature) which is an UHMW-PE (Ultra High Molecular Weight Polyethylene) formulation. Its maximum operating temperature is 135°C [1]. As noted in the previous section, the current inlet temperature used for the steam is 138°C. Our computational model of the system will show whether a temperature of 135°C is reached or exceeded at the location of the seals during steam sterilization. From this analysis it can be determined if thermal degradation is occurring. As seen in Figure 5, thermal degradation will cause the seals to exhibit radial cracks and exhibit signs of

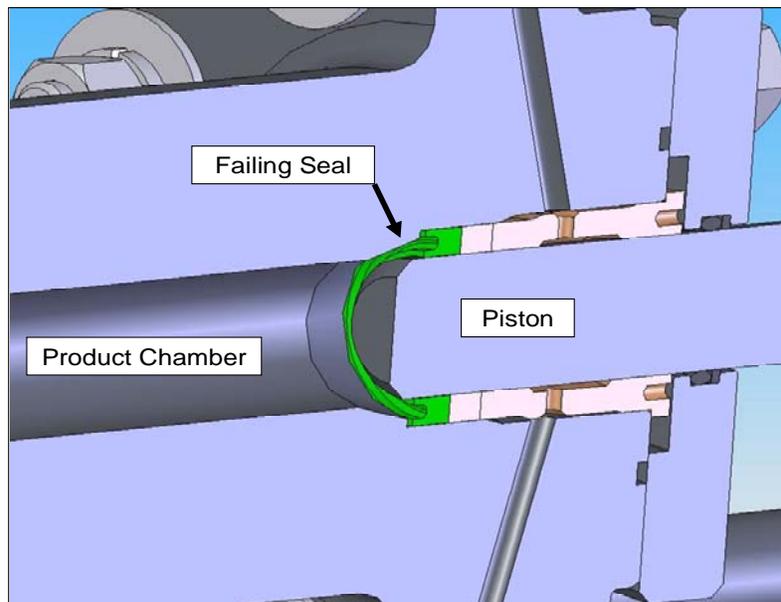
softening. This is a common occurrence in elastomers that experience excessive temperatures and thermal cycling.



**Figure 1: Effects of thermal degradation on a seal**

It is not until normal operation of the machine begins again that the seals fail. As seen in Figure 2, the seal is located on the piston of the intensifier pump used to pressurize the product. It is believed that the immense pressure achieved (up to 30,000 psi) during operation is causing the weakened seals to fail.

#### FAILING SEAL WITHIN INTENSIFIER PUMPS



**Figure 2: Sectioned View of Intensifier Pump with Seals**

The design group has looked into a variety of different seal materials as potential substitutes. It does not appear that any material which meets our set of requirement conditions is superior to TIVAR H.O.T. No

other material which would be compatible with the process material and pump operation is able to withstand both the temperatures during steam sterilization and pressures during normal operation.

## **1.3 PROBLEM STATEMENT**

### **1.3.1 Verification of Steam Sterilization**

The first problem faced is that in the current process being used, there is no way to verify that all points that come into contact with the product are reaching appropriate sterilization temperatures. At this point, only the inlet and outlet temperatures of the steam are known. A computational model using Fluent will determine the temperature at any point within the system.

### **1.3.2 Seal Failure within the Intensifier Pumps**

One problem occurring in some customer's microfluidizers is that the seals located on the pistons of the intensifier pumps are failing. Seal failure is being caused by excessive heat exposure during the steam sterilization process. Unfortunately, as discussed in the previous section there is no way to measure how hot the seals are getting during the sterilization process. The system must be computationally modeled using the known inlet and outlet pressures to obtain the seal temperatures. With an accurate model of the system, it will be possible to prove that the current process employed by Microfluidics is compliant with ASME standards (ASME BPE-a-2004) and will also produce the temperatures experienced by the seals.

### **1.3.3 Why is a Solution Necessary?**

Solving these problems is beneficial to all manufacturers who use Microfluidizers. Eliminating the problem of failing seals will increase the reliability of the machine by decreasing the amount of time that the machine may be offline for what could potentially be costly repairs. By decreasing the amount of time it takes for the sterilization cycle to be completed there is less down time when the machine is not being used to process product. If more product can be produced the production costs will be lowered, possibly lowering the cost to the consumer. Since these machines are used in a variety of different fields, decreased costs are something that is a positive effect for all microfluidizer users - and the consumers who buy their products.

# CHAPTER 2 MICROPARTICLE PROCESSING TECHNOLOGY

## 2.1 MICROFLUIDICS™

Microfluidics™ designs and manufactures material processing machines that allow users to produce uniformly sized nanoparticles in mass quantities. The ability to produce extremely small uniform particles is necessary for use in a growing number of pharmaceutical, personal care, biotechnology, food and chemical applications. Each of these different applications requires that their products to have consistent and controllable properties that can be easily reproduced. The equipment produced and sold by Microfluidics™ which are capable of attaining these results are known as Microfluidizers. The specific series of microfluidizer we will be focusing on is the Microfluidics M710 Microfluidizer Processor.

This microfluidizer works by directing product streams under extremely high pressure through fixed geometry micro-channels. This process is illustrated in Figure 3. Starting particles are contained in the inlet reservoir. The initial particles vary in size and shape – as can also be seen in Figure 3. The solution containing these particles is pumped at low pressure into the intensifier pumps. The intensifier pumps increase the pressure on the product to as high as 40,000 psi. This immense pressure created by the intensifier pumps forces the initial coarse particles through the fixed geometry micro-channels. Massive impact and shear forces inside the chambers transform the product. The initial solution, containing bulky odd shaped particles of as large as 500 microns, is converted to uniform solution with particles now sized at 0.74 microns. Microfluidics technology allows for consistent repeatable results at nano-levels, which were previously not possible at this quantity or scale by any other means.

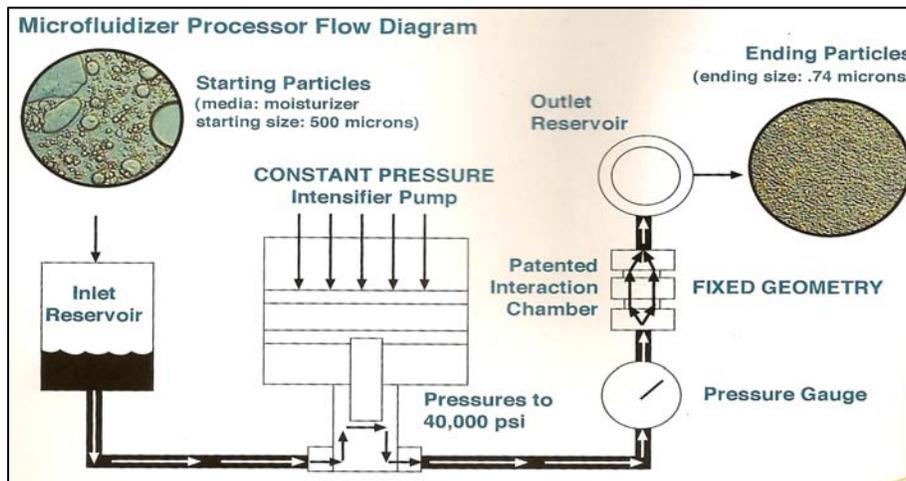
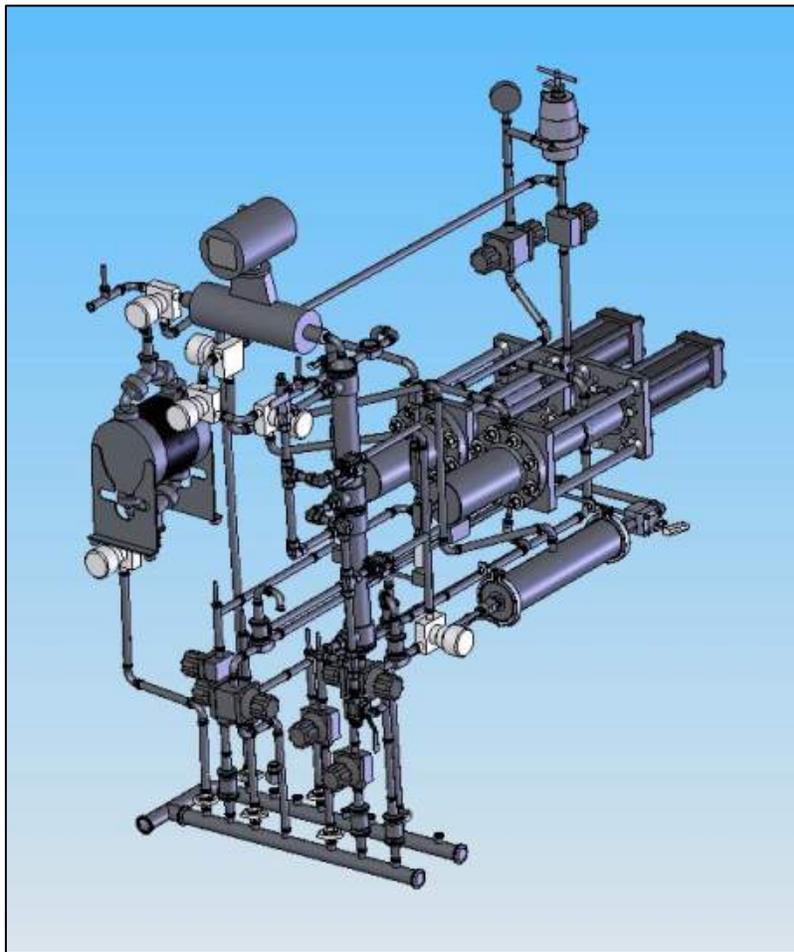


Figure 3: Microfluidizer Processor Flow Diagram



**Figure 4: 700 series Microfluidizer**

## **2.2 Alternate Technology**

Other machinery exists which can create results similar to those produced by microfluidizers. The most common of these include micro-level grinders, pulverizing mills, crushers, sonic sievers and high shear dispersers/dissolvers/emulsifiers.

### ***2.2.1 Crushers, Grinding and Pulverizing Mills***

The grinders, pulverizing mills and crushers all work similarly. These devices consist of a bowl and a grinding/crushing element – similar to a mortar and a pestle. The two parts are vibrated or rotated in contrasting directions, thus reducing the overall particle size due to the impact forces produced by the bowl and grinding element. These machines are very effective and are able to crush particles to as small as 1 micron. [6] They are limited greatly by the fact that they can process at most one liter of product at a time.

### 2.2.2 High Shear Dispersers/Dissolvers/Emulsifiers

High shear dispersers, dissolvers and emulsifiers all work in a similar manner. In layman terms, these products can be described as highly advanced blenders. Engineered mixing bits coupled with high powered motors allow for intense vortex control within the mixing chamber. The high shear forces created within the chamber cause the particle size to decrease and the product to become uniformly mixed. This technology is limited by the size of the final product, as it is not capable of creating particles smaller than 20 microns. [2]

### 2.2.3 Autosiever

The autosiever has the most in common with the microfluidizer. A vertically oscillating air column lifts particles back into a sieve mesh. The pulsing of the air column causes the particles to work their way through the sieve, thus decreasing their size. Unfortunately, the autosiever is unable to create particles smaller than 20 microns and can not process more than 4 cubic centimeters at a time. [3]

### 2.2.4 Sterilization Process in Alternative Technology

Since no other technology is able to replicate the results attained by the Microfluidizer, none are widely used for pharmaceutical or biotechnology applications. This means that they are not obligated to comply with the ASME BPE-a-2004 code. Communication with these companies revealed that none use a steam sterilization process. The most commonly used procedure is to run the machine with a cleaning solution which removes all leftover product and sanitizes the machine. Purified water is then used to flush the machine.

## CHAPTER 3 SOLUTION APPROACH

### 3.1 ANALYSIS OF THE SYSTEM

In order to accurately determine the environment within the machine and more specifically the environment surrounding the seals of the two intensifier pumps, a fluid flow analysis is necessary. This process first requires the creation of a digital model of the system, which is then imported into a flow analysis program. The result will be a three-dimensional model of the entire inside of the system. This model will be able to tell a variety of attributes, such as flow velocity, temperature and pressure for any point along the pipe. An in-depth analysis of the current seals will also be completed to shed some light onto what is causing them to fail.

#### 3.1.1 Fluid Flow Analysis

The system will be analyzed using Fluent flow analysis software. The first step in this process is to create an accurate model of the system using a Computer Aided Drafting (CAD) program. The CAD program used on this project was Solidworks. Microfluidics provided Solidworks files for the entire system. Their model was not entirely perfect and required several tedious alterations. Parts of the flow path in question, were blocked by closed valves or other components which were not model in their entirety. With help from Microfluidics, corrections were made and an accurate and working model was created. The next step was to import these Solidworks files into Gambit. Gambit is the CAD program which works in tandem with Fluent. Once the files had been imported, all of the inner surfaces of the flow paths needed to be isolated. This process proved to be extremely arduous as the system is very complex. Identification of the correct inner surfaces of the numerous check valves and two intensifier pumps proved to be difficult. Following completion of this, the same needed to be done for all of the outer surfaces of the machine. These needed to be identified so that the correct wall thickness was used during the analysis. Identification of the outer surfaces was not nearly as difficult as identifying the inner surfaces. The chambers with the fixed geometry micro channels were modeled using hand calculations. This was because the amount of extremely small sized pipes in them would have been impossible to model correctly using computational analysis. The following calculations were done to calculate the pressure drop through the chambers.

$P_1$  = inlet pressure

$P_2$  = outlet pressure

$\mu$  = viscosity

$V$  = velocity

$D$  = Diameter

$L$  = length of chambers

$$P_1 - P_2 = (64 * \mu * V * L) / (2 * D^2)$$

$$P_1 - 0 = [(64) * (0.000013 \text{ Ns/m}^2) * (7.4 \text{ m/s}) * (.3 \text{ m})] / [(2) * (0.000078 \text{ m})^2]$$

$$P_1 = 151,794 \text{ Pa}$$

$P_2$  is atmospheric pressure. This represents the outlet pressure for the chambers.  $P_1$  is the pressure going into the chamber, and is what is being solved for. By calculating  $P_1$ , the chambers could be removed from the model and  $P_1$  becomes the new outlet pressure at the end of the system.

During sterilization the intensifier pumps are cycled once a minute. It is very important that this is accounted for in our model. To represent this in our simulation a draw pressure for the pump chamber was calculated using the following equation. This draw pressure was applied to the end of the pump chamber. Without these draw pressures applied, the pump chambers act as reservoirs and very little steam flow enters into them.

$$\begin{aligned} P_1 &= \text{inlet pressure} & P_2 &= \text{draw pressure created in pump} \\ V_1 &= \text{volume with piston pushed forward} & V_2 &= \text{volume with piston pushed back} \\ P_1 * V_1 &= P_2 * V_2 \\ (35 \text{ psig}) * (1.1 \text{ in}^3) &= (P_2) * (13.18 \text{ in}^3) \\ P_2 &= 2.92 \text{ psig} \end{aligned}$$

Once all inner surfaces of the flow path had been identified, Gambit software was used to “mesh” these surfaces. “Meshing” of the surfaces is a process in which the entire system is converted into a three-dimensional nodal structure. This nodal structure is what is used by Fluent to computationally create the fluid flow model. Using Fluent, inlet and outlet faces are assigned by the user. Other parameters which were assigned in Fluent are listed below.

$$\begin{aligned} \text{Ambient Temp} &= 25 \text{ }^\circ\text{C} \\ \text{Ambient Pressure} &= 101325 \text{ Pa (1 atm)} \\ \text{Inlet flow temp} &= 138 \text{ }^\circ\text{C} \\ \text{Inlet Pressure} &= 241300 \text{ Pa (35 psig)} \\ \text{Outlet Pressure} &= 151000 \text{ Pa} \end{aligned}$$

For most of the system, the piping consisted of 316L Stainless Steel. Other parts of the system such as the pumps, elbows, tees and valves were assigned their own individual values. Once all parameters had been set, the flow was initialized and Fluent did the rest. The following pressure, velocity and corresponding Reynolds number plots illustrate analysis convergence.

# Static Pressure (Pa)

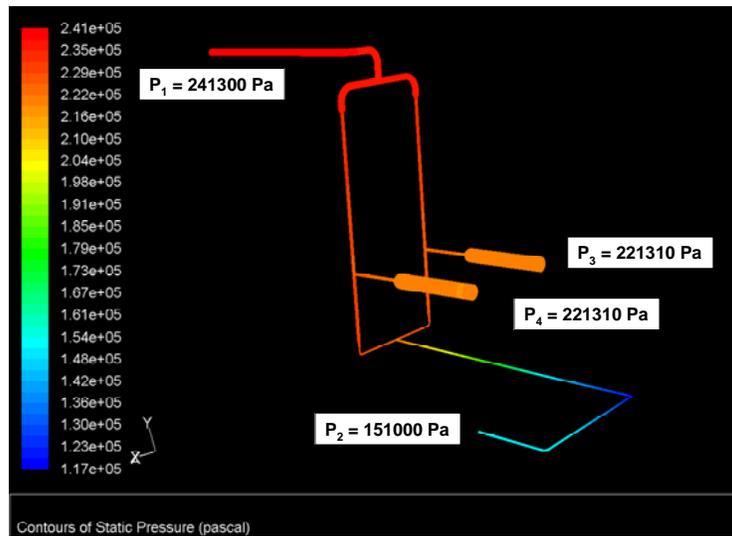


Figure 5: Baseline Static Pressure Plot

# Velocity (m/s)

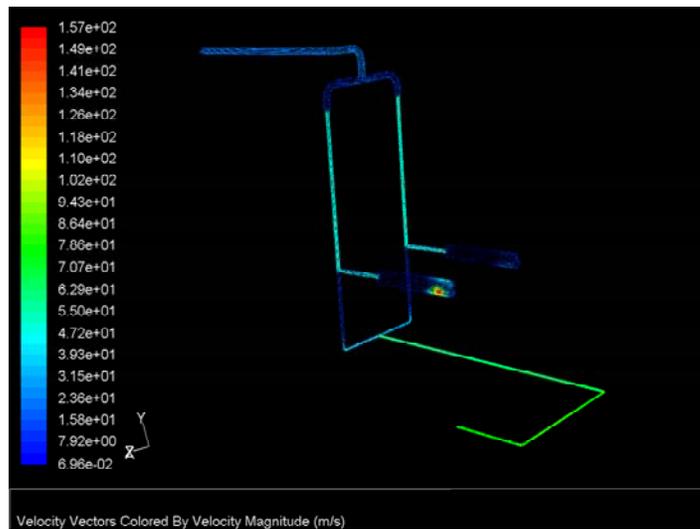
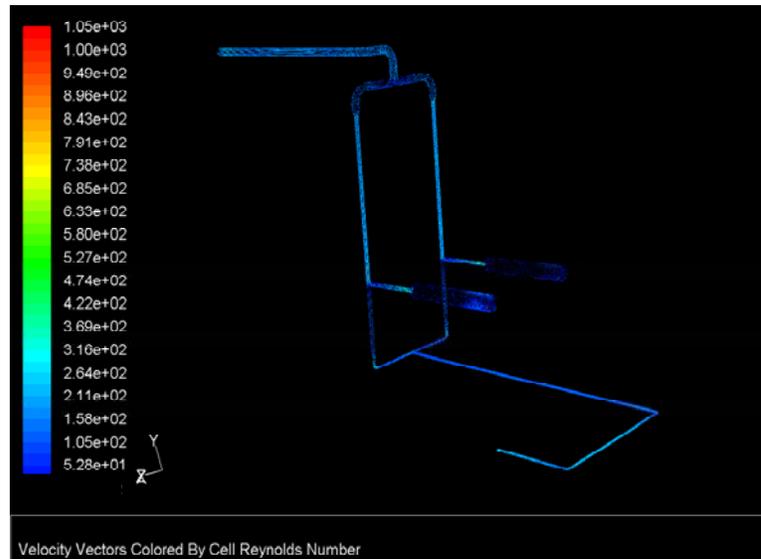


Figure 6: Baseline Velocity Plot

# Reynolds Number



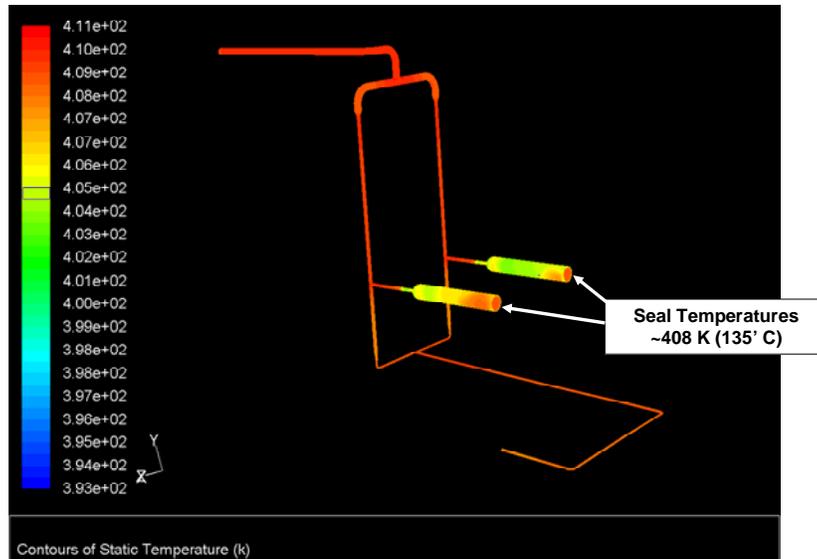
**Figure 7: Reynolds Number Plot**

## 3.2 VERIFICATION OF STERILIZATION

There were several issues that needed to be addressed in this design project. As discussed in previous sections, there was no way to know the state (temperature, pressure) inside the system during steam sterilization. The best way to attain this information was by creating a computational model of the system which would calculate the temperature of the inner pipe walls and the pressure. In doing so, the properties at any point within the system can be determined. This solved one of challenges of this project by verifying that the current steam sterilization process is in compliance with ASME BPE-a-2004 sterilization standards.

As you can see from the static temperature plot, all surfaces are sufficiently sterilized, and none

## Static Temperature (K)



**Figure 8: Baseline Static Temperature**

Using the information gained from this analysis it is also possible to address the problem of the failing seals within the system. This failure is being caused by thermal degradation occurring during sterilization. One obvious solution is to simply replace the seals within the system. A seal made of a newer more thermally resistant material would be ideal. In addition to this, the new material must be compatible for use within the machine, and with the materials that are processed by it. After extensive research, no superior seal material was identified. The design group believes that given what is available, the TIVAR H.O.T. seals currently used are the best option.

### 3.3 SEAL FAILURE

Once the model was complete, it became obvious that the temperature levels at the location of the seals exceeded the maximum operating temperature of 135°C for TIVAR H.O.T. [4] As you can see in Figure 8, temperatures around the location of the seals are approaching the maximum operating temperature.

The obvious solution to this problem is to somehow lower the temperature levels at the seals. A variety of options were brainstormed, each with its own advantages and disadvantages.

### 3.3.1 Thermostatically Controlled Bypass Valve

In this solution a valve controlled by a thermo stat would be installed at a strategic spot within the machine. The thermostat would take readings on the temperatures of the steam heading toward the intensifier pump chambers which contain the failing seals. Once the temperature became close to the maximum operating temperature the valve would be programmed to operate. The operation of the valve would redirect flow along a new bypass route, thus keeping it away from the seals. Once the temperature fell below the temperature, the valve would reverse its' position; allowing steam to reenter the intensifier pump chambers.

This solution has many downsides. Firstly, it would require a redesign of several parts of the system. New parts would have to be purchased, fabricated and then integrated into the machine. It would prove to be a time-consuming task to remodel every machine in service. Another major issue is that with the hot steam being diverted around the pump chambers, one can not be certain that the surfaces have been sufficiently heated in compliance with the ASME BPE-a-2004 code. It was decided that this solution was not a very easy or plausible solution to the problems faced by the design team.

### 3.3.2 Implementation of Additional Steam Outlets

By adding several new outlets to the system one could potentially run the steam sterilization cycle with superheated steam. Using these outlets, the steam could be released before it enters the pump chamber. By introducing super heated steam in small amounts you could control the temperature in the intensifier pump reservoir. A technician would then be able to raise the temperature level enough so that sterilization is completed in compliance with code.

A major set back of this solution is that it would require a significant modification of the system. Outlets and ways to control them would have to be implemented. An additional thermocouple would also be needed to be added to monitor temperature levels within the pump chamber. Controlling the temperatures in the chamber would also be difficult and would require a technician to monitor the system the entire course of the sterilization. By using the superheated gas, and by controlling the temperature inside the pump reservoirs sterilization would be ensured. This design requires modification of the system which makes it very difficult, but overall it is a better option then the previous solution.

### 3.3.3 Reduction of Steam Inlet temperature

Although simplistic, the solution is very logical. Since the inlet temperature (138°C) is already above the maximum operating temperature of the TIVAR H.O.T. seals (135°C), it only makes sense to lower it below this level. As long as the temperatures on the inside of the system remain above 121°C for the duration of the steam sterilization cycle, compliance with ASME BPE-a-2004 is achieved. The design group decided

this solution was the best, because it seemed to be the most sensible and would require the least amount of work. The following section contains an in-depth discussion of this solution and computational verification that it is effective.

# CHAPTER 4 RESULTS AND RECOMMENDATIONS

## 4.1. VERIFICATION OF SOLUTION

To verify that proper sterilization is achieved with the lower inlet temperature, the FLUENT analysis was re-run with that sole adjustment made. This analysis shows that the entire area of concern reaches at least 124°C, which is well above the required 121°C needed for sterilization. By ensuring that all inner points of the machine were reaching at least 124°C, the group felt confident in the validity of the adjusted temperature. This temperature distribution can be seen in Figure 19. . The new lower steam inlet temperature level is less than the maximum operating temperature of the seals that are currently used. At the same time, the new level is sufficient enough to ensure a compliant sterilization of the area analyzed.

In order to verify the heat loss of the system, we created a test problem and calculated the energy loss through a small section of pipe. This was directly applicable to our system analysis, as the boundary conditions and materials/fluids were the same.

## Thermal Verification

$$\text{mass flow rate} = m = \rho \cdot V \cdot A$$

$$m = (.546 \text{ kg/m}^3)(300 \text{ m/s})(.000792 \text{ m}^2)$$

$$m = .192 \text{ kg/s}$$



$$\text{Heat Loss} = q = m \cdot C_p \cdot [T_{\text{in}} - T_{\text{out}}]$$

$$= h \cdot A_s \cdot [T_{\text{ave}} - T_{\infty}]$$

$$q = (.129 \text{ kg/s})(2.0133 \text{ Ws/kgK})(408.1 - 407.9 \text{ K}) = .026 \text{ Watts}$$

$$q = (6 \text{ W/m}^2)(.00374 \text{ m}^2)(407.95 - 298.1 \text{ K}) = .024 \text{ Watts}$$

## 4.2 RECOMMENDATION

Preliminary results show identified a simple solution of inlet temperature adjustment. The recommended temperature change, is to 133°C, down from the current 138°C. This level will ensure a complete sterilization of the machine in accordance with ASME BPE-a-2004 code. In addition, preliminary analysis results show it will also cause no thermal degradation to the seals within the intensifier pumps. This will increase the lifespan of each seal used. Another benefit of this lower inlet temperature is that the machine will not require as much cool down time. This only increases the amount of time that the machine is available for use processing product. The decrease in temperature also means that the steam boiler will not require as much energy, thus lowering the user's overall cost of operation for the machine.

### Static Temperature (K)

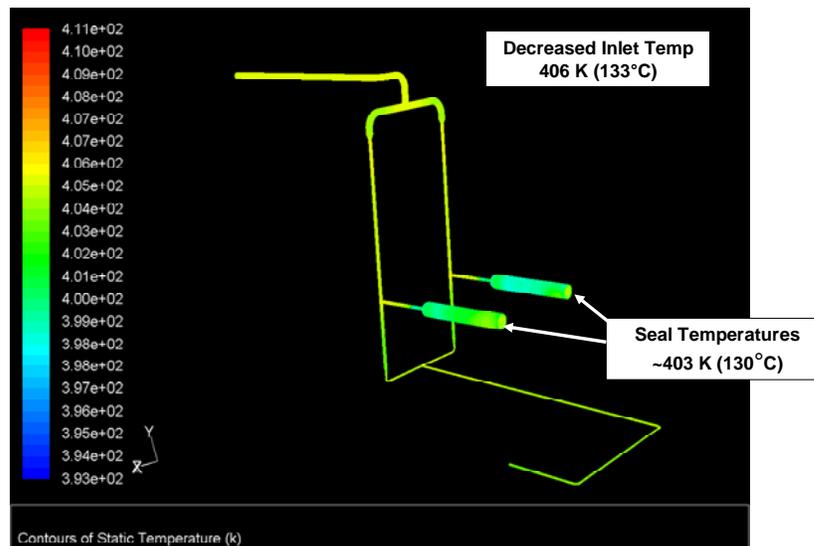


Figure 9: Static Temperature Plot with decreased inlet temperature

## 4.3 FUTURE WORK

Throughout the project there have been many complicated problems with the analysis software. While modeling in Gambit, repeated software crashes resulting in loss of data and time has slowed progress. The group's inexperience with the software made overcoming these problems much more difficult.

The model which was created does not give accurate results when operated at the actual boundary conditions. To make the current model match up with the actual operating conditions the heat transfer coefficient was lowered. Altering this has allowed us to produce relatively accurately results. The data

should be looked at as a baseline solution to be built upon with further modifications to the model. Ideally, the pump areas of the system would be remodeled with the actual piston motion incorporated. Finally, the remaining phases of steam sterilization would need to be modeled in order to ensure the 133°C inlet temperature will be sufficient throughout the entire process.

# Appendix A



## TECHNICAL INFORMATION

### TIVAR® H.O.T.

(Higher Operating Temperature)

Meets requirements of FDA regulation 21CFR 177.1520, item 2.1 and 2.2, for articles intended for direct and indirect food contact usage and regulation 21CFR 178.2010 governing additives and food contact usage.

#### Physical Properties

Property	Method	SI Unit	SI Value	English Unit	English Value
Density	ASTM D-792	kg/m <sup>3</sup>	941	lbs/ft <sup>3</sup>	58.8
Yield Point	ASTM D-638	MPa	24.7	psi	3584
Elongation at Yield	ASTM D-638	%	13.7	%	13.7
Tensile Break	ASTM D-638	MPa	52.5	psi	7618
Elongation at Break	ASTM D-638	%	242	%	242
Tensile Modulus	ASTM D-638	MPa	820	psi	120000
Flexural Modulus	ASTM D-790	MPa	760	psi	110000
Izod Impact	ASTM D-4020	kJ/m <sup>2</sup>	60	ft-lbs/in <sup>2</sup>	29
Tensile Impact	DIN 53448	kJ/m <sup>2</sup>	2200	ft-lbs/in <sup>2</sup>	1050
Sand Wheel Wear	ASTM G-65,	AR-01 Steel=100	90	AR-01 Steel=100	90
Hardness	ASTM D-2240	Type D	68	Type D	68
Static Friction	ASTM D-1894	Unitless	0.15	Unitless	0.15
Dynamic Friction	ASTM D-1894	Unitless	0.12	Unitless	0.12
Coefficient of Thermal Exp.	ASTM D-898	<sup>0</sup> C <sup>-1</sup>	0.0002	<sup>0</sup> F <sup>-1</sup>	0.00011
Maximum Operating Temp.		<sup>0</sup> C	135	<sup>0</sup> F	275
Compressive Modulus	ASTM D-895	MPa	536	Psi	77750
Compressive Deformation	ASTM D-821	% at 454.5 kg	'6-8	% at 1000 psi	6-8
Volume Resistivity	ASTM D-257	Ohm-cm	>10 <sup>13</sup>	Ohm-cm	>10 <sup>13</sup>
Surface Resistivity	ASTM D-257	Ohm	>10 <sup>13</sup>	Ohm	>10 <sup>13</sup>
Water Absorption	ASTM D-570	%	nil	%	nil

\* Values are averages and are not specifications.

\*\* ASTM test methods are under current procedures.

**IMPORTANT:** Most plastics will ignite and sustain flame under certain conditions. Caution is urged where any material may be exposed to open flame or heat-generating equipment. Use [Material Safety Data Sheets](#) to determine auto-ignition and flashpoint temperatures of materials, or consult Poly Hi Solidur, Fort Wayne, Indiana if additional information is needed. The information contained herein is believed to be reliable, but no representations, guarantees or warranties of any kind are made as to its accuracy, suitability for particular applications or the results to be obtained therefrom. This information is based on laboratory work with small-scale equipment and does not necessarily indicate end product performance. Because of the variations in methods, conditions and equipment used commercially in processing these materials, no warranties or guarantees are made as to the suitability of the products for the applications discussed. Full-scale testing and end product performance are the responsibility of the user. Poly Hi Solidur, Inc. shall not be liable and the customer assumes all risk and liability of any use or handling of any material beyond Poly Hi Solidur's direct control. THE SELLER MAKES NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. Nothing contained herein is to be considered as permission, recommendation, nor as an inducement to practice any patented invention without permission of the patent owner. TIVAR® is a registered trademark of Poly Hi Solidur, Inc.

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Table 1: TIVAR H.O.T. seal spec. sheet

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