INDIGENOUS DEVELOPMENT OF A PORTABLE LAMINATOR FOR SMALL SCALE PRODUCTION OF SOLAR PANELS

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ABSTRACT

For in-house production of solar panels in Pakistan, an indigenous and low-cost solar panel laminator is designed and fabricated. Lamination process entails melting a layer of polymer material Ethylene Vinyl Acetate (EVA) which maintains a protective layer on each side of solar wafers. Using Finite Element Modelling, optimum dimensions of the laminator were calculated under different vacuum and temperatures. The cuboidal geometry of the laminator with outer ribs turned out to be ideal with least stresses and deformation on the lamination chamber. Pneumatic based pressure system was installed inside the laminating chamber to ensure proper contact of EVA adhesive with the solar wafers. Ideal combination of pressure, heating, heating time and curing was found experimentally to obtain optimum quality laminated solar panels. The cost of panels per Kilo Watt was considerably low compared to the panels available in market. The total cost of the lamination machine is of critical importance in this research as the entire laminator is fabricated locally and therefore, the laminator provides a cost-effective alternative to the imported lamination machines available commercially.

Keywords**:** PV panel laminating machine; Finite Element Analysis; Vacuum Chamber; PV solar panel; solar wafers; Lamination of Solar Cells; EVA Encapsulation.

1. INTRODUCTION

Lamination is the process in which two or more materials are combined to form a composite material having high strength to bear shock and weather effects. A protective layer over a primary material is formed by melting and pressing an adhesive material. It forms a sandwich of materials to achieve more stability and toughness than the single layers of the materials.

The lamination process is used in PV solar panels manufacturing to protect the solar wafers from external effects. The solar cells are made up of very fragile material (i.e. silicon) and can be broken on applying even a force of small magnitude. The solar panel lamination also protects the solar wafers from environmental effects say moisture, dirt etc. It also preserves the thermo-electric properties of the wafers and allows an efficient conversion of the solar energy into electrical energy. The front and back sides of the solar wafers are laminated using a glass sheet and Tedler Polyester Tedler (TPT) sheet, respectively. Ethylene Vinyl Acetate (EVA) is used as an adhesive material between both the layers.

Amrani *et al*. [1] studied different aspects of the lamination process of solar panels with a special focus on the thermal treatment. The tempered and textured glass of 4 mm thickness was studied using spectrophotometer and found to give an optical transmission around 95% in the useful range of 380-1200 nm solar irradiation. Schulze *et al*. [2] performed a combined experimental and numerical study to investigate the effects of different parameters in the vacuum lamination technology on the laminated solar panels. The optimum temperature values required for an efficient polymerization of different layers during heating and curing processes were numerically predicted. Lange *et al*. [3] investigated that a homogenous temperature profile during the lamination process produces the high homogenous cross-linking of EVA sheet to the solar wafers. It ultimately results in efficient, long lasting solar panels giving high yields of electrical currents. Such temperature profiles can be achieved by hybrid heating technology.

The recent developments have allowed the production of much thinner solar wafers ultimately reducing the cost of the solar panels. Komp *et al*. [4] modified the encapsulation based solar panels manufacturing method to allow the newly developed thinner but more fragile solar wafers to be used without expensive standard industrial machinery. The cottage solar panels manufacturing was demonstrated as a practical, cost-effective and sustainable option for the production of electricity in remote areas of developing countries. Pingel *et al*. [5] investigated the mechanical stability of the solar panels using solar panels of different thicknesses available in the open market. The current-voltage and electroluminescence images methods were used to study the mechanical stability. The reduction in solar wafers thickness decreases the overall price of the solar panel but it also results in lower mechanical stability. An optimised unique set of processes was described to attain a stable solar panel with 160 micrometres thick solar wafers. An alternative was also suggested to reduce the stresses developed during the soldering process.

Ghule and Bindu [6] presented a detailed design and development of an optimized vacuum chamber using Finite Element Analysis method. The problems of excessive stresses and deformation of the chamber was faced in the initial design of the chamber. The problems were overcome by using fillets at the sharp corners and ribs of suitable thickness at weaker parts of the chamber.

Cattaneo *et al*. [7] studied the limitations of glass sheet at the front and EVA as an encapsulant at the back-layup module. The EVA sheets, when exposed to moist air and ultraviolet radiations, degrades significantly thus reduces the solar panels performance. They reported that the problem can be overcome by using glass-glass layup module and highly efficient smart bus-wire connection technique. Poulek *et al*. [8] compared the performance of the solar panels using silicone gel and conventional polymer-based encapsulant materials. It was estimated that silicone gel based solar panels would have 50 years lifespan, almost twice of EVA based ones, because of the high durability of the silicone gel. Drabczyk and Panek [9] stated the EVA material is one of the most important components and used in about 80% of the solar panels produced worldwide. It is found that the production, transportation and storage conditions of EVA material greatly affect the cross-linking density in the lamination process. It was concluded that EVA sheets must be stored at the temperature as low as -15°C to achieve an optimum cross-linking density. Badiee *et al.* [10] investigated the effects of different parameters resulting in the thermal degradation of EVA sheets. The transient temperature found to be the key factor causing the most thermal degradation of the EVA and thus the overall performance of the solar panels. Poulek *et al.* [11] designed, developed and compared performance of three different solar panel systems. The bifacial solar panels with silicone gel as encapsulant material and mono crystalline silicon solar wafers were used in the lamination process. About 167% increase in daily production of energy was observed for pseudo parabolic concentrator systems as compared to conventional fixed PV panel systems. Dross *et al.* [12] studied a novel cost-effective method of manufacturing the solar panels especially in third world countries using local materials. They prepared the solar panels with an innovative cast encapsulation-based method where vulcanizing silicone was used to minimize the problem of air trapping during the curing. The layer of vulcanizing silicone also offered an ease in the handling and positioning of cell strings and a proper application of pressure on the cells during the curing thus resulting in less air entrapment. The other advantages of the method reported were no requirement of vacuum, heating and pressing processes. The method requires materials which are easily available in the developing countries.

Hardy *et al.* [13] used polyethylene terephthalate as a replacement of EVA as encapsulant and polycarbonate sheet as a replacement of glass sheet with an objective to develop cheaper PV solar panels. It was successfully demonstrated that the alternative cheaper materials and techniques can still produce high quality solar panels.

Bastari *et al.* [14] presented an automated procedure for grading the quality of polycrystalline silicon solar cells with respect to their electrical characteristics during the lamination process. The method was validated in an experimental investigation and found to give high quality PV solar panels.

According to the authors' knowledge, in Pakistan, an attempt for indigenous manufacturing of solar panels has not yet been made. Currently, in all the projects the PV solar panels are imported. The authors feel that the cottage PV solar panel manufacturing industry has a wide scope in the country. The current study is the first step towards the above-mentioned goal. A small-scale PV solar panel lamination machine is designed and fabricated in the current study and the performance of the PV modules is checked by plotting the I-V curves.

2. COMPONENTS OF PV MODULE

Photovoltaic Solar panel is a composite of 5 layers of different materials as shown in Figure 1.

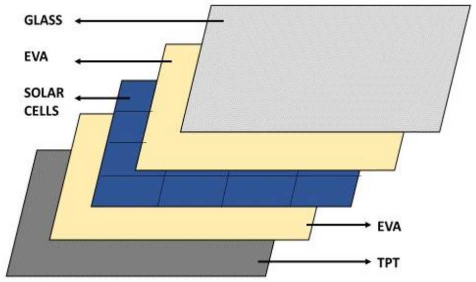


Figure 1. Arrangement of layers of different materials in a PV Solar Panel

In current study, the front face that receives light and the back of the cells are covered with a glass and a plastic sheet

(TPT), respectively. The EVA sheets are used as an encapsulant. The electrical circuit is made with bus wire and tabbing wire and soldered at the solar wafers.

The EVA material starts melting at temperature around 60^{0}C [15] and completely melts at 90-120^{0}C [16]. The curing process is very important to achieve the optimal efficiency as it encounters major structural changes. Glass is the top most part of a PV solar module which receives the solar radiation. The tempered glassed is preferred as it offers high resistance to shock loads. The iron content in glass determines the overall transparency. Lesser the iron content greater will be the transmission of sunlight. The glass sheet may be of thickness ranging between 3 mm to 5 mm. Solar module glass is normally coated with anti-reflective material that reduces the reflection. The glass should be as this thin as possible to keep the panel light weight. In the current work, glass sheets of different thickness were used and compared the mechanical stability of the panels as well as the resistance to the heat transfer during the heating process. The glass sheet of 3 mm thickness was found to be the optimum one with reference to overall strength of the panel and resistance to the heat being transmitted to EVA from heating plate.

3. LAMINATION STYLE

The major processes in the laminating chamber are described. Firstly, vacuum is created in the chamber to evacuate the air which prevents entrapment of air bubbles between the layers of solar module. The vacuum is maintained till the last phase of the lamination process. The presser applies a pressure of 60 Psi with pneumatic actuators. This pressing ensures the proper contact of layers with each other. The presser starts applying the pressure when the vacuum is built and is kept till the curing. A heating plate is used to melt the adhesive material (EVA) which leads to the crosslinking of EVA. Heating is done for 10-20 minutes after which heating plate is turned off. Curing is the key process in which adhesion and optimal transparency between different layers is achieved. Curing takes around 15-40 minutes. At the end of the curing the pressure plate releases its pressure and vacuum is turned off.

4. DESIGN, ANALYSIS AND FABRICATION OF VACUUM CHAMBER

The material selection is the most critical aspect of design. The technical and economic aspects were considered during the material selection for the fabrication of the vacuum chamber used in the lamination process. Ideally the material should be easy to cast, light in weight, economical and should bear thermal and mechanical stresses during the lamination process. The most widely used alloy of 6xxx series is 6061 because of its availability and relatively low cost. Thus, Aluminium 6061 T6 is selected as material for the vacuum chamber since it is solution heat treated and artificially aged to obtain the optimum mechanical characteristics, high resistance to corrosion, workability, weldability and machinability.

The properties of Al 6061 T6 are 276 MPa Yield Strength, 310 MPa Ultimate Tensile Strength, 2700 kg/m^3 Density, 0.33 Poisson's Ratio, 68.9 GPa Young's Modulus.

In the current work, Finite Elements Analysis (FEA) was used to obtain the optimum shape and dimensions of the vacuum chamber. Firstly, a simple cuboidal chamber was analysed, and significant amount of deformations were observed. To overcome this impediment, the ribs of certain thickness were added to the chamber.

The minimum thickness of vacuum chamber wall was calculated using the formula used in the work of Ghule and Bindu [6]

$$t = \frac{cza}{10}\sqrt{\frac{P}{f}} \rightarrow \quad \rightarrow \quad \rightarrow \quad \rightarrow \quad \rightarrow (1)$$

where C, a, P and f represent the number of joints, width of the chamber, external pressure on the chamber and allowable stress of the chamber material, respectively. The design values of these parameters are 0.550 m Width (a), 0.660 m Length (b), 101325 N/m^2 Design Pressure, 276 Pa Allowable Stress.

The factor Z depends on the length b and width a of the chamber and its value is found to be 1.235 at a/b = 0.83 from the graph given in Figure 2.

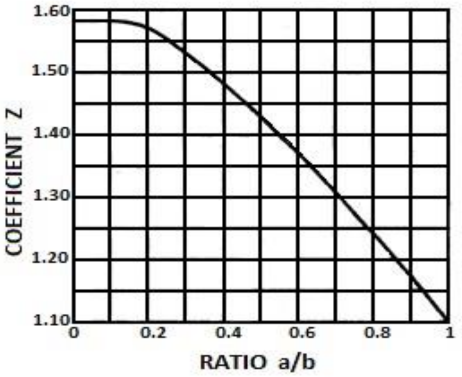


Figure 2. Coefficient Z values plot with respect to the ratio of width to length [17]

Taking C = 1 as the chamber is made in one part, Eq. (1) gives t = 0.013 m. This thickness is determined by just considering the vacuum conditions. Therefore, the thickness used in design was twice of the minimum thickness value to compensate for the thermal load in the chamber.

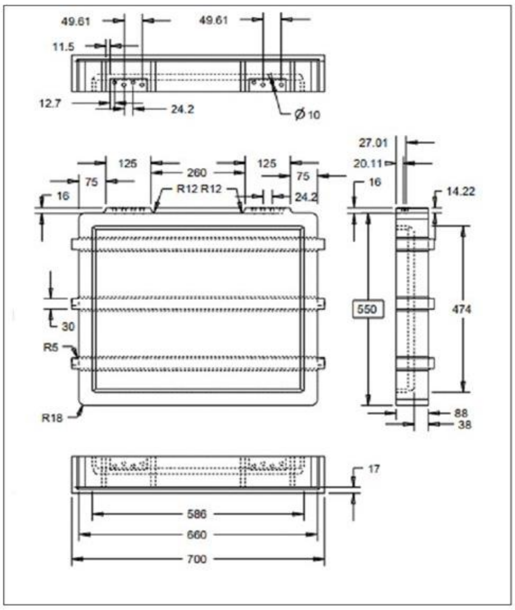


Figure 3. CAD model of vacuum chamber (Orthographic views)

The discretization of the CAD model was done in ANSYS Workbench. The temperature distribution was determined using Thermal Transient module and stresses/deformations were determined using Static Structural module. The properties of the chamber material used in the analysis are the same as of Al-6061 T6 while a summary of the boundary conditions used in the simulations are shown in Table 1.

Table 1. Boundary conditions used in FEA simulations

Simulation	Module	Conditions Applied
Temperature Distribution	Transient Thermal	135°C temperature inside the chamber
		25°C temperature outside the chamber
Stresses & Deformation	Static Structural	External Pressure of 1 atm
		Thermal load from temperature distribution

The FEA analysis of different design configurations of the chamber was done and the design having the least values of stresses and deformations was selected. Firstly, a cuboidal chamber was modelled without ribs. Then three CAD models were made with tibs of varying thicknesses (20 mm, 25 mm, 30 mm respectively) and each model was analysed through FEA simulation.

Table 2. Stresses generated in the chamber & their FOS respectively

Chamber Description	Maximum Stress	FOS
No ribs	264.7 MPa	1.043
20 mm thick ribs	285.3 MPa	0.967
25 mm thick ribs	265.5 MPa	1.039
30 mm thick ribs	225.9 MPa	1.223

It can be seen in the results, that the maximum stress in the chamber was reduced as the rib thickness was increased. The FOS was also increased when the rib thickness was increased and FOS of around 1.223 was observed at rib thickness of 30 mm.

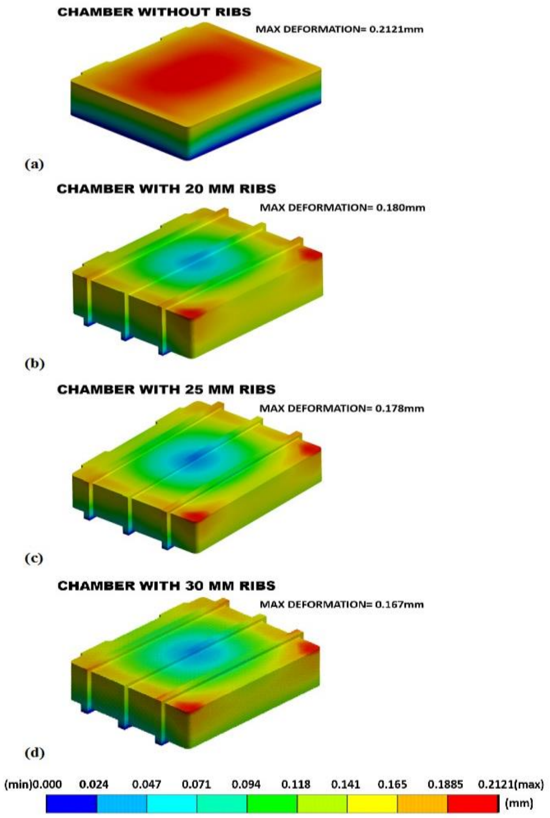


Figure 4. Deformation produced in the chamber

Figure 4(a) shows the deformation produced in the chamber without ribs. It can be seen that a deformation of around 0.212 mm in a major portion of the chamber and a low Factor of Safety (FOS) around 1.043 were observed.

In order to decrease the deformation produced in the chamber, ribs of 20 mm, 25 mm and 30 mm were added to the chamber walls. Figures 4(b), 4(c) and 4(d) show the deformation produced in the chamber with ribs of thickness of 20 mm, 25 mm and 30 mm, respectively. The deformation at the upper and lower portion of the chamber was significantly reduced. The chamber design with rib thickness of 30 mm was selected as it is giving the least values of stresses and deformation and the highest value of FOS. Although, the rib thickness can further be increased in order to enhance the factor of safety. But, adding more material would increase the weight and most importantly the cost of the vacuum chamber which is not required at all. Since, the aim of this study was to produce a low-cost Laminating Machine for the indigenous production of PV panels. The chamber was fabricated through Sand Casting. The milling process was used for the surface finishing and drilling was used to create holes for the hinges. A metallic frame was also built to place the laminator, vacuum pump and mount the other accessories.

In the initial testing of the vacuum chamber, the vacuum condition of about 400-450 mmHg was achieved. Very small pores were found in the chamber, which were causing the leakage of air into the chamber. The problem was detected by connecting the vacuum chamber with air compressor and doing the soap water test. The pores at many points on the surface of the chamber were observed. The possible causes of porosity in Aluminium casting include air entrainment, blow holes, oxides and pinholes as discussed by Monroe [18]. The holes were blocked by applying the high temperature aluminium paint on the outer surface of the vacuum chamber as shown. During the application of paint, the vacuum pump was kept on producing the suction effect, so that the pores get filled completely. After painting, the vacuum chamber was tested again and finally the level of vacuum reached the value of 705-710 mmHg.

5. DIFFERENT SUBSYSTEMS OF THE LAMINATOR

The CAD design of the complete laminator with different sub systems is shown in Figure 5.

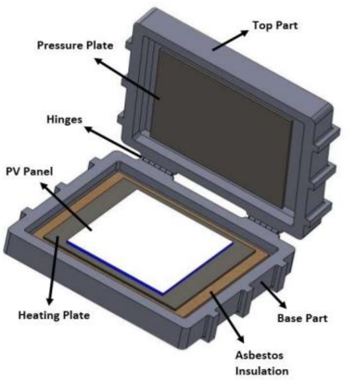


Figure 5. CAD design of the complete laminator

The design and fabrication of these sub systems are described in following sections.

5.1 Vacuuming System

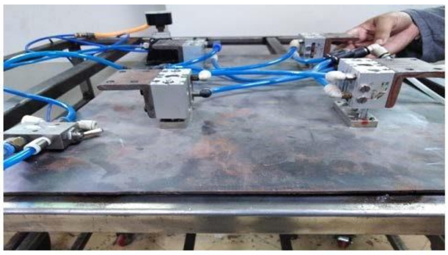
The vacuum chamber is made in two parts which are connected by hinges. The length and width of the vacuum chamber are 660 mm and 550 mm, respectively. The sealing is used between the two parts to maintain the vacuum conditions in the chamber. The different layers of the materials, according to the layup module shown in Figure 1, are put in the chamber. The vacuum was created in the chamber with the vacuum pump. It is done to remove air and other Volatile Organic Compounds (VOCs) produced during chemical reactions. Their improper removal may lead to the formation of bubbles in the PV module. The commercial laminators have upper and lower chambers separated by a flexible silicon membrane, and vacuuming is done only in the lower portion of the chamber while upper portion is filled with atmospheric air which presses and applies pressure on the layers of the module. In the present work, vacuum is produced in the whole chamber and a pneumatic system is devised for applying pressure on the module. The optimum results were obtained at vacuum pressure of around 705 mm Hg.

5.2 Pressure System

In the present work, pneumatic pressure system is used. The limited financial budget of the project restricted the use of complex and expensive pressure systems. The designed pressure system mainly consists of a pressure plate and four air cylinders. The cylinders are mounted on the inner surface of the upper chamber while a 3 mm cast iron pressure plate is attached at the other ends with the help of countersunk bolts. All the connections were made using male connectors and pneumatic pipes. The connections of the pressure plate with the pneumatic actuators and position of the pressure plate in the chamber are shown in Figures 6(a) and 6(b), respectively. The central compressor of Mechanical Engineering Department of NED University of Engineering & Technology was used to control the actuators. The pressure regulating switch was also incorporated to provide compressed air at the desired pressure. The reasons for choosing cast iron plate were its heavy weight and good strength.

5.3 Heating System

The heating system used in the current work is of electric type. A 2kW electric coil was carried inside the heating plate. The size of the plate is 19 x 15 inches, and it is covered with aluminium sheet of thickness 2 mm. The heater takes the temperature of the heating plate to 150°C in around 2 minutes. A temperature controller (FOTEK MT48-R) and a K- Type thermocouple was used to control and measure the temperature during the heating process. The controller automatically shuts off power supply to the heater once the desired value of the temperature is achieved. A single-phase solid-state relay (FOTEK SSR-25 DA) was used to control the thermostat. When the temperature gets lower than the set value, the controller automatically starts the heating plate. The asbestos sheet of 20 mm thickness was used as an insulator between heating plate and the bottom surface of aluminium chamber.



(a)

(b)

Figure 6. (a) Connections of the pressure plate with actuators (b) Position of the pressure plate in the chamber

6. TESTING OF THE LAMINATOR

Figure 7 shows the completely assembled PV panel laminating machine. The stack of glass-EVA-wafers-EVA-TPT was prepared and placed on heating plate. The laminator was closed and made air tight. The vacuum pump was turned on to remove all the air inside the chamber. The pressure was applied using the pressure plate and heating was also done simultaneously. The heating temperature plays a critical role in the lamination process. If the temperature is too low the EVA would not melt down and if the temperature is too high, then bubbles would appear. In the commercial laminators, temperature is normally set between 120-150°C.

Figure 7. Completely Assembled PV Panel Laminating Machine

The ambient conditions play an important role in defining the lamination temperature. The problems of air bubbles in the solar panel, non-uniform melting of EVA, bond breakage and improper crosslinking were observed at different temperature values in the testing phase. The air bubbles were mainly produced at the soldering points of the electric circuit which was due to the non-uniform soldering of tabbing wire on solar cell. To overcome this problem, the soldering was also done with precautions that joints of least and uniform thickness were obtained. This allows a proper and smooth contact of the glass and back sheet with the solar wafers and reduces the problem of glass breakage and bubble formation during the lamination process. The Laminator performance was checked, and suitable range of the operating parameters was found in a series of tests as shown in table 3.

Table 3. Laminating conditions in various tests

Test No.	Laminating Conditions			
	Temperature (℃)	Vacuum (mm Hg)	Heating Time (min)	Curing Time (min)
1	95	705	20	20
2	98	705	18	22
3	150	705	15	18
4	100	705	15	40
5	120	705	6	30
6	120	705	10	36
7	120	705	10	22

In first two tests, the set temperature was quite low, and the EVA remained un-melted at some points. Also, the pressure was applied simultaneously with the formation of vacuum which resulted in the air entrapment. In third test, the vacuum was created first, then the heating plate was turned on, and pressure was applied through the pressure plate when the temperature exceeded the melting point of EVA (i.e. 63˚C) to prevent the air entrapment. The module was heated to 150˚C for 15 minutes and the results found were drastic. The melting of EVA was non-uniform and the crosslinking was affected because of the bond breakage due to high temperature. Ultimately, EVA lost its transparency that is achieved after crosslinking of EVA with solar cell. The temperature was then lowered to 100˚C in the fourth test, but the EVA was still not melted at some points and the bubbles were observed. Although, the curing time was significantly increased in this attempt, but improper melting of EVA resulted in the bubble formation. From fifth test, the temperature was set to 120˚C and changes were made in heating and curing time to get the optimum results. Also, the layers were pressed by pressure plate once the heating plate reached the temperature of 95˚C. This allows proper contact of melted EVA with solar wafers, glass and back sheet, and the problem of air bubbles was significantly reduced. The pressure plate's pressure was set constant to 60 Psi. The values of the other parameters used during the lamination and outputs of the final panel are summarized in Table 4.

Table 4. Laminating conditions and output of the final panel

Laminating Conditions	
Temperature	120°C
Vacuum	705 mmHg
Pressure	60 Psi
Heating Time	10 mins
Curing Time	20 mins
Panel Output	
Open Circuit Voltage	3.4 Volts
Short Circuit Current	1.21 Amp

The temperature and vacuum curves of the final panel is shown in Figure 8. The performance of the panel is investigated by plotting the I-V curve as shown in Figure 19. The maximum power point of the panel is when the open-circuit voltage and short-circuit current are 3.4 V and 1.21 A, respectively. The fabrication cost of the complete laminating machine is around PKR 350,000/- while the production cost of the PV panel produced from this machine is PKR 37 per Watt. The solar panels available in the market cost around PKR 45-200 per Watt.

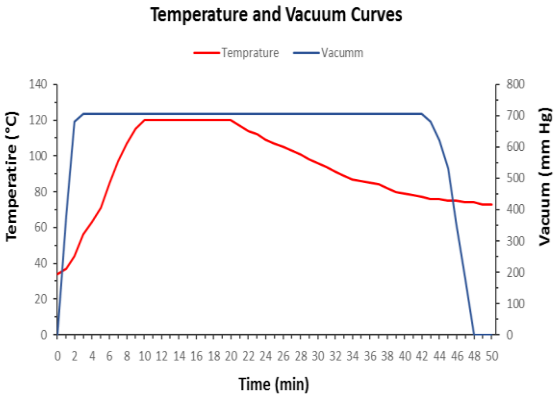


Figure 8. Temperature and vacuum curves of the final panel

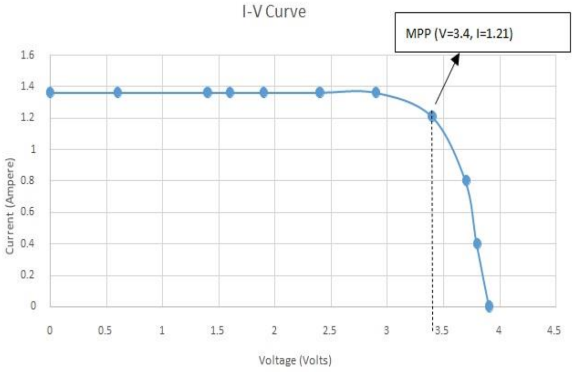


Figure 9. I-V curve of the final panel

7. CONCLUSIONS

The current work presents the first study for an indigenous production of the PV solar panels in Pakistan. A small-scale lamination machine is designed and fabricated using material and facilities available locally. CAD modelling and FEA analysis were used to design an optimum vacuum chamber. The ribs of 30 mm thickness were used at the outer surface of the vacuum chamber to avoid excess stresses and deformations. The vacuum, pressing and heating systems were designed and developed. An optimum combination of vacuum pressure, presser pressure, heating temperature, heating time and curing time were found using a series of tests to produce high quality PV solar panels. The output performance of the PV solar panels was found to be satisfactory. The study shows a successful production of the PV panel using only the local materials and facilities. The laminating machine can be scaled up depending on the size of the required panels.

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