Estimation of Injection Molding Process for a Thin Fresnel lens By Plastic Flow Simulation

Atish Kumar, Harry Garg, B. S. Pabla

Abstract*: This paper is based on the plastic flow simulation of a thin Fresnel lens to estimate the injection molding process. Nowadays Fresnel lenses are made of transparent plastics materials instead of silica-based glass to reduce handling and processing cost. For mass manufacturing of plastic parts, the injection molding process is best suited. Thus in this study plastic flow analysis of a thin Fresnel lens is carried for the evaluation of injection molding process. Plastic flow analysis helps in estimating how molten plastic will flow during the process Plastic flow analysis is also very helpful in evaluating the manufacturing defects such as air traps and weld lines without real-time experimentation. The simulation results evaluate the values of the parameters such as fill time, filing pressure, pack pressure, etc. Also, the manufacturing defects observed by the simulation results are reasonable and met the design requirement.

Keywords: Fresnel lens,* Injection *molding simulation, Plastic Flow Analysis, Solidworks Plastics.

I. INTRODUCTION

Fresnel lenses are widely used in solar concentrator applications as a replacement of the conventional concentrating lens [1]. The reason behind this is their lightweight, low cost, thin structure and excellent light-gathering ability [2]. Fresnel lenses are mostly used in non-imaging systems where optimized images are not required like in solar concentrator and illumination systems [3, 4].

First Fresnel lens was made of glass by manual grinding and polishing [5], which is a time and money consuming process. But due to advancements in material engineering, replacements for glass are available such as PMMA, Polycarbonate(PC), Polystyrene(PS). These plastic materials have optical properties similar to glass [6]. Thus nowadays Fresnel lenses are produced by injection molding of transparent plastic materials. This process leads to high accuracy replication and good surface finish [7] which is good for optical application.

The injection molding process is famous for its fast production, complex part design, and low cost. Also, injection molded parts possess enhanced strength. Because plastic products deal with more than half of the commercial products. Thus it is very important to analyze the injection molding process before the production begins. Due to the constant improvement of computer technology, computer technology can be utilized in the enterprise to meet the production requirements of injection molding through computer aided engineering/design/manufacturing (CAE/D/M). CAE provides some easy to use injection molding simulation tools which simulate how the molten plastic flow during the injection molding process to predict and avoid manufacturing-related defects. Injection molding simulation also evaluates various key molding attributes, such as melt temperature, pressure profile or time-to-fill, etc. Thus injection molding simulation can help in evaluating some important attributes and manufacturing-related defects without real experimentation.

In this study, Solidworks Plastics module of Solidworks is used for the plastic flow simulation of a thin Fresnel lens. The thin fresnel lens is designed for Natural light illumination system (NLSI). The Fresnel lens is designed for uniform illumination of visible light over an area focus. Dimensional parameters of the fresnel lens like prism angle, groove pitch and facet thickness are very important and critical factors for achieving the uniform illumination. Manufacturing defects during injection molding can affect these dimensional parameters and so the desired output. Also, injection molding parameters can be estimated by injection molding simulation. Thus Solidworks Plastics software is used to analyze the plastic flow and evaluate key injection molding attributes.

II. 3D MODELING OF THE FRENSL LENS

The 3D modeling of the Fresnel lens is carried out in Solidworks. A 2D model of the Fresnel lens is sketched in Solidworks. The dimensional parameters of the Fresnel lens are selected in such a way that when the 2D sketch is revolved about the axis it gives a circular 3D shape and also uniform illumination over a circular target area.

The dimensional parameters of the designed Fresnel lens are given in table 1.

Table 1 Dimensional parameters of Fresnel lens

Parameter	Value
Aperture shape	Circular
Aperture size	120mm diameter
Target area	6mm diameter (Area focus)
Base thickness	2mm
Prism angle	25.837297°-1.78292°

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Groove Pitch	3.43036mm-3.32070mm
Facet Thickness	1.66105mm-0.10309mm
Volume	28800 mm^3

The complete 3D part of the designed lens is shown in fig. 1.

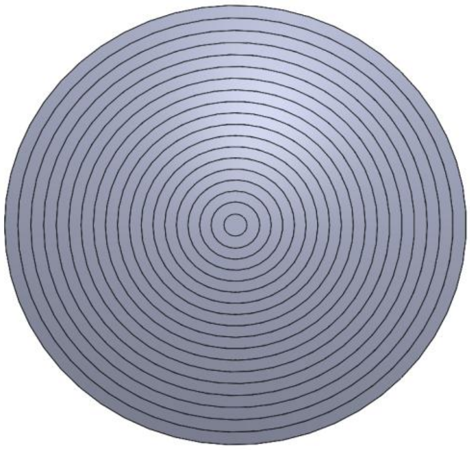

Fig. 1. 3D Model of the designed Fresnel lens

III. PLASTIC FLOW ANALYSIS

The plastic flow analysis of the designed Fresnel lens is carried out in Solidworks Plastics module of the Solidworks® Premium 2017 x64 edition. Since the geometric model of the Fresnel lens is created it Solidworks, thus it can be directly imported into Solidworks plastic module and no Pre-treatment is required. Various steps in the injection molding simulation are discussed below.

A. Meshing

Earlier than the analysis, it's far essential to perform meshing operation, thus a solid mesh for this model is selected. Tetrahedral elements with four nodes are selected for the meshing process and triangle size of 2.01mm is selected for the whole part. But the facet thickness of the designed Fresnel lens is varying with a minimum thickness of 0.10309mm which is less than the assigned element size. Thus local meshing is required for such facets. The local meshing operation is performed for better meshing and to reduce the simulation run time local meshing is carried out in 3 parts which are given in Table 2.

Table-2: Localized meshing characteristics

Facets	Triangle size
1st to 6th	1.15mm
7th to 12th	0.6mm
13th to 18th	0.1mm

This meshing operation results in 572077 elements and 199211 nodes with an aspect ratio of 3.70. The complete meshed part with localized meshing is shown in the fig. 2.

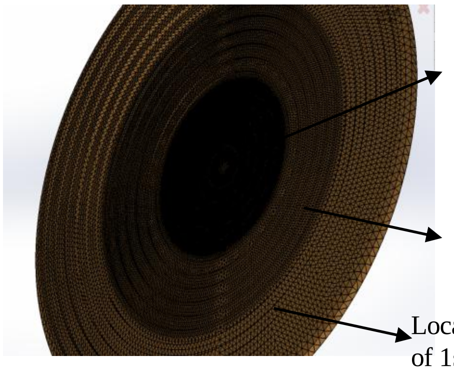

Fig. 2. Complete meshed part

B. Material selection

When the Fresnel lens was invented, glass is used in the manufacturing of the lens. Since silica-based glass is brittle and is difficult to process thus nowadays in most of the Fresnel lenses application PMMA is used which have the following advantages over other transparent plastic materials.

- PMMA is highly transparent.
- High resistance to UV light.
- PMMA block medium and far IR.
- Excellent resistance to weathering and long life under the sun.

Thus PMMA material is selected for the designed Fresnel lens and Generic PMMA is assigned to the lens from the material domain of the Solidworks Plastics whose processing parameters for the injection molding process are given in Table 3.

Table-3: Processing parameters for PMMA

Parameter	Value
Melt temperature	250°C
Mold temperature	60°C
Ejection temperature	85°C
Glass transition temperature	100°C
Ambient temperature	25°C
Specific heat constant	2300 J/(Kg-k)

C. Best Injection location

Injection location in injection molding specifies the location of the point from where the melted plastic enters into the mold. Injection location for a simple design is equal to 1 but may vary (2 or more) according to the complexity of the specimen. Since our designed Fresnel lens is simple in shape and also is symmetric thus only one injection location is to be added and that too in the center of the Fresnel lens as shown in the fig. 3.

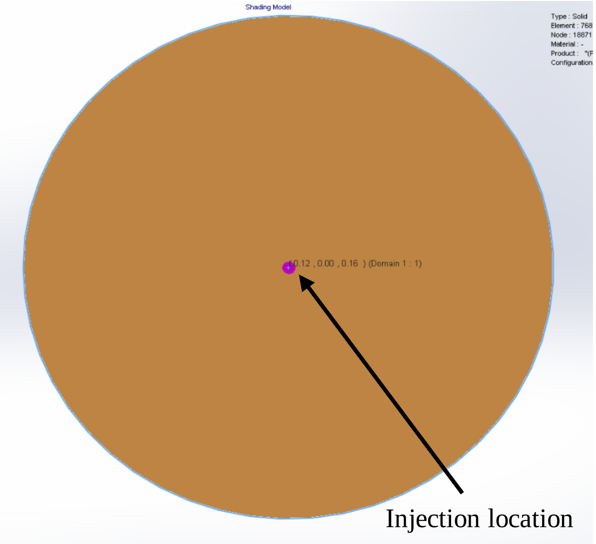

Fig. 3. Best injection location.

IV. RESULTS AND DISCUSSION

The injection molding simulation is completed with two analysis modules: FLOW and PACK.

A. Flow analysis

Flow analysis is used for the prediction of how molten plastic fills the cavity. During the filling stage, mold cavities would be filled about 95%. Flow analysis accounts for the transfer of heat between the material and mold during the filling stage. It also anticipates the changes to viscosity as the material starts solidifying, distributions of pressure and temperature within the cavity. Flow analysis can determine the process conditions like fill time, filling pressure, shear stress, etc. which will be discussed in this section.

1) **Fill Time:** In order to make sure that the melt is filled, on the one hand, it will not cause uneven filling due to too short time, on the other hand, it will not cause problems such as flashing due to too long filling time, it is important to select the best filling time by fill time analysis. Fig. 4 display the fill time plot for the designed lens which shows the profile of the molten plastic as it flows in the mold cavity during the filling stage. The filling time estimated by the fill time analysis it comes out to be 2.2674 sec.

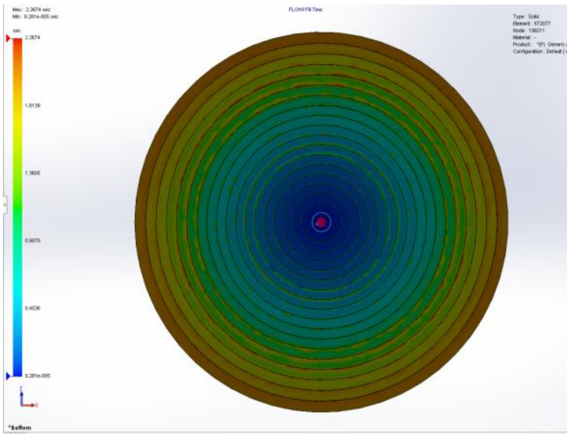

Fig. 4. Filling time analysis results

2) **Filling pressure:** For the duration of the filling stage, the forward injection velocity of the reciprocating screw is managed, which ends up in the pressure required to fill the cavity. Mold cavity filling pressure is usually influenced by the number and location of injection, product wall thickness, plastic viscosity characteristics, and injection speed. Filling pressure plot is displayed in the fig. 5 which shows 84.67MPa pressure is required to successfully fill the mold cavity which is 84.67% of the maximum pressure (100MPa) of the injection molding machine.

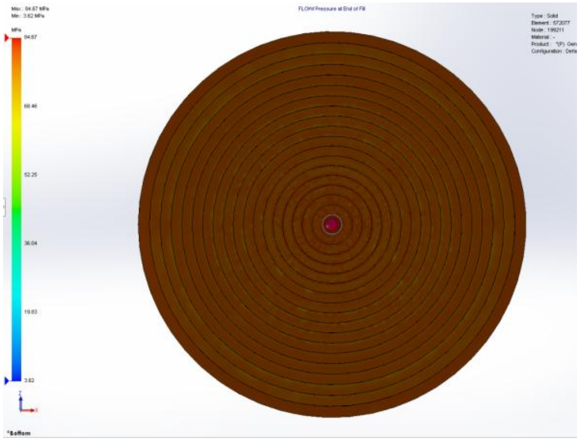

Fig. 5. Filling pressure analysis results

3) **Shear stress at the end of the fill:** Shear stress is shear force per unit area. This shear force arises when the molten plastic flows in the mold cavity. The shear stress plot shows the shear stress variation at the end of the fill for the molten part as shown in fig. 6 with the maximum value of 49.98MPa.

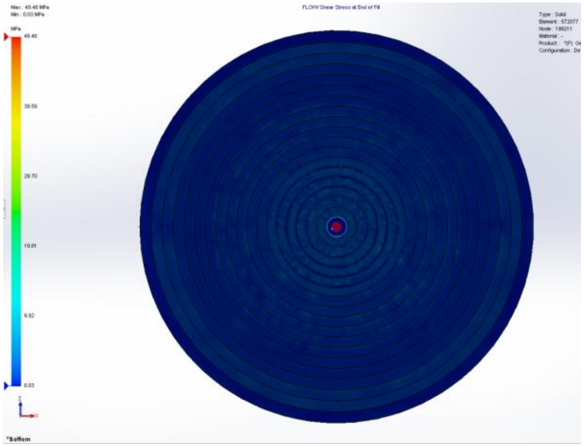

Fig. 6. Shear stress analysis results

4) **Bulk temperature at the end of the fill:** Bulk temperature at the end of the fill plot shows how much the molten material has modified from the predefined melt temperature. Due to shear stress developed, the temperature of the molten plastic increase by 26.25°C in the mold from the molten temperature (250°C). The bulk temperature plot in the fig. 7 indicate this increase in the temperature.

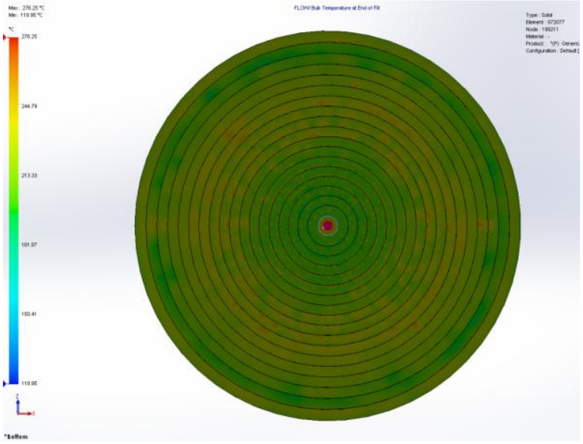

Fig. 7. Bulk temperature at the end of the fill

5) **Volumetric shrinkage at the end of the fill:** Volumetric shrinkage is the percentage decrease in the volume of the material when it solidifies from the molten state. The high rate of volumetric shrinkage will be observed in thick parts which result in the form of voids. These voids are not air bubbles but they are vacuum voids. These voids can affect the efficiency of the Fresnel lens. Volumetric shrinkage plot in fig. 8 shows the percentage shrinkage in the various parts of the Fresnel lens.

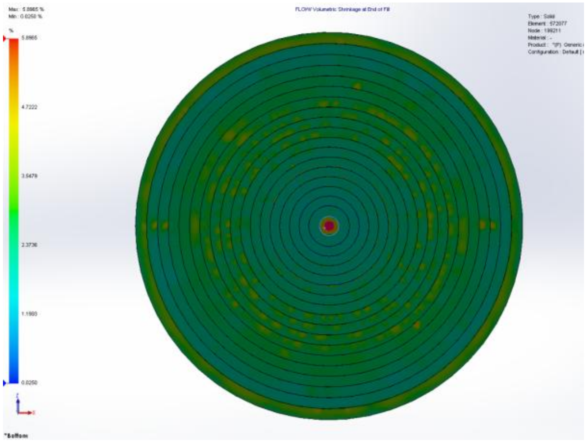

Fig. 8. Volumetric shrinkage plot

6) **Cooling time:** Once molten plastic has been injected into the mold cavity, it takes time before the Part has cooled and become sufficiently rigid to allow it to be demolded. This period is known as the cooling time. Typically cooling time is 70% of the cycle time in injection molding. Mold temperature and the melt temperature are the two aspects which influences the cooling time. The values for the selected mold temperature and melt temperature are given in table 3. Cooling of the molten part starts at the end of filling (t1=2.7674 sec) as shown in cooling time lot in fig. 9 and end when the part reaches at the ejection temperature (t2=21.5864 sec).

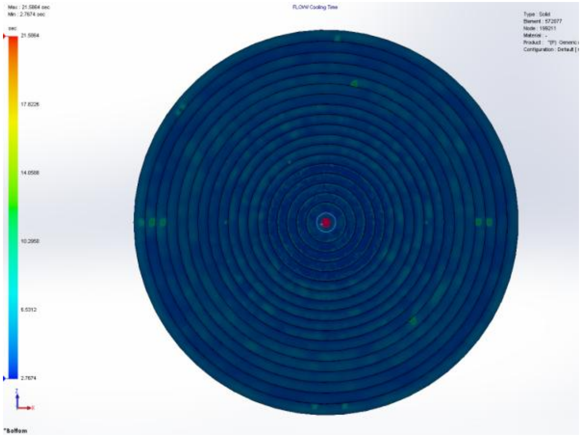

Fig. 9. Shear stress analysis results

Thus cooling time for the molten part = $t_2 - t_1$ = 21.5864 - 2.7674 = 18.819 sec.

7) **Gate filling contribution:** When only one injection location is used, the cavity is filled by the contribution of that injection location alone. But when multiple locations are used, the cavity is filled partially by each injection location. Gate filling contribution plot shows the contribution of each injection location in the filling of the mold cavity as shown in fig. 10.

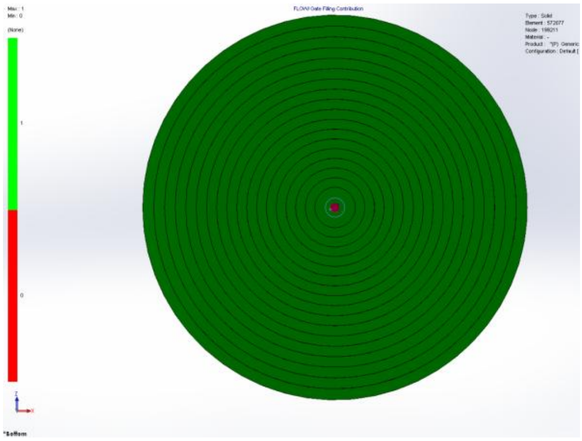

Fig. 10. Gate filing contribution plot

8) **Ease of fill:** Ease of fill plot determines whether the cavity will fill successfully or not. The green region indicates the areas that can be filled under normal injection pressure whereas yellow and red areas are of potential concern. Since the whole plot is green as shown in fig. 11 which indicates that the molten part can be filled easily under normal pressure.

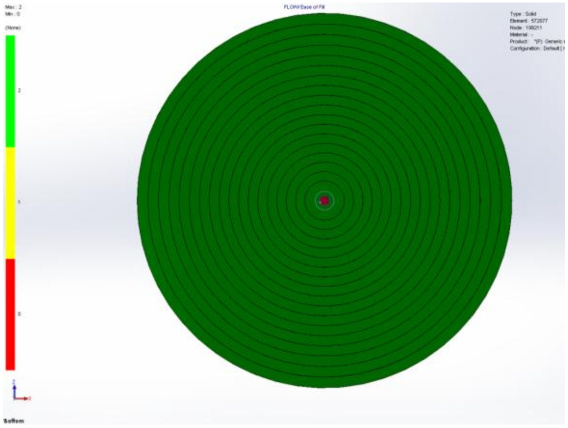

Fig. 11. Ease of fill plot

B. Pack analysis

Any plastic part that is filled should undergo through a packing phase to keep away from surface finish issues. Pack analysis estimates the solidification process of the material in the cavity. During Pack, the pressure is applied to the injection system to cause additional material to enter the cavity as the part shrinks and freezes. In the packing stage, plastic mold wall is cooled down and solidified until the gate is closed. Pack analysis is carried out for pressure required at the end of the pack, bulk temperature at the end of the pack, volumetric shrinkage at the end of the pack, etc.

1) **Pressure at the end of the pack:** Pressure at the end of the pack plot shows the distribution of the pressure which is required for the successful pack operation. The pressure applied during the packing stage is managed by the reciprocating screw. The plot in fig 12 shows the maximum pressure required near the injection location (35.76 Mpa) which reduces as we move away from the center with a minimum value of 0.10Mpa at the outer periphery.

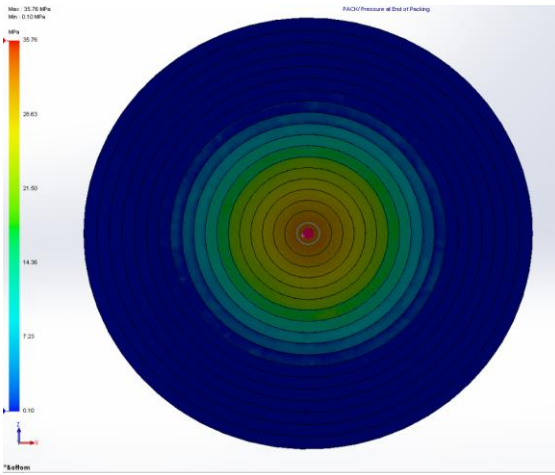

Fig. 12. Pressure at the end of the pack plot

2) **Temperature at the end of the pack:** At the end of the packing stage, the part has cooled down to the mold temperature. The core volume of the part may be still into molten phase but the outer surface starts cooling to the mold temperature. The plot of temperature at the end of the pack in fig. 13 shows the temperature distribution at the end of the pack.

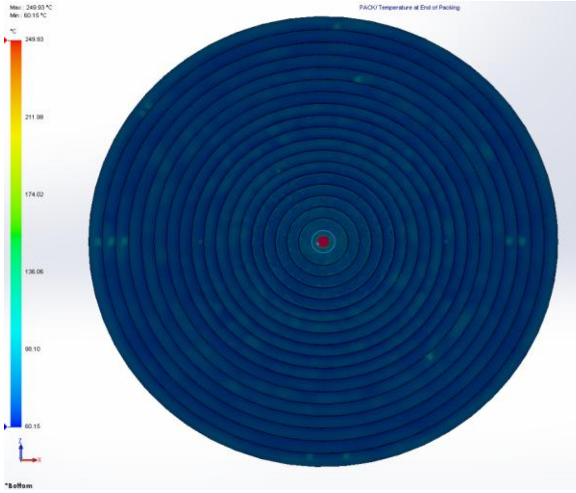

Fig. 13. Temperature at the end of the pack plot

3) **Volumetric shrinkage at the end of the pack:** Plastic parts are compressible because of their specific volume as a function of temperature and pressure. The high rate of shrinkage will occur in the areas which do not undergo sufficient pack stage. Volumetric shrinkage plot in fig. 14 shows that the minimum shrinkage occurs near injection location and maximum occurs at the outer periphery of the lens core.

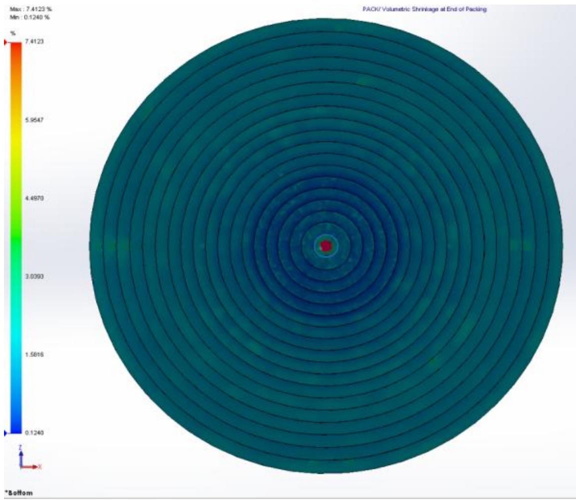

Fig.14. Volumetric shrinkage at the end of pack plot

C. Defects

Two common types of manufacturing defect are observed in injection molding: Weld lines and Air traps. Injection molding simulation is very helpful in detecting such defects.

1) **Air traps:** The air in the mold cavity which cannot be vented out during the filling stage is trapped. This trapped air can prevent plastic material from filling the volume where the air trap is located. These air traps can affect the efficiency of the Fresnel lens due to the different refractive

index of the air and PMMA. Due to the symmetric design of the Fresnel lens, the air traps are almost negligible as shown in fig. 15.

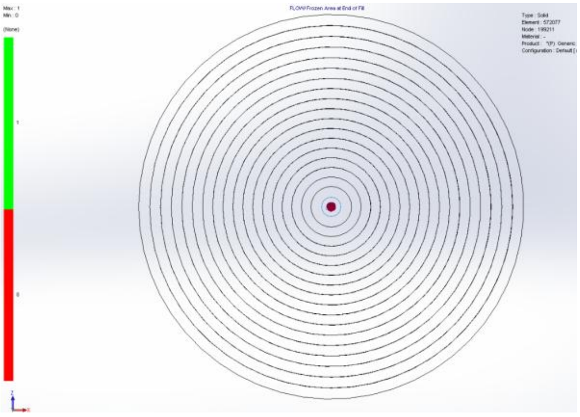

Fig.15. Air traps results

2) **Weld lines:** Weld lines are formed when two or more plastic melt flow fronts meet during the filling stage. Weld lines are typically weaker than the areas without weld lines. They can also act as stress concentrator in molded parts. Fig. 16 shows the formation of weld lines are mostly on the draft facets.

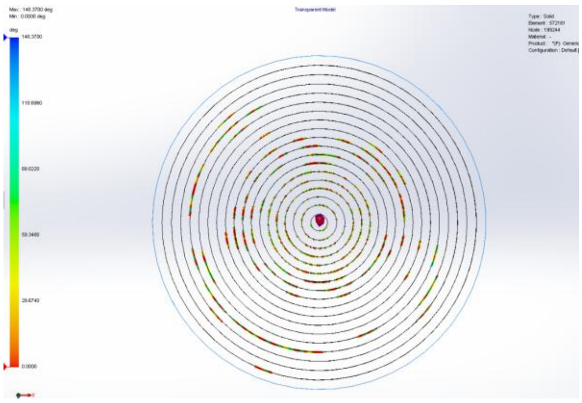

Fig.16. Weld lines results

V. CONCLUSIONS

A thin Fresnel lens is designed for Natural light illumination system (NLSI) which results in the uniform illumination over the target plane. 3D model of the Fresnel lens is generated in Solidworks. Plastic flow analysis of the designed lens is carried out in the Solidworks plastics module of Solidworks to estimate the injection molding process. The plastic flow analysis is carried out in two modules: Flow and Pack. Flow and pack results are listed in the tables below.

Table-4: Flow results

Fill time	2.2674 sec
Filling pressure	84.67MPa
Shear stress	49.98MPa
Bulk temperature	276.25°C
Volumetric shrinkage	5.8965%
Cooling time	18.819sec

Table-5: Pack results

Packing pressure	35.76MPa
Temperature at the end of pack	249.93°C
Volumetric shrinkage	7.4123%

The injection molding simulation helps in evaluation of flow and pack parameters without real time experimentation and estimation of injection molding process for the manufacturing of thin Fresnel lens. Also, the manufacturing defects detected by simulation are reasonable and met the design requirement.

REFERENCES

1. I. Ullah, H. Lv, A. J. W. Whang, and Y. Su, “Analysis of a novel design of uniform illumination for Fresnel lens-based optical fiber daylighting system,” *Energy and Buildings*, vol. 154, pp. 19–29, 2017.
2. A. Davis and F. Kühnlenz, “Optical Design using Fresnel Lenses: Basic Principles and some Practical Examples,” *Optik & Photonik, Wiley*, no. 4, pp. 52–55, 2007.
3. V. Kumar, R. L. Shrivastava, and S. P. Untawale, “Fresnel lens: A promising alternative of reflectors in concentrated solar power,” *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 376–390, 2015.
4. J.R. Egger, “Use of Fresnel lenses in optical systems: some of some advantages and limitations,” *Proceeding of SPIE*, vol. 193, pp. 63–69. 1979.
5. C-M Lin, H-K Hsieh, “Processing optimization of Fresnel lenses manufacturing in the injection molding considering birefringence effect,” *Microsystem Technologies*, vol. 23, pp 5689–5695, 2017.
6. R. Leutz, A. Suzuki, “Nonimaging Fresnel Lenses: Design and Performance of Solar Concentrators,” *Springer, NewYork*, 2001.
7. D. Loaldi, M. Calaon, D. Quagliotti, P. Parenti, M. Annoni and G. Tosello, “Tolerance verification of precision injection moulded Fresnel lenses,” *Proceeding of CIRP*, vol. 75, pp. 137–142, 2018.
8. Q. Chuan-zhen, W. Yong-tao, Z. Jian and Z. Ya-jun, “Study of Injection Compression Molding of thin-wall Light-guide plates with Hemispherical Micro structures,” *Proceedings of the 1st International Conference on Mechanical Engineering and Material Science*, pp. 447–450 2012.
9. D. Loaldi, M. Calaon, D. Quagliotti, P. Parenti, M. Annoni and G. Tosello, “Manufacturing Signatures of Injection Molding and Injection Compression Molding for Micro-Structured Polymer Fresnel Lens Production,” *micromachines*, vol. 9, pp. 653-675, 2018.
10. B. Zink, F. Szabo, I. Hatos, A. Suplicz, N.K. Kovacs, H. Hargitai, T.Tabi and J.G. Kovacs, “Enhanced Injection Molding Simulation of Advanced Injection Molds,” *polymers*, vol. 9, pp. 77-88, 2017.
11. L. Zhang, J. Lei, Junle and X. Dai, “Design and Optimization of Injection Mold for Camera Shell Based on Mold Flow Analysis,” *Proceedings of the International Symposium on Big Data and Artificial Intelligence - ISBDAI '18*, pp. 205-208, 2018.
12. X. Xiaofeng, S. Qi and X. Qiong, “Design of Spin-tub’s Hot Runner Injection Mold based on Pro/E,” *Plastics*, vol. 41(1), pp. 101-104, 2012.

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