Modelling Of Pressure Profiles In A High Pressure Chamber Using COMSOL Multiphysics

P. Srinivasa Rao, Chamanooru Kartik Chandra
Agricultural and Food Engineering Department
Indian Institute of Technology, Kharagpur –721302

ABSTRACT:

High Pressure Processing (HPP) is a leading non-thermal food processing technology that is often cited as a major technological innovation in food preservation. Although it is very early to place this emerging technology among the list of breakthroughs in food processing, HPP has started to become a viable commercial alternative for pasteurisation of value added fruits, vegetables, meat, and seafood products to be safely enjoyed by the consumer.

In a High Pressure process, the food product to be treated is placed in a pressure vessel capable of sustaining the required pressure; the product is submerged in a liquid which acts as the pressure-transmitting medium. The working pressure for any HP process is a very important parameter, not only because the capital investment of such an equipment increases steeply with increases in working pressures, but also because a decrease in working pressure can reduce significantly the number of failures, increasing the work life of the equipment (Otero et al., 2000).

The objectives of this study were to model the stress profiles in a High Pressure chamber, modelling of Temperature – time plots in a High Pressure chamber using COMSOL 4.2a and understand the yield criteria for the vessel and the temperature gradient in the vessel with time in the presence of a constant heat source.

Firstly, a pressure of 200 MPa was applied internally to an empty pressure vessel. Subsequent to that, a polyethylene core was introduced into the vessel's core and the same pressure of 200 MPa was applied internally. The Von Mises stress produced in both the cases was different owing to the introduction of the polyethylene core. A plot showcasing the change in the Von Mises stress with changes in operating pressure was plotted later on. Studies of the changes in the temperature of the vessel with changes in operating pressure were also made and have been depicted pictorially. The changes in the temperature of the vessel were of the order of 10K at an operating pressure of 300 MPa in a time span of about 120s.

The results obtained as part of this study were primarily profiles that are time independent as well as dependent as the case maybe. The stress profiles were obtained with increase in working pressure in the vessel. The Temperature – Time plots were for a fixed working pressure applied for a time duration of 120s.

The increase in the Von Mises stress in the case of an empty pressure vessel and upon the introduction of a polyethylene core was in accordance with the theoretical background of HP processing. Depending on the material used in the manufacture of the vessel, the yield point of the vessel varies. The Von Mises stress is an important parameter that is used to find the operating pressure that a certain vessel can undertake without fatigue or failure. This study emphasises the importance of such an analysis and the use of COMSOL Multiphysics for the same.

Key Words: Modelling, Pressure Profiles, High Pressure Chamber, COMSOL Multiphysics

INTRODUCTION:

Studies on the effects of high pressures on foods date back over a century. In 1899, Bert Hite of the Agricultural Research Station in Morganstown, West Virginia, designed and constructed a high-pressure unit to pasteurize milk and other food products (Hite, 1899). He constructed a machine that could reach pressures in excess of 6800 atmospheres (700MPa) and along with his co-workers, examined the potential use of HPP for a wide range of foods and beverages, including the pressure inactivation of viruses. The level of sophistication that was accomplished is remarkable, given the technological disadvantages of that time period regarding processing systems and packaging materials (Hoover, 1993). In 1889, Hite reported that treatment at pressures of 450 MPa or greater could improve the keeping quality of milk (Hite, 1899). In 1914 he showed that yeasts and lactic acid bacteria associated with sweet, ripe fruit were more susceptible to pressure than other organisms, especially spore-forming bacteria associated with vegetables (Patterson et al., 1995). Compared to today's HP processing equipment, the prototype system utilized in the 1890s by Hite is very primitive. Today, with advances in computational stress analysis and new materials, high capacity pressure systems can be manufactured to allow reliable HP treatment of food products at even higher pressures (Hoover, 1993). Although the potential for HP processing of foods has thus been known since the late nineteenth century, its application and potential have only recently been widely recognized. While this potential was largely ignored through most of the last century, basic work on the effects of hydrostatic pressures on biological systems steadily developed. In recent years, the use of HP as a food preservation technique has gained momentum throughout the world as an alternative to traditional heat-based methods, for the reasons cited earlier. Much of the research regarding the use of HP for food preservation has concerned inactivation of microorganisms; the pressure stability of food enzymes is now also beginning to attract increasing attention (Ashie and Simpson, 1996; Krebbers et al., 2003).

REVIEW OF LIETERATURE:

The effects that high pressure exerts on the structure of food have been studied for more than a century (Hite, 1899). However, their potential for commercial utilization has not been discussed at large, mainly due to the limitations on the capacity of the large pressure vessels, making the process impractical (Defaye, Ledward, MacDougall, & Tester, 1995; Farr, 1990). With sufficient advances in technology in recent times, the process has become feasible for a number of high value-added products and a much greater variety of products around the world (Sizer, Balasubramaniam, & Ting, 2002). High Pressure Processing can be used at low temperatures (considered a heatless process) where the product can be packed in a flexible material and exposed to hydrostatic pressures up to 1035 MPa (Calik, Morrissey, Reno, & An, 2002). Its application results in an instantaneous and uniform transmission of the pressure throughout the product and is independent of the product size and geometry (Knorr, 1993). HPP utilization provides a number of benefits for the treated product. It has the capacity to inactivate product-spoiling microorganisms and enzymes at low temperatures without changing most of the organoleptic and nutrient characteristics of the product (Ting, Balasubramaniam, & Raghubeer, 2002). High Pressure High Temperature (HPHT) processing, or Pressure-assisted Thermal Processing (PATP) involves the use of moderate initial chamber temperatures between 60^0C and 90^0C in which, through internal compression heating at pressures of 600 MPa or greater, in-process temperatures can reach 90^0C and 130^0C. The process has been proposed as a high-temperature short-time process, where both pressure and compression heat contribute to the process's lethality (Leadley, 2005). In this case, compression heat developed through pasteurization allows instantaneous and volumetric temperature increase, which, in combination with high pressure, accelerates spore inactivation in low-acid media. Some of these microbial spore inactivation approaches proposed combining (de Heij et al., 2003; Leadley, 2005): a) two low pressure pulses at 200-400 MPa (the first one for spore germination and the second for germinated cell inactivation); b) a low pressure pulse at 200 to 400 MPa for spore germination followed by a thermal treatment at 70^0C for 30 minutes for vegetative cell inactivation; c) package preheating above 75^0C and pressurization at 620 to 900 MPa for 1 to 20 minutes; d) package preheating above 70^0C and applying two or more pulses at 400 to 900 MPa for 1-20 minutes. Three of the above-mentioned principles [cases a, b and d] have proven inconvenient from either a microbiological or an economic perspective.

Apart from choosing the right process times for a particular food material, it is of prime importance to choose the right vessel for the HP process. Because the materials contained in the vessels are subject to very high pressures, the strength of the container is of great importance. Stress analysis of thick walled cylinders subject to various types of axi-symmetric loading has been carried out by many investigators for constant and varying material properties. A thorough stress and fatigue analysis is to be conducted prior to the operation of the vessel. More than 100000 work cycles are to be carried out for the successful operation of a pressure vessel at 500 MPa and to make the operation a cost effective process (Alegro, 2009). To improve the fatigue characteristics of the vessel, a technique known as autofrettage is done. It involves loading the vessel to an over-pressure which locks plastic strain in an internal core. When the vessel is unloaded, some residual compression stresses are generated in the internal core, decreasing the mean tangential stresses on the inside. Thus, the fatigue characteristics of the vessel are significantly improved.

METHODOLOGY:

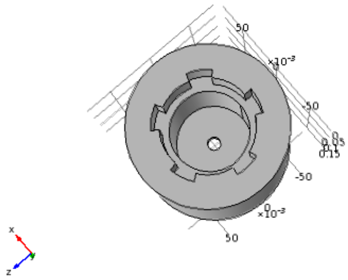
An FEM analysis of a pressure vessel used for HPP was performed. Surface von Mises stresses were first modelled, after which thermal stresses arising from the cylinder not being free to expand and contract to changes in temperature were modelled together with the von Mises stress. Considering the compressive medium to be a fluid at 70^{0}C, the changes in the temperature of the vessel with time was modelled. All the pre-processing, processing and post processing work has been done using COMSOL 4.2a. The effects of axial loading were neglected in the case of the pressure vessel as the effects of the boundary and the thermal stresses far outweigh the axial component of stress.

The dimensions of the pressure vessel have been assumed to be the following:

Inner radius = r_i = 40 mm
Outer radius = r_o = 80 mm
Vessel height = h = 100 mm
Volume of vessel = V = 500 mL

A representative figure of a pressure vessel generally used in a HPP chamber was designed using SolidWorks and has been used in COMSOL 4.2a for further pressure and stress analysis. A general pressure vessel has an inlet at its bottom surface for the working fluid to enter the chamber. The top of the vessel has constrictions for the yolk to enter and lock into the constrictions. 5 constrictions have been placed on the vessel designed in this case. Fixed constraints have been placed on the outer surface of the vessel so as to induce thermal stresses into the system accordingly.

The geometry and the loading surfaces of the pressure vessel are shown below:



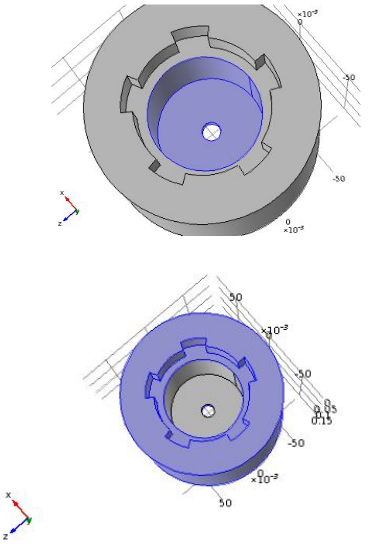


Figure 1: Pressure Vessel (empty) – Geometry, Loading profile and Fixed Constraints

Fixed constraints have been used on all the outer surfaces of the pressure vessel because the vessel is held inside the High Pressure Processing equipment. A representative figure of the surfaces with fixed constraints has been indicated above. An initial internal pressure of 300 MPa is applied on the loading surface shown above. A suitable mesh is then generated and the stresses induced due to the pressure and the fixed constraints are then modelled.

The mesh generated was a physics controlled mesh having the following properties:

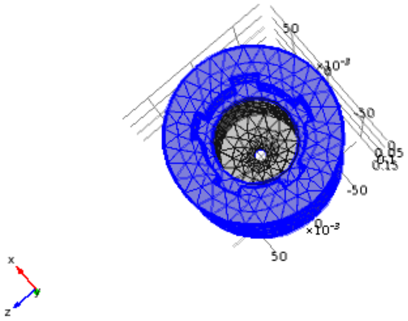
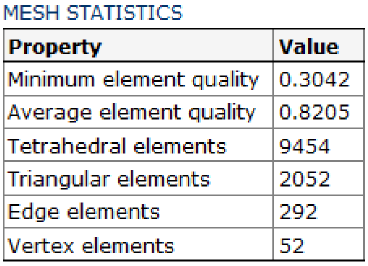


Figure 2: Pressure Vessel (empty) – Mesh and Mesh Statistics



MESH STATISTICS

Property	**Value**
Minimum element quality	0.3042
Average element quality	0.8205
Tetrahedral elements	9454
Triangular elements	2052
Edge elements	292
Vertex elements	52

The stress profile obtained in the case of the pressure vessel shown above is:

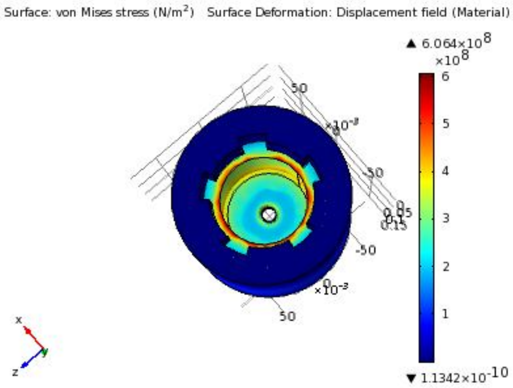


Figure 3: Pressure Vessel (empty) – Stress profile

The variation of the maximum von Mises stress with variation in Internal Pressure was then computed and tabulated. Change in the von Mises stress with changes in the structure of the vessel is not feasible, and hence has not been depicted. For the 300 MPa pressure shown in this case, the maximum von Mises stress is found to be 606.4 MPa. For a hollow cylinder of the same internal pressure and without any fixed constraints, the von Mises stress was found to be 735.18 MPa.

Table 1: Pressure vs. von Mises Stress in an empty pressure vessel

Internal Pressure (MPa)	Maximum von Mises Stress (MPa)
200	358.21
250	447.77
300	606.4
350	626.9
400	716.47
450	806.03
500	895.61

From the table above, we can see that the von Mises stress increases with an increasing rate as the pressure applied internally increases at a constant rate. A cylindrical element made of polyethylene was then introduced into the central chamber and the stress profiles were generated as shown above. The cylindrical element was suspended in the chamber and was not placed in contact with any of the vessel walls.

The geometry of the steel pressure vessel and the cylindrical polyethylene element are as shown:

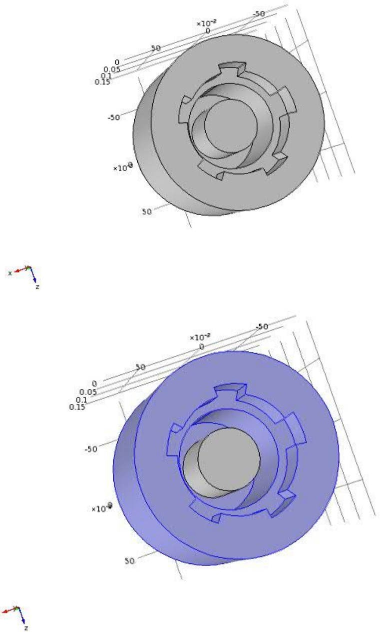


Figure 4: Pressure Vessel (with core) – Geometry

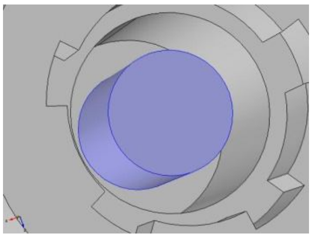


Figure 5: Pressure Vessel (with core) – Polyethylene Core

The loading surfaces in the pressure vessel are the interior surfaces of the vessel and the outer surfaces of the polyethylene element. This is because according to Pascal's Law, pressure is transmitted uniformly throughout the element when placed in a fluid medium. Hence, the 300 MPa pressure acts uniformly on the surface of the cylindrical element.

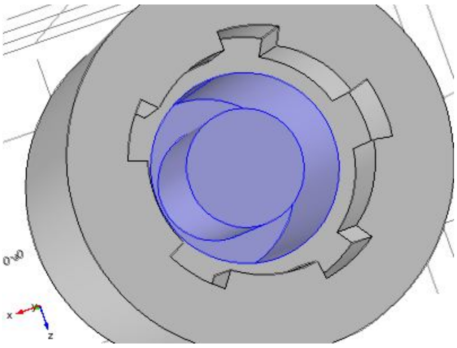
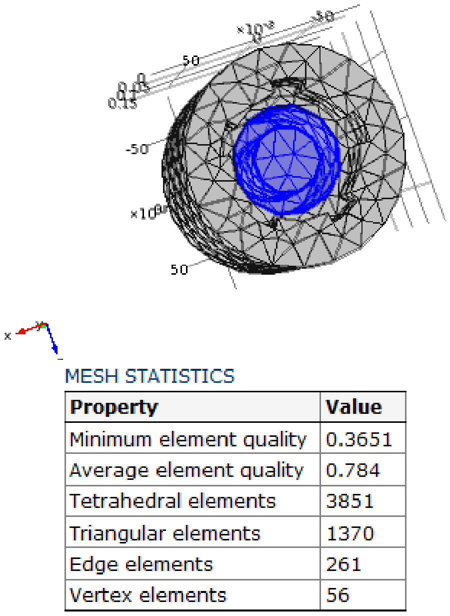


Figure 6: Pressure Vessel (with core) – Loading profile

A suitable mesh was generated, and the stress in the pressure vessel was modelled.



MESH STATISTICS

Property	Value
Minimum element quality	0.3651
Average element quality	0.784
Tetrahedral elements	3851
Triangular elements	1370
Edge elements	261
Vertex elements	56

Figure 7: Pressure Vessel (with core) – Mesh and Mesh Statistics

The surface von Mises stress and the thermal stress in the cylindrical element for the pressure vessel shown above were found to be:

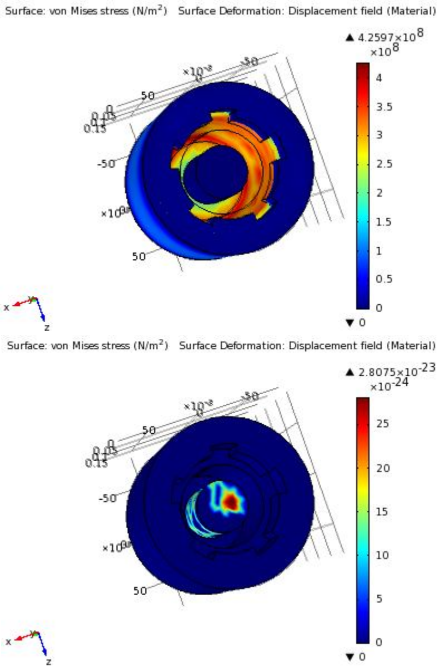


Figure 8: Pressure Vessel (with core) – Surface Stress and Thermal Stress profiles

The variation of the maximum surface von Mises stress with changes in the internal pressure of the vessel have been computed and tabulated below.

Table 2: Pressure Applied vs. von Mises and Thermal von Mises Stresses in a vessel with a core

Internal Pressure (MPa)	Maximum von Mises Stress (MPa)	Maximum von Mises Stress - Thermal (Pa)
200	283.98	2.8075x10^{-23}
250	354.97	2.8075x10^{-23}
300	425.97	2.8075x10^{-23}
350	496.96	2.8075x10^{-23}
400	567.96	2.8075x10^{-23}
450	638.95	2.8075x10^{-23}
500	709.95	2.8075x10^{-23}

The thermal stresses are constant and do not change with temperature because the temperature difference between the working fluid and the ambient temperature is the same under all the pressures taken in the above scenario.

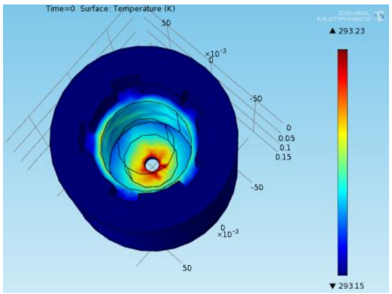
The variation of temperature in the wall of the vessel with time has been depicted in the figures below. The working fluid temperature has been taken to be 343.15 K (70^{0}C) and an inward heat flux of 6963 W/m^2 has been applied to the cylindrical polyethylene element. The inward heat flux has been computed by assuming the cylindrical element to be of 40 mm diameter and 80 mm height. So, the net volume of the working fluid drops to 400 mL after inserting the polyethylene element. Now, the heat flux in W/m^2 can be calculated by assuming that the change in temperature of the fluid over the process changes by 9^{0}C for a pressure of 300 MPa. The increase in temperature causes an inflow heat flux into the cylindrical element as well as an outflow heat flux through the walls of the vessel. If properly insulated, the increase in temperature of the fluid can be restricted to about 5^{0}C because the temperature of the fluid decreases upon decompression of the system if no heat is lost or gained through the system. Thus,

Mass of water in the vessel = 400 g
Specific Heat Capacity of water = 4200 J/KgK
Holding Time = 120 s
Surface Area of Polyethylene Core = $2\pi rL$ = $2*\pi*0.02*0.085 = 0.01005$ m^2

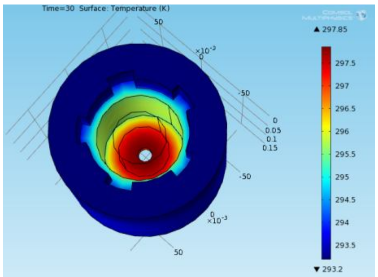
Flux = (0.4L) x (1 Kg/L) x (4200J/KgK) x (5K)/[(120s)x0.01005 m^2] = 6963.029 W/m^2

The above calculated value of flux is an estimate of the heat transmitted by the fluid to the cylindrical element and not the actual experimental value.

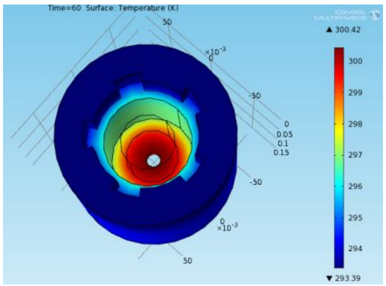
The temperature vs. time plots at t = 0, 30, 60, 90 and 120s have been shown below:



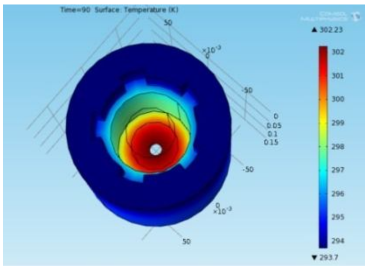
t = 0



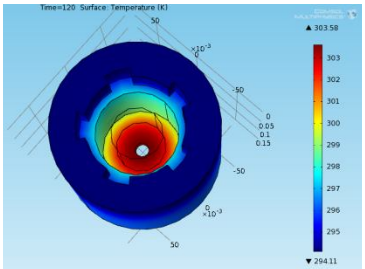
t = 30s



t = 60s



t = 90s



t = 120s

Figure 9: Pressure Vessel (with core) – Temperature variation (top view)

From the temperature – time plots, it is clear that the temperature of the vessel increases with time in the radial sense indicating the movement of a flux front with time, and also from bottom up because the fluid entering is hotter than the surroundings and the inlet is closer to the bottom. Also, the maximum temperature of the vessel at the inlet of the fluid increases with a falling rate as time passes by because the amount of heat absorbed by a hotter body is lesser than when the same body were cooler.

A summary of all the results found in this work and a discussion on them have been made in the next section.

RESULTS AND DISCUSSION:

From the above observed readings, it can be concluded that the effect of changing the pressure on the von Mises stress far outweighs the effects of changing the thickness of the vessel. This is because the magnitude of the pressure applied on the wall is very high.

In a three dimensional body that is subjected to a system of loads, a complex three dimensional system of stresses is developed. That is, at any point within the body there are stresses acting in different directions, and the direction and the magnitude of stresses changes from point to point. The von Mises criterion is a formula for calculating whether the stress combination at a given point will cause failure. There are three Principal Stresses that can be calculated at a point, acting in the directions X, Y, Z. Even though none of the principal stresses exceeds the yield stress of the material, it is possible for yielding to result from the combination of stresses. The Von Mises criterion is a formula for combining these 3 stresses into an equivalent stress, which is then compared to the yield stress of the material and hence is considered in the static load design and fatigue design of pressure vessels. The results obtained would have had a greater amount of accuracy if the mesh was finer. However, this would require larger processing speeds and such systems weren't available for use.

In the case of the empty pressure vessel, the plot between the internally applied pressure and the maximum von Mises stress has been found to be essentially a linear plot. This is in accordance with the theoretical findings of the plot in case of a TWC under loading. The plot has been shown below:

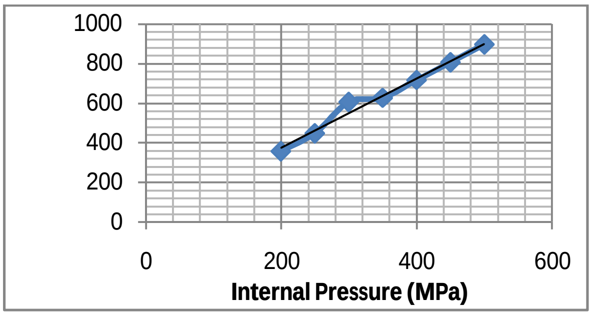


Figure 10: Pressure Vessel (empty) – Pressure vs. Stress plot

As the pressure applied in the high pressure chamber increases, the maximum von Mises stress produced in the vessel walls increases. This increase is linear and is attributed to the fact that the amount of expansive force on the surface has been increased leading to an increase in the principal stresses in the walls and consequently, in the magnitude of the von Mises stress. The linear increase results from the fact that with an elastic range, the relation between pressure applied or stress applied results in a linear variation of the strain produced in the vessel, in accordance to the Young's relationship between stress and strain.

When a cylindrical polyethylene core has been introduced into the pressure vessel, there has been a fall in the maximum von Mises stress of the surface of the vessel. Plotted against the pressure applied internally, the relation between the surface von Mises Stress and the pressure applied has been found to be in perfect correlation with the theoretical findings, the plot of which is shown below:

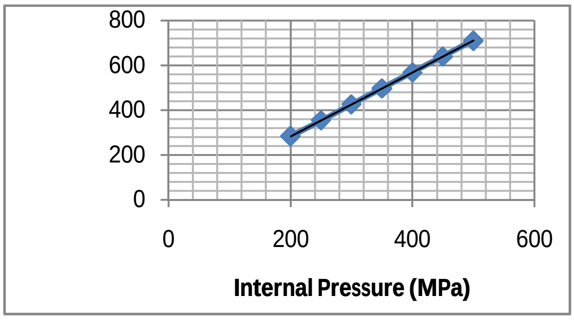


Figure 11: Pressure Vessel (with core) – Pressure vs. Stress plot

Thermal Stresses are stresses arising due to a temperature difference between two surfaces of different temperatures. In the case of the pressure vessel with a polyethylene core representing a packaged food product, there has been no effect of pressure alone on the magnitude of the thermal stresses induced in the core. This is because the factor for generation and induction of a thermal stress is a certain temperature difference between the working fluid and the polyethylene core. Since this temperature difference has been assumed to be constant at all the considered pressures, the amount of thermal von Mises stress developed has been reported to be the same.

In any material, energy is transferred fastest by the process of conduction. In the pressure vessel considered above, the system is assumed to be insulated from the outside sufficiently to reduce the amount of heat dissipated. This helps in the temperature of the fluid falling back to its original inlet temperature after the processing of the material and the decompression of the system. If the system was perfectly insulated, the outlet and inlet temperatures of the working fluid would be similar. However, such a system is purely theoretical, and insulation of such high standards is not practically possible. Due to the change in temperature of the fluid with time, the temperature of the vessel also changes accordingly. At pressure as high as 300 MPa, sudden changes in the temperature of the vessel could give rise to fractures. Hence, the modelling of the vessel's temperature is important to prevent fractures in the vessel's surface or any other damages in the equipment.

Theoretically, the temperature of the vessel should increase with a hot fluid entering the system, from the inlet upwards towards the neck of the vessel. In general, the temperature rise in a cooler object would be higher than in a hotter body within the same time frame. Having these theoretical considerations in mind, the model was generated.

The variation of the temperature of the vessel with time has been in accordance with its theoretical findings. Temperature of the vessel rose quickly at lower temperatures and the rate of increase started to fall with time. Also, temperature of the vessel increased radially outward with a falling rate against time.

Acknowledgements

The authors acknowledge the National Agricultural Innovation Project, ICAR New Delhi for providing financial assistance and IIT Kharagpur for necessary facilities to carry out this work.

REFERENCES:

Alegro JM, Bravo P, Preciado M (2009) Fatigue behaviour of an autofrettage high-pressure vessel for the food industry. *Engineering Fatigue Analysis*, **14**, 396-407.

Ashie INA, Simpson B (1996) Application of high hydrostatic pressure to control enzyme related fresh seafood texture deterioration. *Food Research International,* **29** (5-6), 569-575.

Balasubramaniam S, Balasubramaniam VM (2003) Compressive heating influence of pressure transmitting fluids on bacteria inactivation during high pressure processing. *Food Research International,* **36** (7), 661-668.

Cheftel JC, Culioli J (1997) Effects of high pressure on meat: A review. *Meat Science,* **46** (3), 211-236.

Da Poian AT, Johnston JE, Silva JL (1994) Differences in stability of the three components of cowpea mosaic virus: implications for virus assembly and disassembly, *Biochemistry,* **33**, 8339-8346.

Defaye AB, Ledward DA, MacDougall DB, Tester RF (1995) Renaturation of metmyoglobin subjected to high isostatic pressure, *Food Chemistry,* **52**, 19-22.

de Heij WBC, van Schepdael LJMM, Moezelaar R, Hoogland H, Matser AM, van der Berg RW (2003) High-pressure sterilization: Maximizing the benefits of adiabatic heating. *Food Technology,* **57** (3), 37-41.

Erkmen O, Karatas S (1997) Effect of high hydrostatic pressure on *Staphylococcus aureus* in milk. *Journal of Food Engineering,* **33**, 257-262.

Farr D (1990) High pressure technology in the food industry. *Trends in Food Science & Technology,* **1**, 14-16.

Hite B (1899) The effect of pressure in the preservation of milk. *West Virginia Agricultural Experimental Station Bulletin,* **58,** 15-35.

Hoover DG (1993) Pressure effects of biological systems. *Food Technology,* **47** (6), 150-155.

Kalchayanand N, Sikes A, Dunne CP, Ray B (1998) Interaction of hydrostatic pressure, time and temperature of pressurization and Pediocin AcH on inactivation of food-borne bacteria. *Journal of Food Protection,* **61** (4), 425-431.

Kihiu JM, Mutuli SM, Rading GO (2003) Stress characterization of autofrettage thick-walled cylinders. *International Journal of Mechanical Engineering Education,* **3**, 370-389.

Kingsley DH, Hoover DG, Papfragkou E, Richards GP (2002) Inactivation of hepatitis A virus and a calicivirus by high hydrostatic pressure. *Journal of Food Protection,* **65**, 1605-1609.

Krebbers B, Matser AM, Hoogerwerf SW, Moezelaar R, Tomassen MMM, Van der Berg RW (2003) Combined high-pressure and thermal treatments of tomato puree: evaluation of microbial inactivation and quality parameters. *Innovative Food Science & Emerging Technologies,* **4** (4), 377-385.

Linton M, McClements JMJ, Patterson MF (2001) Inactivation of pathogenic *Escherichia coli* in skimmed milk using high hydrostatic pressure. *Innovative Food Science & Emerging Technologies,* **2**, 99-104.

Linton M, Patterson MF (2000) High pressure processing of foods for microbiological safety and quality. *Acta Microbiologica et Immunologica Hungarica,* **47** (2-3), 175-182.

McClements JMJ, Patterson MF, Linton M (2001) The effect of growth stage and growth temperature on high hydrostatic pressure inactivation of some pyschrotrophic bacteria in milk. *Journal of Food Protection,* **64** (4), 514-522.

Olsson S (1995) Production equipment for commercial use. In *High Pressure Processing of Foods,* (Ledward DA, Johnston DE, Earnshaw RG, Hastings APM, eds). Nottingham: Nottingham University Press, Ch 12, pp. 167-180.

Otero L, Molina-Garcia AD, Sanz PD (2000) Thermal effects in foods during quasi-adiabatic pressure treatments. *Innovative Food Science & Emerging Technologies,* **1**, 119-126.

Palou E, Lopez-Malo A, Welti-Chanes J (2002) Innovative fruit preservation using high pressure. In *Engineering and Food for the 21st Century* (Welti-Chanes J, Barbosa-Canovas GV, Aguilera JM, eds). Food Preservation Technology Series, Boca Raton: CRC Press, Ch 43, pp. 715-726.

Patterson MF, Quinn M, Simpson R, Gilmour A (1995) Sensitivity of vegetative pathogens to high hydrostatic pressure treatment in phosphate-buffered saline and foods. *Journal of Food Protection,* **58** (5), 524-529.

Smelt JPPM (1998) Recent advances in the microbiology of high pressure processing. *Trends in Food Science & Technology,* **9**, 152-158.

Ting EY, Marshall RG (2002) Production issues related to UHP food. In *Engineering and Food for the 21st Century* (Welti-Chanes J, Barbosa-Canovas GV, Aguilera JD, eds). Food Preservation Technology Series< Boca Raton: CRC Press, Ch 44, pp. 727-738.