Indian J Dairy Sci 76(4): 334-342
https://doi.org/10.33785/IJDS.2023.v76i04.004

RESEARCH ARTICLE

Design of micro-perforated PTFE mould for manufacture of *Paneer*, *Cheese* and *Tofu* using finite element analysis

Jayanth KJ*[1], Mahesh Kumar G[2], Rajunaik B[3], CT Ramachandra[4], M Manjunatha[5] and Arun Kumar H[6]

Received: 17 March 2023 / Accepted: 29 March 2023 / Published online: 18 August 2023

Abstract: The idea of utilizing a micro-perforated PTFE (polytetrafluoroethylene) mould to manufacture paneer, cheese, and tofu was conceived and mould was designed, developed and tested. The micro-perforated PTFE mould is intended to work at temperature 65 to 110ºC, 200 kPa inside pressure. This new generation pressing mould contains micro perforations of 300μm diameter which are drilled using advanced high precision 4 and 3 axis CNC machines. There will be failure (due to induced hoop stress) in the mould when Von Mises(equivalent) stress generated is more than yield stress of virgin PTFE (30 MPa). Wall thickness of mould was optimized by Finite Element Analysis (FEA) by hyper tetrahedron meshing using ANSYS- 22. The results obtained from stress analysis were expressed as Von Mises stress, deformation and factor of safety. A design software developed by ASME was employed to validate shell thickness. The model prediction was shown to be in good agreement with the analytical calculation. Micro-perforated PTFE mould was fabricated as per FDA, c-GMP standards from 6.00 mm thick virgin PTFE material. The FEA resulted in Von Mises Stress of 14.7 MPa, deformation of 2.1535×10^{-10} m and factor of safety of 2.04. The working drawings were developed and actual fabrication was carried out adopting the prescribed sanitary standards. Satisfactory production of paneer was carried out in the newly designed and developed PTFE paneer mould resulted in excellent quality product.

Keywords: Cheese hoop, FEA Micro-perforated PTFE mould, Paneer mould

[2] Department of Dairy Engineering, Dairy Science College, Hebbal, Bengaluru-560 024
[3]Department of Dairy Engineering, Dairy Science College, Hebbal, Bengaluru-560 024
[4]Department of Processing and Food Engineering, College of Agricultural Engineering, UAS, GKVK, Bengaluru – 560 065
[5]AICRP on PHET, UAS, GKVK, Bengaluru– 560 065
[6]Department of Dairy Technology, Dairy Science College, Hebbal, Bengaluru-560 024

[1] Jayanth K J (✉)
Department of Dairy Engineering
Dairy science College, KVAFSU
Hebbal, Bengaluru-560 024
Email: jayanthkj18@gmail.com

Introduction

A notable technological improvement in Dairy and Food Industry have taken place by the utilization of food-grade plastic, such as virgin polytetrafluoroethylene (PTFE) which is

FDA-approved and adheres to FDA (CFR 21-177.2600). PTFE is a fluoropolymer, classified among thermoplastics. It was invented by Roy J. Plunkett in 1938 at the DuPont company and it goes by the brand name Teflon in the commerce. Tetrafluoroethylene, the monomer, is used to polymerize PTFE (TFE). It has the C-F bond and the chemical formula $[(CF_2\text{-}CF_2)_n]$ in the PTFE formulation (Dhanumalayan and Joshi, 2018).

PTFE is chemically inert & non-reactive to almost all known chemicals, excellent thermal resistance up to 260°C, compatible with all manufacturing practices without leaching its contents during operation in the wide range of pH 0 to 14, anti-stick properties, exceptionally low coefficient of friction, outstanding electrical insulation properties, excellent weathering resistance, high resistance to radiation, non-absorbent of water, self-lubricant, non-toxic material, anti-microbial, FDA approved and resistant to magnetic field (Puts et al. 2019).

The application of virgin PTFE in dairy and food industries includes PTFE gasketing material: Gaskets, O/D/V/U rings, Universal rope, Expansion joints, Ball valves seats and Seals, Diaphragms of diaphragm valves and pumps, Sleeves of plug valves, Mechanical seals of pumps, Impellers / body of pumps, Tubing and hoses, Liners of reactors, Storage vessels, pipes and flanges, Thread seal tapes, Liners of butterfly valves. The use of PTFE in the food processing industry helps to prevent biofilm formation, food contamination, and fouling (Puts et al. 2019)

Legg et al. (2017) reported that pressing and moulding are crucial process in the production of paneer, cheese and tofu which involves using a hoop or mould, a special container which are basically cylindrical or rectangular in shape which is fabricated to hold and shape the curd into the desired shape while allowing for the application of pressure at the desired level which helps in removal of whey and further gives the curd into the desired mould shape. For whey drainage, holes were precisely drilled through the sides, base, and lid or pressure plate of these moulds. In conventional method which uses muslin cloth and stainless steel mould for production of paneer, cheese and tofu. The usage of muslin cloth is unhygienic and prone to microbial contamination which leads to deterioration, reduced yield and loss of pleasing appearance.

An innovative research was taken up to address the aforementioned drawbacks in traditional paneer production. In this research FDA-approved virgin PTFE has been successfully utilized to develop innovative new generation paneer, cheese and tofu press hoop or mould. In this new technology by the adoption of microholes, with a diameter of 300 µm, for the efficient drainage of whey without any loss of curd mass during pressing, thereby eliminating the need for cheese or muslin cloth.

In recent numerical methods such as Finite element analysis (FEA) are popularly employed in design and evaluation of processing equipment's including pressure vessel. The mould will be exposed to atmospheric pressure on the outside surface during working while inside applied pressure was on curd mass for moulding and dewheying.

Von-Mises stress (Von Mises, 1913; Mahesh and Ravindra, 2017) have used FEA concept to ascertain their design to verify the stability at given load conditions. By knowing Von Mises stress induced in material designer can make changes in materials of construction, wall thickness, stiffeners etc. so that Von - Mises stress (also known as equivalent stress) induced shall be less than yield stress of the material selection (for virgin PTFE material the induced stress should less than yield stress i.e., 30 MPa). FEA is a computational technique used to obtain Von Mises stress, deformation and factor of safety by providing loads or pressure, boundary conditions, material properties and meshing to ANSYS computational software (Ramachandra et al. 2021).

Material and Methods

The micro-perforated PTFE mould was fabricated from virgin PTFE material. The mould comprises of 3 components flanged micro-perforated cylindrical body, flat top micro-perforated circular disc which acts as pressure plate and flat bottom micro-perforated circular disc. Top disc was designed such a way that during pressing it will move inside the cylindrical body and further hot coagulum will be moulded under the action of pneumatic press, while bottom disc is fixed and it supports cylindrical body.

FDA-approved PTFE material of suitable size of bush and sheets were selected for development of mould on which micro holes of size 300 µm were drilled on the surface using flute type drill bits having tip size of 300 µm and length of 7 mm.

In pursuit of the major objective of the study, the first stage was to develop the major conceptualized micro-perforated PTFE mould. The standard engineering design procedures were adopted. Mechanical strength of conceptualized mould has been analyzed using ANSYS software by FEA method. Based on the optimized design, fabrication was done using 3 and 4-axis CNC machines. The newly developed mould was then tested with actual production of product. Following design data viz., mechanical properties of material, required for FEA for stress analysis are shown in table 1. The design boundary conditions required for stress analysis by FEA are given in the table 2. The actual dimensions of micro-perforated PTFE mould in terms of diameter and height were derived based on desired processing capacity as given in table 2. A wall thickness of 6 mm was considered for developing the micro-perforated mould based on FEA and ASME results. The inside temperature was assumed to similar with coagulum temperature which is ranges 65 to 110ºC and table 1 describes all other parameters. The size of the unit was designed based on capacity of processing and the major dimensions are shown in figure 1 a (micro-perforated bottom insert), 1 b (micro-perforated top insert or pressure plate) and 1c (micro-perforated cylindrical body) which also describes the other constructional features of mould.

Determination of actual pressure acting inside the developed micro-perforated PTFE mould

Pressure acting inside the pneumatic cylinder which is equipped in the automatic paneer pressing machine - maximum 5 bar (g) or 0.5 N/mm^2. Bore diameter of pneumatic cylinder (measured using Vernier caliper) is 80 mm. Cross- Sectional area and pressure acting inside mould was calculated using eq1 and 2.

$A = \pi r^2$ ———— Eq -1

F = P×A ———— Eq-2

Stress analysis cycle (FEA)

In order to optimize the wall thickness of micro-perforated PTFE mould based on FEA stress analysis which includes induced Von-mises stress or equivalent stress, total deformation and Factor of safety was performed using ANSYS 22 software as procedure detailed by Mahesh and Ravindra (2017). The stress analysis cycle followed as shown in flowchart.

Validation of Shell thickness

To validate shell wall thickness obtained by FEA (ANSYS-22), results were compared with wall thickness of mould calculated by ASME design equation (Mahesh and Ravindra, 2017). The calculation done by adopting ASME norms which is basic strength calculation and doesn't account for stress induced while operation.

Calculation code as per ASME norms shown in equation 3.

Wall thickness of the cylindrical shell was calculated using

$$t = \frac{P \times R}{(2SE - 0.6P)} \quad \text{——— Eq -3}$$

Where,

t = Cylinder thickness (mm)

P = Design pressure (MPa)

R = Cylinder Inside radius (mm)

S = Maximum Allowable Stress at design temperature (MPa)

E= Joint Efficiency

Procedure to run software programme for calculation of shell thickness (ASME 2011)

The calculation also requires the user to enter dimensions of model, pressure, operating temperature, mechanical of Virgin PTFE as shown in figure 2 (Virgin PTFE is resistant to corrosion, however, it may experience wear and tear over time. ASME design equation-based software does not provide an option to ascertain values for wear and tear allowances. To account for this, a corrosion allowance of 1 mm was included).

Development of 3D model using Solid works platform

↓

Conversion of 3D model version into (**Initial Graphics Exchange Specification)** IGES format

↓

Initiation of ANSYS 22 Workbench

↓

Import of IGES format model to workbench

↓

Input of parameters (MoC, Poisson ratio, Yield stress, Young's modulus)

↓

Discritise model to form Finite Element Mesh

↓

Providing boundary conditions (Pressure, Temperature and Fixed support)

↓

Run FEA

↓

Result (Von - Mises stress, Deformation and Factor of Safety)

↓

Review of result

Stress Analysis Cycle

Results and Discussion

The results obtained by FEA for the optimization of wall thickness of

Micro-perforated PTFE mould and comparison between the paneer made from micro-perforated PTFE mould and conventional stainless steel paneer mould were also depicted. The FEA result were presented in terms of Von-Mises (equivalent) stress, total deformation and factor of safety (FoS).

Determination of actual pressure acting inside the developed micro-perforated PTFE mould

The result obtained for calculating cross-sectional area of pneumatic cylinder of OD 80 mm was found to be 5024 mm^2 by using eq-1. The force exerted by pneumatic cylinder while operating at inside pressure of 5 bar(g) was found to be 2512 N using eq-2. Similarly, cross-sectional area of micro-perforated PTFE mould of ID was found to be 12,265.7 mm^2 using eq-1 and pressure acting inside the mould is 200 kPa or 0.2 N/mm^2 using eq-2. Therefore, the mould was designed to withstand pressure of 2 bar.

Stress analysis of the Micro-perforated PTFE mould

The results of FEA stress analysis are presented in terms of Von Mises (Equivalent) stress. The obtained simulation of the stress analysis by FEA using ANSYS 22 is shown in the figure 3a. Comparing the color scheme of the domain with the color legend panel. It depicts the magnified picture of the highest and lowest stress regions developed during the application of pressure during Pressing operation. The highest stress (red and yellow color) 1.47×10^{07} Pa was induced in some regions of bottom perforated plate and around its circumference. The lowest stress (dark blue) 1.08×10^{06} Pa while average stress experienced was 4.2004×10^{06} Pa.

According to the Von Mises criterion, fracture or failure occurs when the energy or stress developed surpasses the yield stress, in this case 30 MPa (Virgin PTFE) (Von-Mises, 1913; Mahesh and Ravindra, 2017). The FEA analysis carried out using ANSYS 22 software, the stress induced during simulation was greater than the yield stress of virgin PTFE material when the envisioned mould was modelled and examined at 2, 3 and 4 mm wall thickness and hence it was decided to use 6mm thick virgin PTFE material to fabricate the micro-perforated PTFE mould. The maximum stress induced in the micro-perforated PTFE mould was 1.47×10^{07} Pa (14.7 MPa) which is much less than the tensile yield strength of virgin PTFE material (30 MPa) and hence stress resulted from

Table 1: Mechanical properties of PTFE

Mechanical Properties	Value	Unit
VIRGIN PTFE		
Color	Milky white	
Density	2.1-2.2	gm/cc
Poisson ratio	0.42-0.44	
Modulus of elasticity (tensile test)	0.4-0.75	GPa
Tensile strength	22 - 30	MPa
Tensile strength at break	-	MPa
Elongation at break	220 -300	%
Shore hardness	55	-
Compression strength	5	MPa
Ball indentation hardness	30	MPa
Coefficient of static friction	0.08- 0.10	-
Thermal Properties	Value	Unit
Crystalline melting point	327	°C
Service temperature (max)	260	°C
Service temperature (min)	-200	°C
Service pH	0-14	
Thermal expansion (CLTE)	9.5	10^{-5} K^{-1}
Specific heat	1000	J/(g*K)
Thermal conductivity	0.20	W/(K*m)
Water absorption	0	%

This material is FDA Approved (FDA CFR 21-177.2600 Compliant)
PTFE is chemically inert & unaffected by all known chemicals except molten or dissolved alkali metals–Sodium; Potassium; Rubidium; Cesium; Francium & Fluorine gas, certain fluorine compounds & complexes at elevated temperatures.

Table 2: Design Data and Boundary conditions

Description	Unit	Value
Material of construction	FDA (CFR 21-177.2600 Compliant)	PTFE
Micro-perforated PTFE mould		
Inner diameter of mould	125	mm
Wall thickness of mould	6	mm
Length of mould	100	mm
Outer diameter of top disc and its thickness	125 and 6	mm
Outer diameter of Bottom disc and its thickness	150 and 6	mm
Actual pressure acting (Inside)	200	kPa
Operating pressure (outside)	101.325	kPa
Operating temperature (inside)	60-80	°C
Operating temperature (outside)	25-30	°C
Fixed support	Micro-perforated PTFE mould will be mounted on SS/ Wooden support to prevent mould from movement	

simulations were considered within in the acceptable limits for operating conditions designed for the study.

Deformations from the FEA stress analysis

To complete the picture of the stress analysis, the total deformation generated in Micro-perforated PTFE mould from stress analysis was evaluated and the result presented in figure 3b. FEA numerical analysis was also extended to the evaluation of anticipated deformation on the mould as result of stress generated. A close visual of results of FEA and the color legend panel indicated that the total deformation induced ranges from 0 to 2.1535×10^{-10} m which seems

Fig. 1a Dimensional drawing of conceptualized Micro-perforated bottom insert

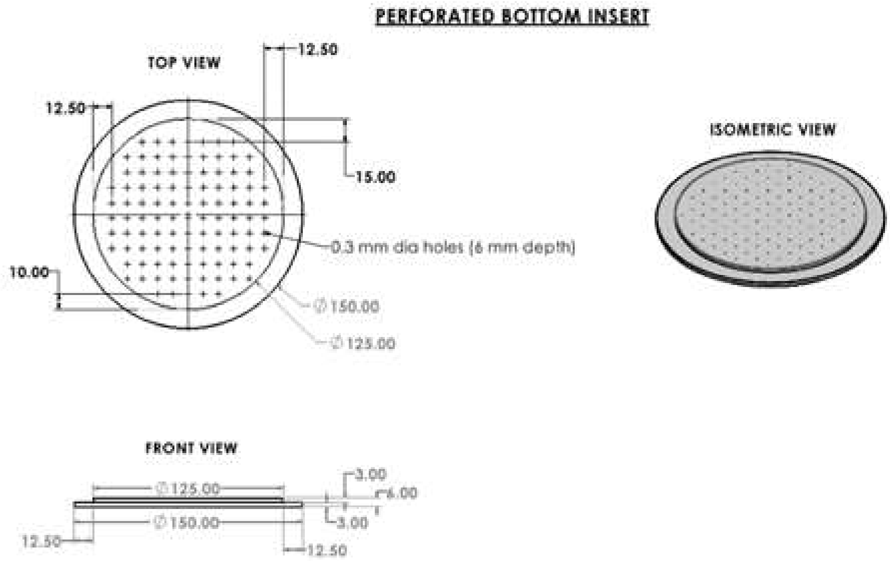
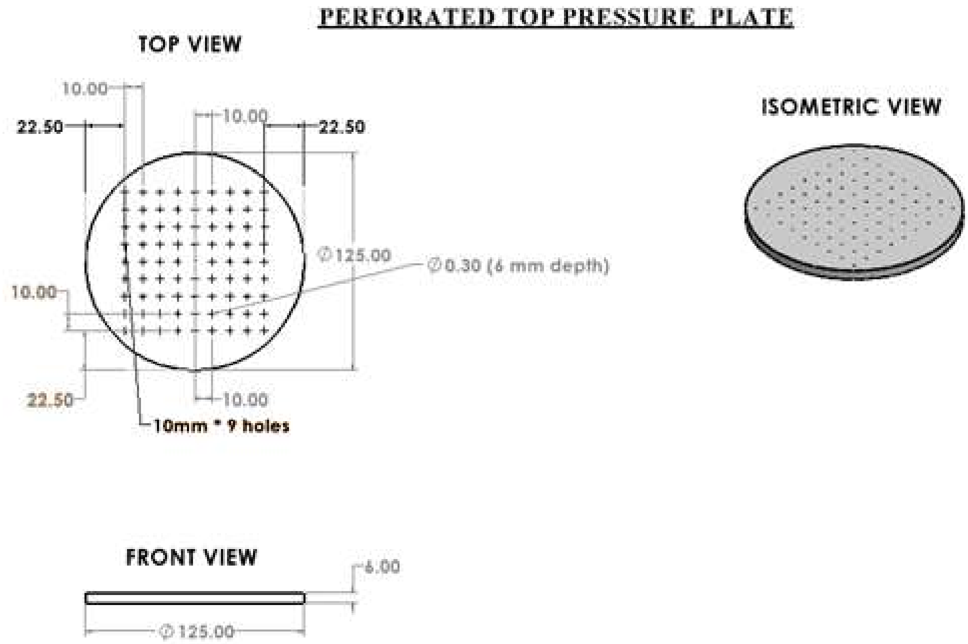


Fig 1b: Dimensional drawing of conceptualized Micro-perforated top pressure plate



to more acceptable due to rigid construction. Dutt (2016) developed the knuckle pin for tractor made of PTFE material, at max load of 50 KN, the deformations occurred was 3.96×10^{-06} mm and the present results was less than the reported and hence FEA analysis is deemed to be appropriate.

Factor of safety

The numerical stress analysis was also carried out to determine the factor of safety for the designed unit. The result of FEA analysis is presented. It is evident from the results shown in figure 3c. The minimum factor of safety obtained was 2.04 (yellow color region) obtained peak induced stress area which greater than 1.0 and hence the design can be deemed to be safe (Krann et al. 2004), maximum FoS was 15 (Blue color region).

Jebelli et al. (2018) suggested that the minimum factor of safety (1.5 to 3.5) should be considered for fabrication of processing equipment's operating under pressure whose MoC was PTFE (23 to 30 MPa yield strength) and the present result of FoS falls in safe side and hence the FEA analysis value was appropriate.

Determination of shell wall thickness by using ASME approved design equation software

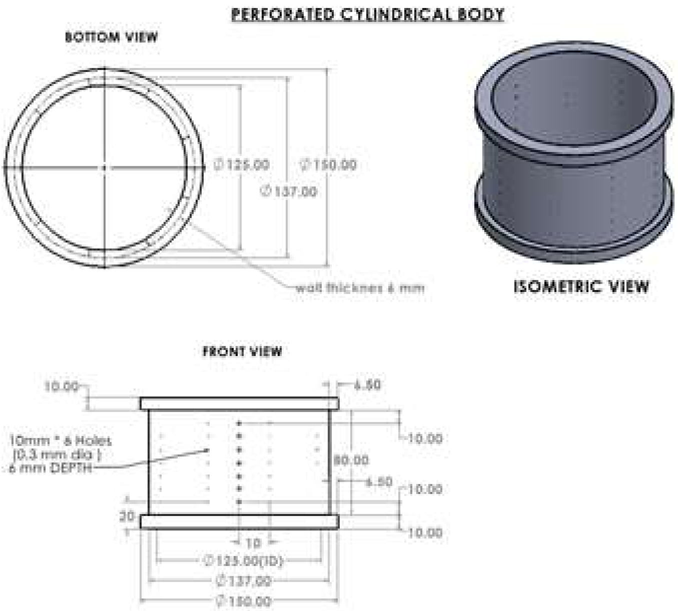


Fig 1c: Dimensional drawing of conceptualized Micro-perforated cylindrical body

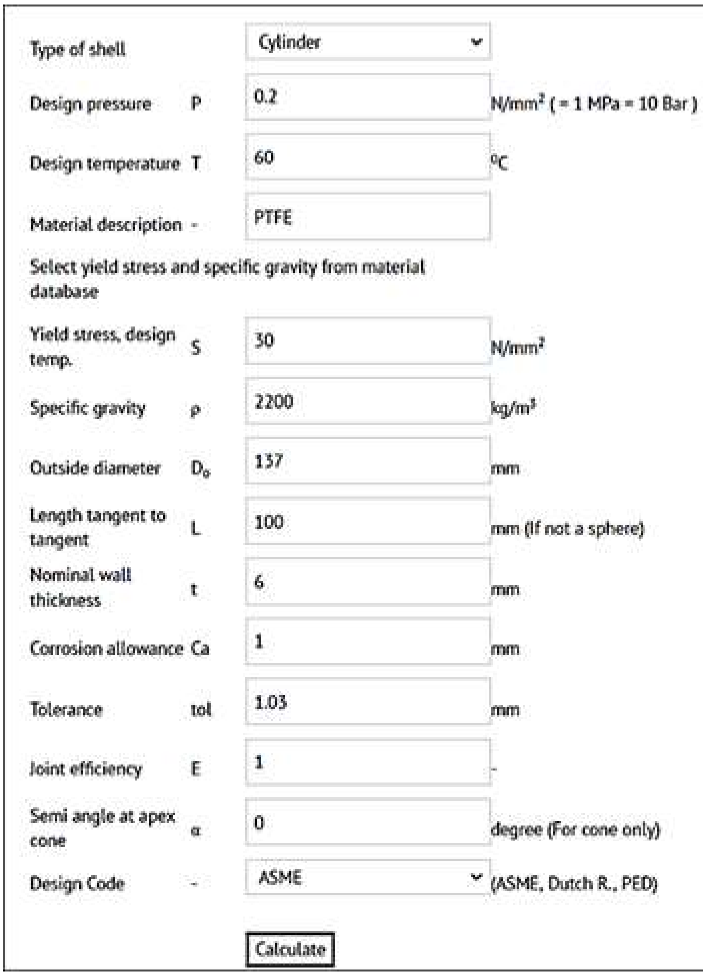


Fig 2: Data input for thickness calculation

To validate wall thickness of Micro-perforated PTFE mould, the design data were fed to ASME design equation based software. The results obtained shown in figure 3d. The wall thickness resulted from the ASME calculation is 2.46 mm. Above calculation doesn't took account of stress concentration, stress developed during fabrication and stress around holes. To overcome above drawbacks, 6 mm wall thickness was considered for the fabrication. It is evident that the FEA analysis and ASME results were appropriate. The developed micro-perforated PTFE mould shown in figure 3e.

Comparison of some selected quality parameters and processing conditions of paneer made from micro-perforated PTFE mould and conventional stainless steel paneer mould.

The developed micro-perforated PTFE mould utilized successfully in production of paneer and it can also implemented in cheese and tofu production. The pressing pressure (3, 3.5 and 4 bar) and time (10,15 and 20 min) were adopted for research study. The pressure and time combinations were optimized to pressure (3.45 bar) and time (20 min) using RSM (Response surface Methodology) statistical analysis tool.

Quality parameters such as moisture content (MC), porosity (PR), bulk density (BD), hardness, chewiness and overall acceptability (OA) of different paneer samples (optimized paneer made from developed micro-perforated PTFE mould and paneer made using SS mould) are shown in Table 3.

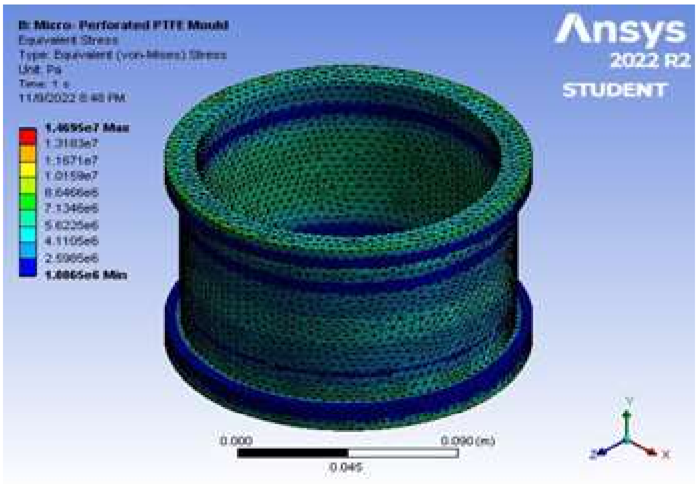


Fig 3a: Von Mises stress Induced in Micro-perforated PTFE mould

The optimized paneer made from developed micro-perforated

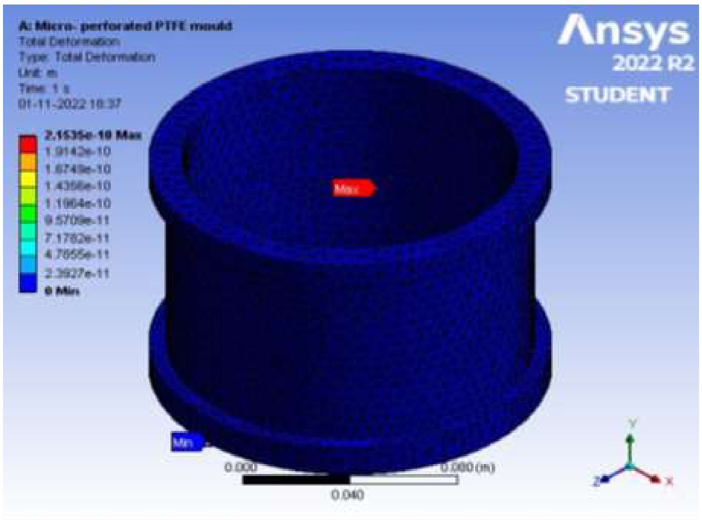


Fig 3b: Total deformation due to induced stress in micro-perforated PTFE mould

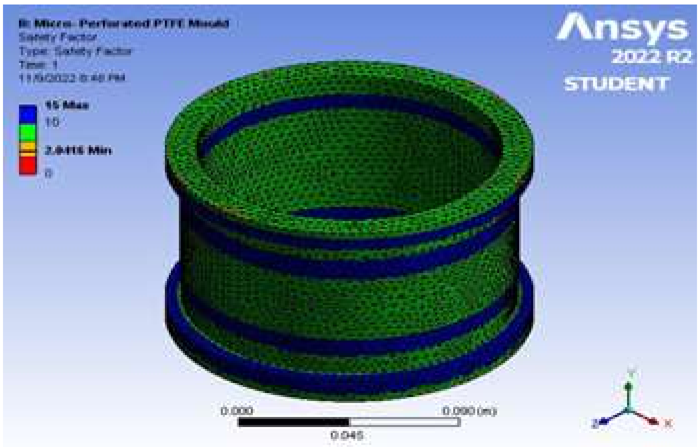


Fig 3c: Factor of Safety in micro-perforated PTFE mould

Wall thickness calculation of Cylinder
according ASME

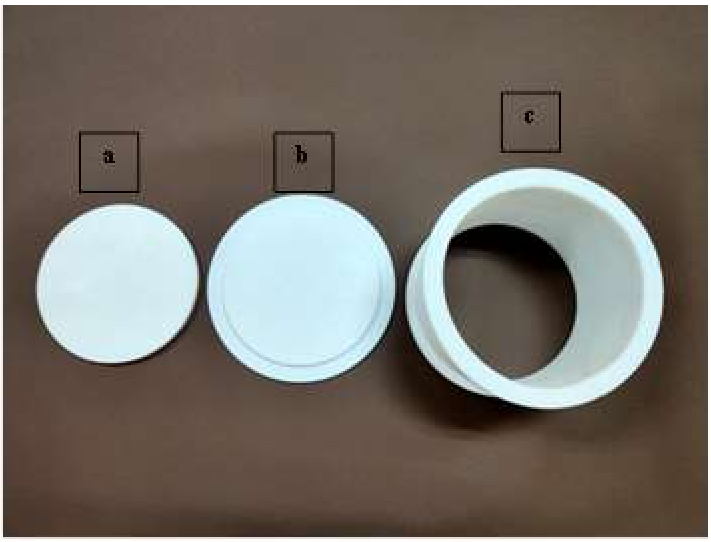
Allowable stress	S =	30 =	30.00 N/mm^2
Corroded thickness	$t_c = t - Ca - tol =$	6 - 1 - 1.03 =	3.97 mm
Cylinder:			
Corroded inside radius	$R = \frac{D_o}{2} - t_c =$	$\frac{137}{2} - 3.97 =$	64.53 mm
Required wall thickness	$t_r = \frac{P \cdot R}{S \cdot E - 0.6 \cdot P} =$	$\frac{0.2 \cdot 64.53}{30 \cdot 1 - 0.6 \cdot 0.2} =$	0.43 mm
Nominal required thickness	$t_m = t_r + Ca + tol =$	0.432 + 1 + 1.03 =	2.46 mm
Max. Allowable Working Press.	$MAWP = \frac{S \cdot E \cdot t_c}{R + 0.6 \cdot t_c} =$	$\frac{30 \cdot 1 \cdot 3.97}{64.53 + 0.6 \cdot 3.97} =$	1.78 N/mm^2
Thickness analysis, $t > t_m$?	t = 6 mm is OK		
Weight			0.54 kg
Enclosed volume			0.001 m^3

Fig 3d: ASME design software result

PTFE mould got higher overall acceptability scores due to its uniform firm and compact body, pleasing appearance. Paneer made from developed micro-perforated PTFE had uniform color and appearance, dryness and rind formation in the surface is nil, while the control sample (paneer made from conventional stainless-steel paneer mould was highly porous, loose and open body, surface of the paneer doesn't appeared as uniform color and rind structure was noticed and hence paneer made from developed micro-perforated PTFE mould at optimized pressure and time combination is highly acceptable and appreciated than the conventional paneer.

Conclusion

The Von mises failure criterion states that failure occurs when the energy of distortion reaches the yield stress (explosion due to high hoop stress developed in mould). The max Von mises (equivalent) stress 1.47×10^{07} Pa obtained by FEA, which is less than yield stress of virgin PTFE, the total deformation induced is also very negligible i.e., 0 to 2.1535×10^{-10} m which depicts the rigidity of construction of mould. Minimum FoS obtained 2.04 and maximum of 15. The result obtained from ASME shell thickness analysis confirms that the wall thickness well within



a: Perforated Top Pressure plate; b: Perforated bottom plate;

c: Perforated cylindrical body

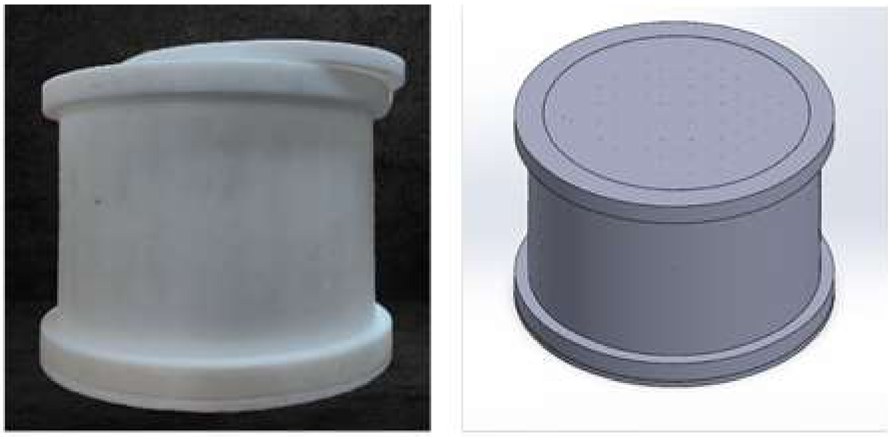


Fig 3e: Developed micro-perforated PTFE mould for paneer pressing

the selected wall thickness (6mm) which was used for stress analysis in ANSYS-22. The designed and required wall thickness was validated to be safe at this thickness. The results from FEA of Stress and stimulation carried out using ANSYS 22 and ASME design equation software confirms correctness of design and development of micro-perforated PTFE mould. Designed Micro-perforated PTFE mould fabricated from 6mm Virgin PTFE bush and 6 mm Virgin PTFE molded sheet. The working drawings of micro-perforated PTFE mould was developed and actual fabrication of designed mould was developed using advanced 3 and 4 axis CNC machines. Newly fabricated mould can withstand operating pressure of 5 bar(g) and even elevated temperature up to 110ºC. The developed PTFE mould performed satisfactorily without any deformation during pressing. Paneer manufactured using newly designed and developed micro-perforated PTFE mould resulted in a excellent quality paneer.

References

Dhanumalayan E, Joshi GM (2018) Performance properties and applications of polytetrafluoroethylene (PTFE). Adv Composites Hybrid Materials 1:247-268

Dutt A (2016) Finite Element Analysis of Knuckle Joint Pin Using Creo 2.0 Software. Int J Res Mechanical Eng Technol 6:45-48

Jebelli A, Yagoub C, Dhillon S (2018) Design and Implementation of an Autonomous Underwater Vehicle (AUV) with PTFE. Adv. Robot. Autom **7**:1-7. doi: 10.4172/2168-9695.1000185

Kraan MJ, Buskop J, Doets M, Snippe C (2004) Structural analysis of the vacuum vessel for the lhcb vertex locator (velo). National Institute for Nuclear Physics and High Energy Physics, Kruislaan, 409:01-25.

Legg AK, Carr AJ, Bennett RJ, Johnston KA (2017) General aspects of cheese technology. In: Cheese, 4th edition, Academic Press. pp 643-675

Mahesh Kumar G, Ravindra MR (2017) Design of vacuum impregnation chamber for soaking of Gulabjamun in sugar syrup and optimization of wall thickness by finite element analysis (FEA). Int J Environ Agric Biotechnol 2:8-18

Puts GJ, Crouse P, Ameduri BM (2019) Polytetrafluoroethylene: synthesis and characterization of the original extreme polymer. Chemical Rev 119:1763-805

Ramachandra CT, Ashoka HG, Kumar GM, Shivanna B, Ray BR, Sivamma P (2021) Design and Development of Environmental Friendly Sub-Baric Storage Bin. Int J Environ Climate Change 11:19-28

Von Mises R (1913). Mechanics of solid bodies in the plastically deformable state. Math Phys 1: 582-592