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Design and simulation of components of vacuum forming machine using household vacuum cleaner

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Abstract

Plastic products ranging from toothbrushes to smartphones are an inseparable commodity in daily human life and their impact cannot be underestimated. This paper aims to design and simulate the vacuum forming process using readily available materials in context of Nepal. Vacuum forming process is a thermoforming process where the heated plastic sheet derives the shape of the mold through the application of vacuum and is used to make packaging products and other household products. Simulations were done to find out the optimum distance between the plastic sheet and the heater, arrangement of the wire in the heater, load bearing capacity of the design and the flow of vacuum in the arrangement. Nichrome wire coiled as heater coil is used as the heating material and laid in a spiral path with the plastic sheet 35mm below provided the best heating results and 1800W vacuum cleaner provided the necessary pressure of 85-90kPa and velocities of 100-115m/s while the steel posts provided adequate strength.

Keywords: *Coiled heater, mold, vacuum forming process, household vacuum cleaners*

1 Introduction

Plastic is material consisting of any of a wide range of synthetic or semi-synthetic organic compounds that are malleable and so can be molded into solid objects. Plastics have been in use in almost every aspect of our lives. Plastics due to their low cost, ease of manufacture, versatility, and imperviousness to water, are used in as many products of different areas, ranging from paper clips to spacecraft. They are specially used in area of packaging and home piping. (Science History Institute, n.d.).

Amongst the various methods of processing plastics, vacuum forming is one of the most common methods for making plastic products. The process involves heating a plastic sheet until soft and then draping it over a mold. A vacuum is applied sucking the sheet onto the mounds. Using prototypes for the mounds makes it economically feasible to produce low quantities of large parts and to operate medium size production runs. The sheet is then removed from the mold. As low pressures are used, the vacuum forming process is a low-cost process. (Awari Mahesh Prakash, 2016). Low vacuum pressures available through vacuum pumps/ cleaners, heating through ceramic heating wires and easy availability of plastic sheets make vacuum forming process suitable for low cost operations. (Sumit G. Wankhade, 2018)

With the significant advantage of low cost initial setup and operation, the paper aims to design a vacuum forming machine and simulate the various components for best specification and configuration.

2 Methodology

This study follows a methodological flow chart as shown in Fig. 1.

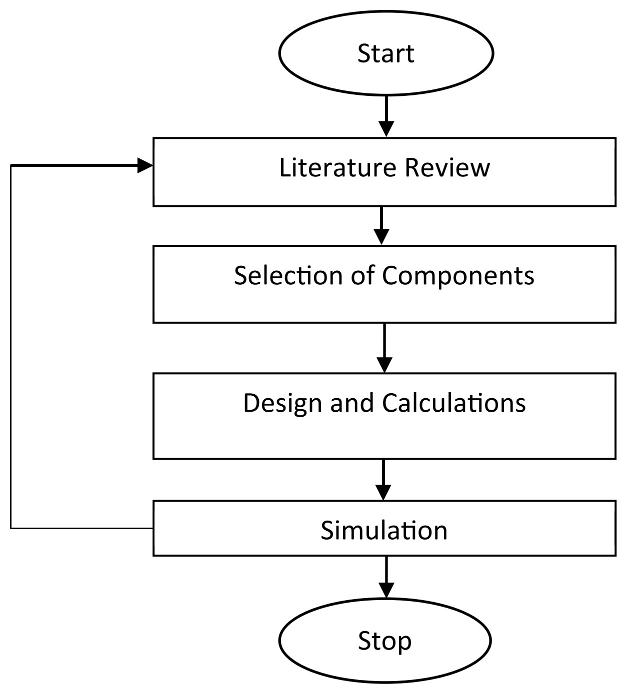

Figure 1: Study design

2.1 Working Principle

The vacuum forming process is explained as follows and depicted in Fig. 2.

a. The vacuum forming tool or mold is loaded in to the vacuum forming machine and warmed

b. The plastic material, in sheet form, is loaded on to the vacuum forming machines material clamp.

c. Heaters, located above the sheet, then heat the sheet of vacuum forming material until it softens.

d. An automatic levelling device then supports the softened sheet of vacuum forming material with air.

e. The mold is either raised to meet the bottom surface of the sheet of material or the clamp is lowered and a vacuum of air is applied in order to draw the sheet over the shape of the vacuum forming tool (mold).

The plastic is cooled with air to set hard. The vacuum forming can be removed by hand or with the use of air to carry out any necessary secondary operations e.g., trimming (by hand). (Toolcraft Plastics, n.d.)

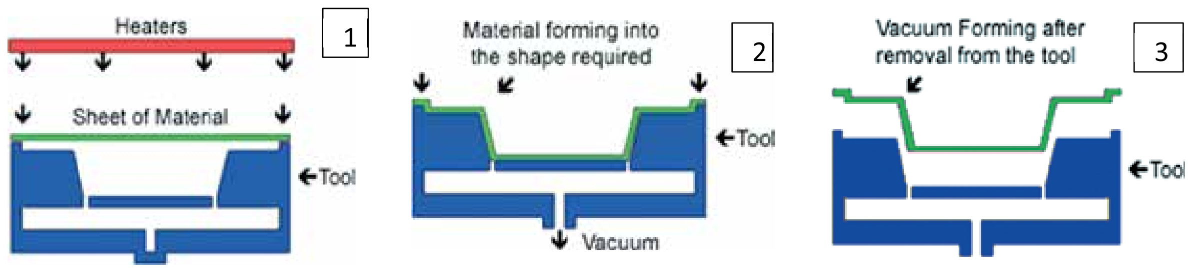

Figure 2: Vacuum forming process : 1-sheet of plastic is heated, 2-heated plastic takes shape of mold, 3-plastic sheet is removed (PVC Plastic Sheets, n.d.)

2.2 Components

The major important components in this process are:

- Clamp: The clamp holds the plastic sheet to be formed. It can be made from wood. (Gringery, 1999)
- Heaters: The heaters will heat the plastic sheet to temperatures ranging from 80°C to 140°C through radiation. (Gringery, 1999)
- Mold: The mold provides the shape of the product. Molds can be made from aluminum, wood, fiberglass etc. The mold has holes so that the air can be sucked out of the mold when the material forms creating vacuum. (Gringery, 1999)
- The Vacuum System: Vacuum pumps are used to suck the air out of mold. The vacuum pumps should be able to main a pressure under 1 bar, approximately -0.83 bar. (Gringery, 1999)
- Plastic Sheet: The material of the plastic sheet is to be determined so as to heat the sheet accordingly to its forming temperature. (Gringery, 1999)
- Trimming Tools: After the sheet is formed and released, it needs to be trimmed to remove the unnecessary parts of the sheet and get the required product Depending on the thickness of the sheet, snippers to chisels may be used. (Gringery, 1999)

2.3 3D Modelling

The heating chamber consists of nichrome wire in loops that will heat the plastic sheet. The clamps will hold the plastic sheet and will allow for the movement of plastic sheets. The vacuum table consists of holes which will create the necessary suction pressure for the vacuum to be applied. The vacuum to be created is to be applied through the vacuum input hole as shown in Fig. 3.

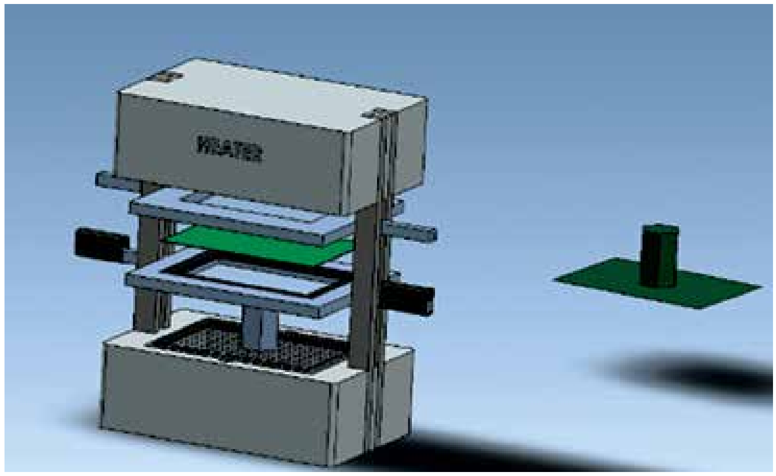

Figure 3: CAD model

2.4 Selection of Components

The major aspects that determine the quality and efficiency of the process are:

i. The selection of heating source
ii. The vacuum created
iii. The time of heating for the plastic to be used

2.4.1 Selection of heating source

For automatic vacuum forming system in industries for mass production, quartz heaters with pyrometer are used as it has less thermal mass compared to other heaters. (Science History Institute, n.d.)But for low cost initial setup, ceramic heater can be taken as a better option. Ceramic heaters consist of coiled resistance wire (such as Nichrome, Kanthal, and Constantan) elements set in molded china clay or ceramic. Due to following properties of ceramic heater, it is a better option compared to other heaters;

1. Slightly more thermal mass compared to quartz heater but has comparatively less thermal mass than other heaters.
2. Available in round, square or rectangular shapes, they can be flat (for maximum proximity) or curved (to provide a parabolic reflector which radiates more effectively).
3. They radiate long wavelength heat which is readily absorbed by thermoplastics.

2.4.2 Selection of vacuum source

The vacuum to be created depends upon the thickness of plastic sheet. The atmospheric pressure is 101700 Pa. (Metrological Forecasting Division, 2020) Generally, the vacuum generated by vacuum cleaner of 1400 Watts to 1800 Watts is about 98,205 Pa to 88,046 Pa. (Gringery, 1999). The aim of vacuum (P) is to create the drag force (F) through the hole of area A in the vacuum table. The drawing force of vacuum is given by,

$$F=P\times A \tag{1}$$

For 'n' no of holes, the vacuum pressure is given by,

$$F=n\times P\times A \tag{2}$$

The vacuum cleaner to be used will be 1800-Watt drum vacuum cleaner having suction power of 350 W.

Table 1: Plastic and thier properties

S N	Plastic Type	Properties	Forming Temp. (°C)	Colors	Price	Applications	Availability
1.	Acrylonitrile Butadiene Styrene (ABS)	• hard, rigid, good impact strength and weather resistance • available in different texture and finishes • good formability	105	L	U	luggage, sanitary parts, electrical parts	R
2.	Copolyster (PETG/ VIVAK)	• Easily forming, good impact strength • transparent	120-200	L	E	Medical; food	U
3.	Polycarbonate (PC/ Lexan)	• Hard, rigid, high impact resistance, • good formability, • translucent	150	A	E	Light diffusers, signs, machine guards	Y
4.	Polypropylene (PP)	• High forming temperature • good impact strength • Sheet sag is inevitable	105-180	L	I	Food containers, toys, tanks	Y
5.	Polyethylene (PE)	• Successful forming • Good impact strength	140-196	A	I	Caravan parts, vehicular parts, enclosures, housing	Y
6.	Polyvinyl chlorine (PVC)	• Strong & tough thermoplastics • Transparent in thin gauge • Good impact strength, fire resistive	110-140	A	I	Packaging, machine guards, car tyres	Y
7.	Polystyrene (PS/HIPS)	• Homopolymer • Transparent • Rigid brittle, poor UV resistance • Low impact strength but high tensile strength (35-55 MPa)	100	A	I	Food packaging, medical applications, electronics, cosmetic, cups, container	Y

A-Any, E-Expensive, I-Inexpensive, L-Limited, R-Rare, U-Unclear, Y-Yes

2.4.3 Selection of plastic sheet

PVC is selected as the material of choice for the purposes of this study because of its availability in sheets, inexpensiveness and relatively easily attainable forming temperature of 110°C. Properties of various types of plastics are summarized in Table 1 and material selection for various components in Table 2.

Table 2: Material selection of components

S.N.	Component	Material	Description
1	Vacuum Source	Vacuum Cleaner	1400-watt drum vacuum cleaner capable of 350 watts suction pressure
2	Heat Source	Nichrome wire coil	1400 watts Length of wire: 10 m
3	Plastic Sheet	PVC sheet	Thickness: 1 mm Size: 270 mm × 210 mm
3	Heating Chamber & Vacuum Table	Aluminum Plate / Ply board	Holes in vacuum table to be made through drilling
4	Pillar	Square steel hollow tube	
5	Clamp	Mild Steel Plate	

2.5 Wire Calculations

Nichrome wire was selected as the heating material in this project owing to its thermal properties and availability.

2.5.1 Wire dimension calculations

The heater coil is to be formed from a nichrome wire. For purposes of the project simulation, the dimensions of nichrome wire are assumed as:

Diameter of heater coil	D=20 mm
Diameter of heater coil wire	d=1.016mm=18 AWG
Total length of heater coil wire	l=10m≈32ft
Length in one turn	$l_1 = \pi(D-d) = 19\pi$ mm
No of turns	$N = \frac{l}{l_1} = 168\ turns$

2.5.2 Power generated by nichrome wire

The wire is to be coiled up and laid in a path and let the wire maintain a temperature of over 500°C using normal AC current.

So, resistance of wire, $R=13.5\Omega$

If the temperature is to be maintained at 538°C (Hotwireformcutterinfo, n.d.), then current, $I=10.1\ A$

From Ohm's law, operating voltage is

$V = I \times R = 10.1 \times 13.5 = 136.35\ V$

From Joule's law, power output is

$P = I \times V (3) \qquad (3)$

$= 136.35 \times 10.1$

$= 1377.22$ W

2.6 Heat Transfer Calculations

Vacuum forming is a thermoforming process where the plastic sheet is heated to its forming temperature and then processed over the mold by vacuum. Heat is transferred from the heating source to the plastic sheet. Heat is transferred from the wire usually through radiation. The three modes of transfer of heat are conduction, convection and radiation. The numerical analysis is done to find out the medium of heat transferred. The setup is as shown in Fig. 4.

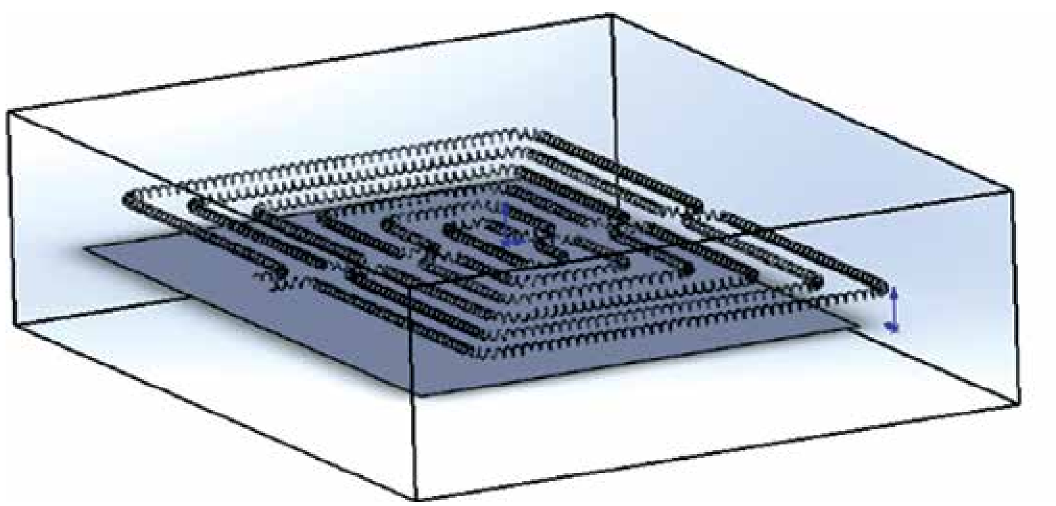

Figure 4: Set-up in CAD model

The coil is made from nichrome and is heated to temperatures around 538°C with the PVC plastic sheet placed 2cm below as shown in Fig. 5. Both the coil and plastic sheet are in the dimensions of A4 (297mm x 210mm). The atmospheric temperature is assumed to be a 25°C. The coil is assumed as a screen or a horizontal surface with lower side hot because the coil heats the plastic sheet placed at its bottom and the upper part of the coil is placed on an insulated rack.

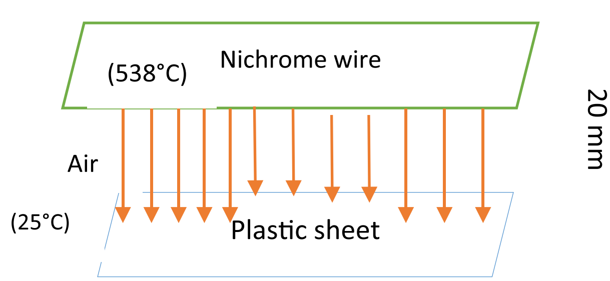

Figure 5: Schematic diagram showing arrangements of Nichrome wire and plastic sheet

2.6.1 Heat transferred by convection

The lower surface of the coil gets heated to temperatures of around 538°C. This causes the air in contact with the surface to flow leading to heat transfer by convection. Since, no fans are used, it is natural convection. Also, the coil is assumed as horizontal surface having hot bottom side with the dimensions of A4. For horizontal surface facing downwards, the characteristic length is

$$L_c = \frac{Surface\ Area}{Perimeter} \qquad (4)$$

$$= \frac{297 \times 210}{2(297 + 210)} = 61.508\ mm$$

$$= 0.0615\ m$$

Surface temperature is $T_s = 538℃$ and the atmospheric temperature is $T_\infty = 25℃$

Film temperature is

$$T_f = \frac{538 + 25}{2} \qquad (5)$$

$$= 291.5℃$$

$$= 554.5\ K$$

At film temperature for dry air properties values are (C.P. Kothandaraman, 2007)

Dynamic Viscosity	$\upsilon = 44.41e - 6\ m/s$
Prandtl Number	$\mathrm{Pr} = 0.676$
Thermal Conductivity	$k = 0.04465\ W/mK$
Coefficient for thermal expansion of air	$\beta = \frac{1}{T_f} = \frac{1}{554.5} K^{-1}$

The Rayleigh number is

$$Ra_L = \frac{g\beta(T_s - T_\infty){L_c}^3 Pr}{\nu^2} \qquad (6)$$

$$= \frac{9.81 \times (538 - 25) \times 0.0615^3 \times 0.676}{554.5 \times 44.41e - 6^2}$$

$$\therefore Ra_L = 7.23e5$$

Nusselt's number is

$$Nu = 0.27{Ra_L}^{0.25} \qquad (7)$$

$$= 7.87$$

Coefficient of thermal convection is

$$h = \frac{k}{L_c} Nu \qquad (8)$$

$$= 5.71\, W/m^2K$$

From the schematic diagram in Fig. 5, the heat transfer can be analyzed by steady state analysis (please refer Fig. 6) as the temperature difference remains constant.

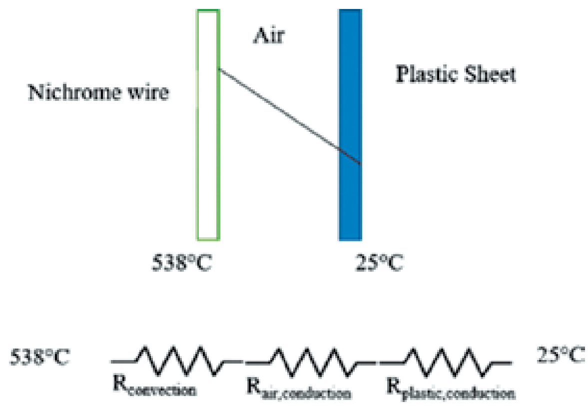

Figure 6: Steady state analysis for convection

Area is A=.297×.210=0.06237 m^2

Length of air film, ,l_a=20 mm=0.02 m

Length of plastic sheet, l_p=1mm=10^{-3} m

Thermal conductivity of air at 25°C,

k_a=0.02634 W/mK

Thermal conductivity of PVC,

k_p=0.19 W/mK

Coefficient of convection,

h=5.71 W/m^2 K

Total resistance is

$$R_{total}=R_{convection}+R_{air,conduction}+R_{plastic.conduction} \qquad (9)$$

$$= \frac{1}{A}\left(\frac{1}{h} + \frac{l_a}{k_a} + \frac{l_p}{k_p}\right)$$

R_{total}=15.07 °C/W

The total heat transfer by steady state is

$$\dot{Q}_{ss} = \frac{\Delta T}{R_{total}} = \frac{538 - 25}{15.07} \qquad (10)$$

$$\therefore \dot{Q}_{ss} = 34.03\ W$$

2.6.2 *Heat transfer by radiation*

The setup is as shown in the schematic diagram in figure4 The various values are as follows

Temperature of nichrome wire	$T_1 = 538°C = 811\ K$
Temperature of plastic sheet	$T_2 = 25°C = 298K$
Area (A4 size)	$A = 0.06237\ m^2$
Emissivity of nichrome (C.P. Kothandaraman, 2007)	$\varepsilon_1 = 0.98$
Emissivity of plastic sheet (C.P. Kothandaraman, 2007)	$\varepsilon_2 = 0.91$
Stefan-Boltzmann constant (C.P. Kothandaraman, 2007)	$\sigma = 5.67 \times 10^{-8} W/m^2K^4$
Shape factor (C.P. Kothandaraman, 2007)	$F_{12} = 0.905$

Hence, the heat transferred by radiation is

$$\dot{Q}_{rad} = \frac{\sigma({T_1}^4 - {T_2}^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A} + \frac{1}{F_{12}A} + \frac{1-\varepsilon_2}{\varepsilon_2 A}} \qquad (11)$$

$$= 1226.8\ \mathrm{W}$$

From above calculations it can be seen that radiation is the main mode of heat transfer rather than convection.

Hence, the effectiveness of the heating setup can be calculated as

$$\epsilon = \frac{\dot{Q}_{rad} + \dot{Q}_{ss}}{P} \qquad (12)$$

$$= \frac{1226.8 + 34.03}{1377.22}$$

$$= 0.915 = 91.5\%$$

3 Radiation Simulation

The radiation simulation was performed for the vacuum forming machine for the following purposes:

- to understand the spread of heat in the plastic sheet due to different wiring path configurations
- to find out the optimum distance between the coil and the plastic sheet

Different wire path configurations affect the temperature distribution in the plastic sheet. The variation of distance affects the amount of heat to be absorbed by the plastic sheet and also, the variation helps to control the heat and thus minimize the risk of melting of plastic sheet.

3.1 Simulation for Wire Path Configuration

3.1.1 Setup

Nichrome wire, which is the heating element in the machine delivers 900W to the plastic sheet placed parallel 2cm below. Due to computing issues, the whole solenoid structure of the wire is not used for the simulation, rather a wire of the same diameter and the path structure were used. The simulation tested spiral path, double spiral path and longitudinal path structures of a 12 AWG (2.05 mm) nichrome wire. The setup is as in Fig. 7.

Figure 7: Set-up for wire configuration

3.1.2 Results

The simulation was done in Solidworks Flow Simulation to find out the spread of heat in the plastic sheet due to different wire paths. From the setup as mentioned above following results (Fig. 8, Table 3) were found:

As the plastic sheet, placed on clamps, gets heated, the sheet expands and drags downwards until it melts. Obviously, due to gravity, the centre most part of the sheet would drag down the most. At both spiral and longitudinal paths, the maximum temperature was above 200℃ at the centres with longitudinal having a larger area above this temperature. So, both wire path configurations are very risky to be used in heating the plastic sheet due to the risk of melting. However, in the double spiral wire configuration, the heat is unevenly divided and is maximum at the centres of each quadrant of the plastic sheet which poses the risk in melting at these sites.

So, considering the risk of melting, the spiral wire configuration is concluded to be used as it offers a minimum area for melting of plastic sheets.

3.2 Simulation for Distance Between Coil and Plastic Sheet

3.2.1 Setup

In this simulation the nichrome heating coil is made into a spring of diameter 2cm and free length of 5cm with pitch of 5mm. So there are 10 turns in the setup coil. The diameter of wire of spring is 1.016mm i.e., 18AWG as in other previous simulation and this wire is heated to 538°C or 811 K. Following this, the plastic sheet and the coils were arranged for different vertical distances. The simulation was done for 2cm, 5cm, 8cm and 10cm distances. Likewise, the material of wire is nichrome and the plastic sheet is PVC and the default values of emissivity were given as in solid works. Emissivity for nichrome and PVC was 0.98 and 0.91 respectively. The simulation was done in Solidworks Flow Simulation.

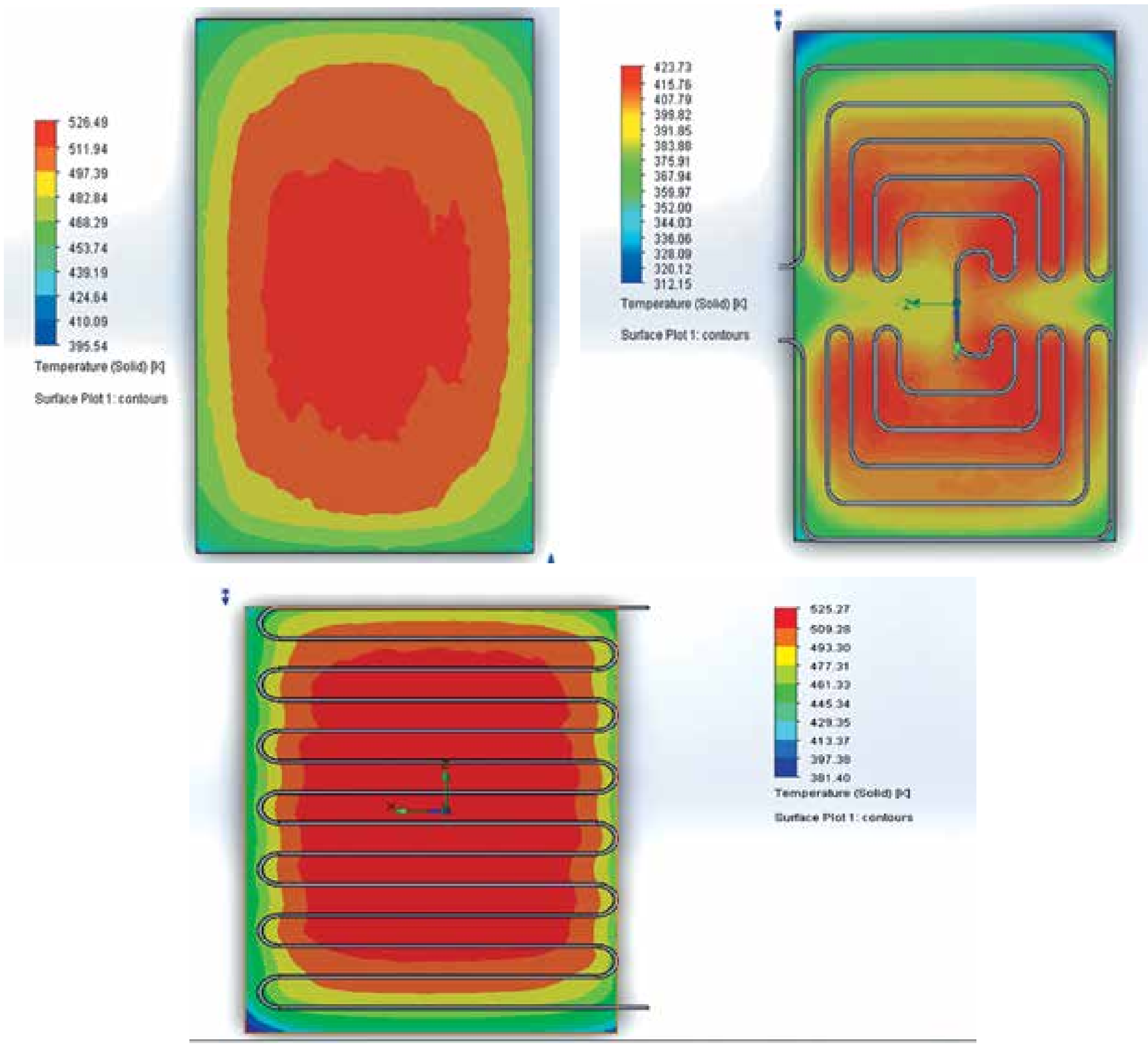

Figure 8: Simulation result for spiral coil (top left), double spiral coil (top right) and longitudinal coil (bottom)

Table 3: Simulation results for wire path configuration

Coil path	Max Temp (°C)	Min Temp (°C)	Heat distribution
Spiral	252	122	Maximum at center and gradual decrease to the outer sides
Double spiral	150	39	Maximum at the centre of each quadrants and heat is distributed as kidney shaped
Longitudinal	252	108	Maximum at center at an larger area than spiral coil

3.2.2 Result

The simulation results are summarized in Table 4 and visualized in Fig. 9 and Fig. 10.

Table 4: Simulation results for distance between coil and sheet

Coil-sheet distance	Max Temp (°C)	Remarks	Forming temperature spread (regions above 110°C)
2cm	190	Above forming temperature	50 mm along the path of wire
3.5 cm	124	In forming temperature range(110-140 °C)	30mm along the path of wire
5cm	103	Below forming temp	-
8cm	30	Below forming temp	-
10cm	30	Below forming temp	-

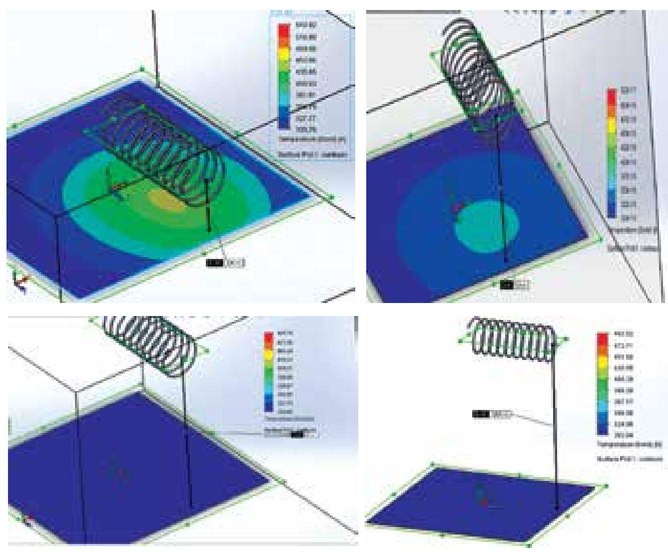

Figure 9: Simulation results for 2cm (top), 5cm(top right), 5 cm(bottom left) and 10cm(bottom right)

From above simulations following can be concluded:

- 2cm-3.5cm is the best distance between the coil and plastic sheet to reach the forming temperature
- Distances above 3.5cm result in heating of plastic sheet below its forming temperature
- Considering the width of temperature distribution in plastic sheet, 3.5 cm results in a lower area of temperature above 110°C while 2cm results in larger area, so 3.5 cm distance can lower the risk of melting of PVC.
- Since, PVC melts at 150°C, heat transferred by 2cm distance resulted in temperatures of 195°C leading to maximum chances of melting of plastic sheet. However, the maximum temperature offered by 3.5 cm is 124°C, so 3.5 cm distance is the safest option to prevent melting of plastic sheet.
- Hence, it can be concluded that 3.5cm is the best vertical distance between the plastic sheet and the coil.

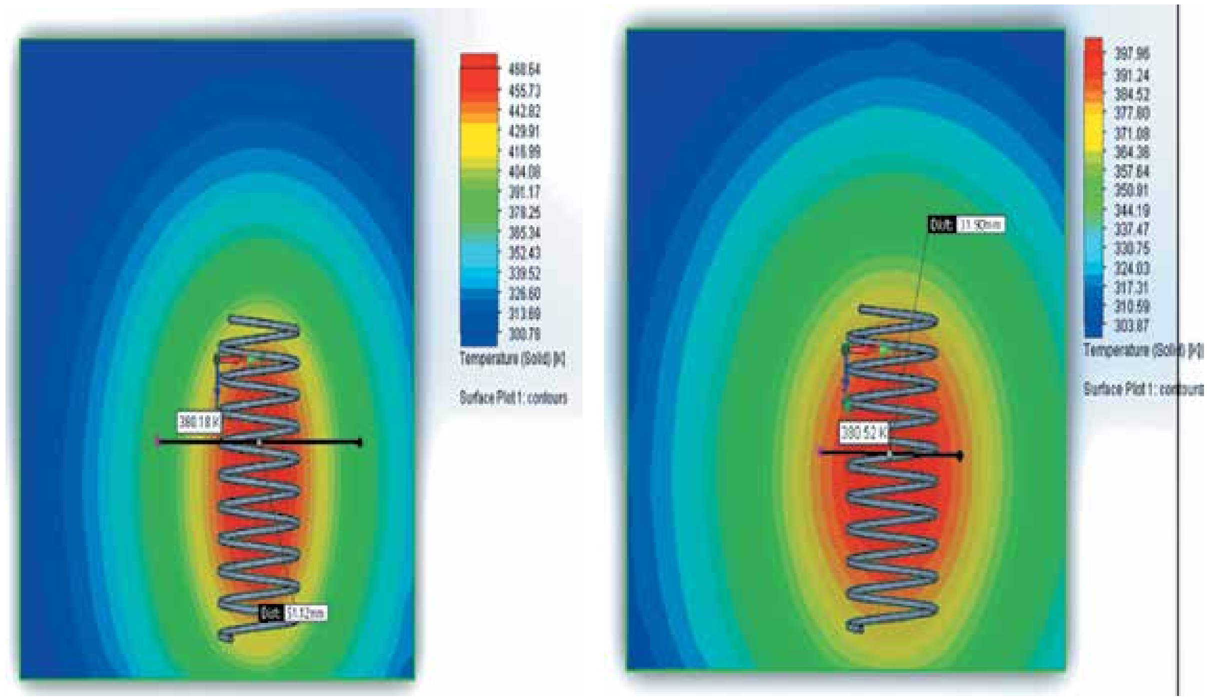

Figure 10: Temperature distribution in 2cm (left) and 3.5cm (right)

4 Fluid Flow Simulation

The fluid simulation was performed for vacuum forming machine for the following purposes:

- to understand the velocity distribution from several input to single output
- to find out pressure distribution

Different values of velocity and pressure of a vacuum for suction has different behavior for final product and also, these wide range of values helps to control the suction pressure to get best version of the final product.

4.1 Calculations

Considering the vacuum cleaner works at full efficiency (i.e., there are no losses), the fluid flow can be analyzed using Bernoulli's equation.

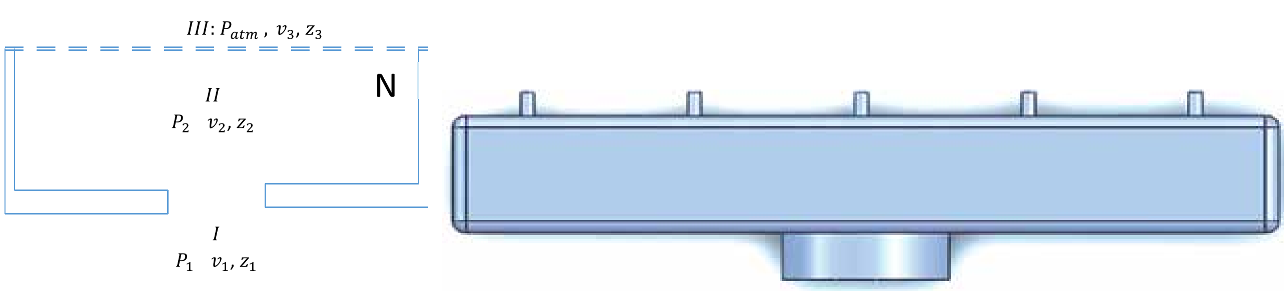

Figure 11: Schematic diagram and CAD diagram

In the schematic diagram (Fig. 11), I, II and III represent the regions of setup at the inlet of the vacuum hose, inside the vacuum chamber and at the holes respectively with P, v and z representing the pressure, velocity and the height at the concerned regions respectively

Corresponding areas in respective regions as per CAD design. Known parameters for calculation and areas of different regions are shown in Table 5 and Table 6.

Table 5: Known parameters for calculation

I Region		II Region		III Region	
P_1	83.2 kPa (Total 1400 Watt Vacuum Cleaner TVC14301, n.d.)	P_2	-	P_{atm}	101.2 kPa
v_1	-	v_2	-	v_3	-
z_1	0 m	z_2	0 m	z_3	0.05 m

Table 6: Areas of different regions

Region	Dimensions	Area
I	Diameter = 60 mm	$A_1 = \pi \times 60^2/_4 = 2827.43mm^2 =$ $2.827e-3\ m^2$
II	Length & breadth of A4 size	$A_2 = 297 \times 210 = 62370\ mm^2$
III	15 holes of diameter=5 mm	$A_3 = 15 \times \pi \times 5^2/_4 = 294.52\ mm^2$

If in the setup, a vacuum cleaner with suction flow rate of $1.9 m^3/min$ (Total 1400 Watt Vacuum Cleaner TVC14301, n.d.)is used, which is connected to the vacuum hose inlet i.e., region I, then the velocity at the inlet is

$$v_1 = \frac{1.9\ (m^3/\text{min})}{2.827e-3(m^2) \times 60(sec/min)} = 11.2\ m/s$$

Since no losses are assumed, we can use the continuity equation i.e., the mass flow rate remains constant. However, air gets compressed at the holes and the density decreases. Considering the fluid flow in vacuum cleaners, the effect of density of air is assumed to be negligible. Hence the analysis is done using constant volumetric flow rate.

Since, there is only one inlet region and one outlet region, from continuity equation, we have,

$$v_1 A_1 = v_3 A_3 \tag{13}$$

$$or, v_3 = \frac{11.2\ m/s \times 2827.43\ mm^2}{294.52\ mm^2} = 107.52\ m/s$$

In regions I and II, applying Bernoulli's equation, we get

$$\frac{P_1}{\rho} + \frac{{v_1}^2}{2g} + z_1 = \frac{P_2}{\rho} + \frac{{v_2}^2}{2g} + z_2 \tag{14}$$

Since, $z_1 = z_2$, i.e., both are at same height

$$\frac{P_2}{\rho} = \frac{P_1}{\rho} + \frac{{v_1}^2}{2g} - \frac{{v_2}^2}{2g} \tag{15}$$

In regions II and III, applying Bernoulli's equation, we get

$$\frac{P_2}{\rho} + \frac{{v_2}^2}{2g} + z_2 = \frac{P_{atm}}{\rho} + \frac{{v_3}^2}{2g} + z_3 \tag{16}$$

Using (15) in above we get

$$\left(\frac{P_1}{\rho} + \frac{{v_1}^2}{2g} - \frac{{v_2}^2}{2g}\right) + \frac{{v_2}^2}{2g} + z_2$$

$$= \frac{P_3}{\rho} + \frac{{v_3}^2}{2g} + z_3 \tag{17}$$

$$\frac{P_1 - P_{atm}}{\rho} = \frac{{v_3}^2 - {v_3}^2}{2g} + z_3$$

Applying values from table 1, we get

$$\Delta P_{I-III} = \rho\left[\frac{{v_3}^2 - {v_1}^2}{2g} + 0.05\right]$$

Applying values of velocities from above and density of air as 1.23 kg/m^3, we get

$$\Delta P_{I-III} = 1.23\left[\frac{107.52^2 - 11.2^2}{2 \times 9.81} + 0.05\right] = 0.72\ kPa$$

So, the pressure difference due to the velocities is just 0.72kPa.

Also, there is a sudden expansion of area from region III to II and the corresponding head loss is

$$h_{L-e} = \frac{{v_3}^2}{2g}(1 - \left(\frac{A_3}{A_2}\right))^2 = 0.584kPa$$

Also, there is sudden contraction of area from region II to I and the corresponding head loss is

$$h_{L-c} = K\frac{{v_1}^2}{2g}$$

For $A_1/A_2 = 0.04$, K = 0.45 (Losses Due to Sudden Contraction, 2021), hence,

$$h_{l-c} = 2.87\ Pa$$

So, the total pressure difference is

$$P_{total} = \Delta P_{I-III} + h_{l-c} + h_{L-e} = 1.307\ kPa$$

4.2 Simulation

For the setup of fluid simulation, vacuum section is divided into simple elements that can be used as discrete local approximation, generally known as mesh as shown in Fig. 12. These influences the accuracy, convergence and speed of simulation. For this section, there are 73,927 nodes and 387,314 elements.

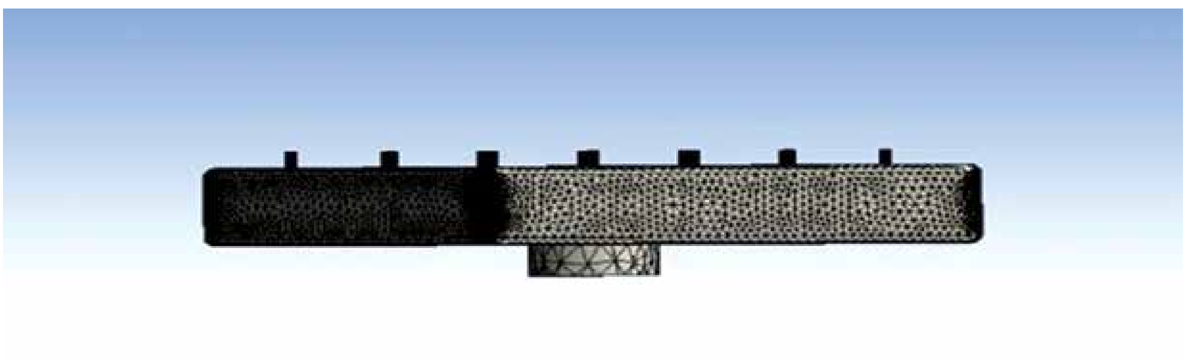

Figure 12: Meshing of CAD model

4.3 Results

In the vacuum section, the maximum velocity of 111.7 m/s was recorded at the tip of the hole. The velocity variation can be seen unevenly distributed from input to output. Similarly, the maximum pressure of 86,150 Pa was recorded ar the wall. The pressure variation can be seen as shown in figure 34. Also, the minimum pressure was 85,040 Pa recorded at the entry holes. The pressure diffrence is 1.1 kPa. The pressure deviations found theorotically was 1.3 kPa. The results are depicted in Fig. 13.

5 Structural Simulation

5.1 Calculation for Steel Pillar

Here,

Modulus of elasticity of steel,

$E=2.14\times10^{11}\ N/m^2$

Cross sectional area, $A=40\times20\ mm^2$

$=800$ mm^2

Assume, Applied load, P =10 N

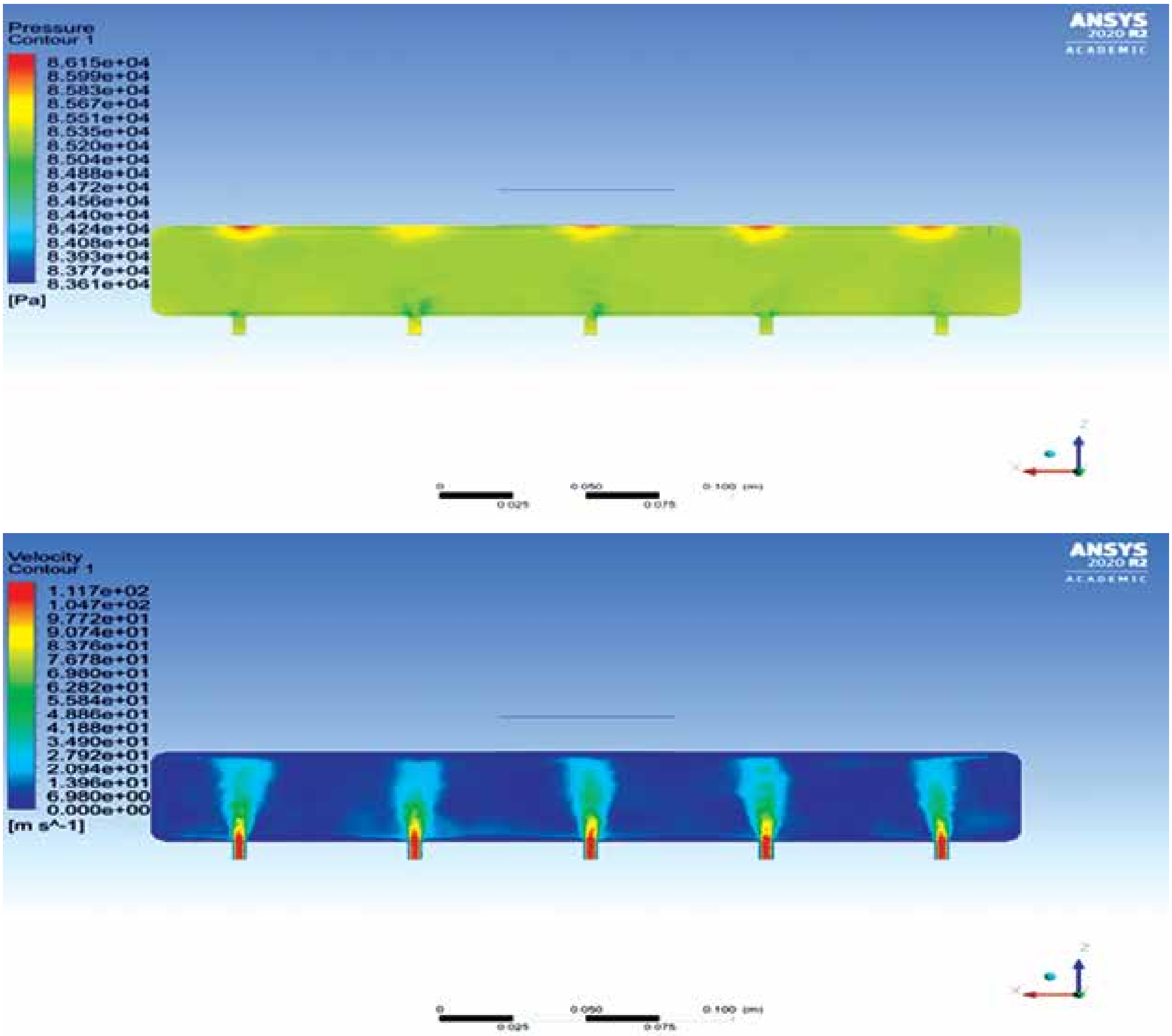

Figure 13: Fluid flow simulation results for velocity(above) and pressure(below)

We know that stress, $\sigma = \frac{\mathrm{p}}{\mathrm{A}} = \frac{10}{800} = 0.0125\ N/m^2$

Again,

$$\mathrm{E} = \frac{stress}{strain}$$

$$\text{Strain} = \frac{\sigma}{E}$$

$$\frac{\partial l}{\mathrm{l}} = \frac{\sigma}{E}$$

$$\partial l = \frac{\sigma \times l}{E} = \frac{0.0125 \times 600}{2.14 \times 10^{11}}$$

$$\partial l = 3.5046 \times 10^{-5}\ mm$$

So, the total deformations are $3.5046 \times 10^{-5}\ mm$

5.2 Results of Simulation of Vertical Frame

From above theoretical calculations and ANSYS simulation analysis, the equivalent stress is 0.0125 N/mm^2 N/mm^2 and 0.0121 N/mm^2 respectively. Both values are nearly equal, so the simulated structure resists the force and it is feasible and applicable.

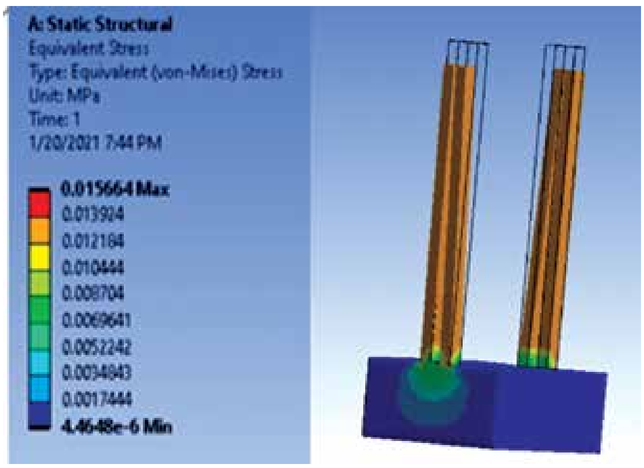

Figure 14 Equivalent stress simulation

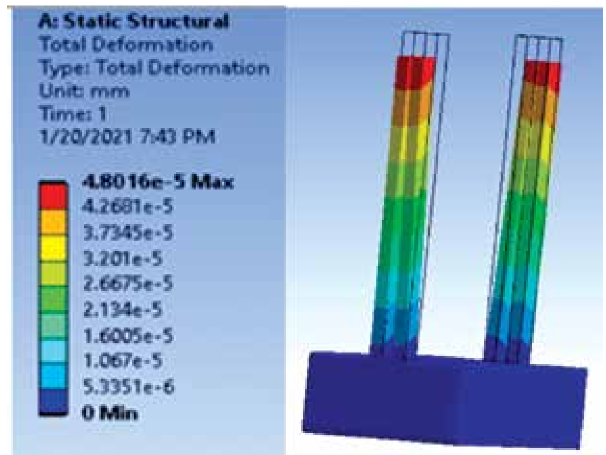

Figure 15 Total deformation simulation

6 Conclusions

From the various simulations the following can be concluded:

- The heating element-nichrome wire coil, should be placed in a spiral path to achieve the better heat distribution and minimum melting risk in comparison to longitudinal and double spiral path configurations
- For heater coil diameter 20mm, the optimum distance between the nichrome wire and plastic sheet was found to be 35mm
- The structural steel pillar was able to supports the clamp and the heater.
- 1400 watt household vacuum cleaner was able to provide velocity of 100-115 m/s at the holes and vacuum pressure of 85-90 kPa which is suitable for vacuum forming..

The above results are only based on simulation and need to be validated by testing.

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Conflict of Interests

Not declared by authors.

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