Design & Development of Multi - Zone Conveyor Curing Furnace for FRP Composites

K.S.Madhu, T. Srinath

Abstract —The present research work confines to having variable temperature zones for influencing curing of Fiber Reinforced Polymer Composite Laminates with a time bound curing cycle, which is not hitherto thought of. All the drawbacks like no control over time, temperature and pressure for curing in the most common manufacturing process i.e., Hand Lay-up were addressed. Optimized matrix content for realizing the controlled curing cycle along with the temperature gradient necessary for enhancing polymerization of the Fiber Reinforced Polymer Composite Laminate was realized in this work thereby eliminating resin rich and resin starved areas in the cured laminates which have a telling effect on the strength properties.. The multi zone conveyor curing furnace design was done with the main intention of minimizing thermal losses, eliminate insulation losses, maintain ideal temperature gradient and thereby enhance complete curability of the Fiber Reinforced Polymer Composite Laminate. Also a Proportional Integral Derivative controller was employed to help maintain the set temperature through each stage of furnace within the defined limit. Temperature measurement is facilitated by high quality thermocouples placed above and below the laminate with an intention to study thermal effects on both surface and also the insulation losses close to the specimen duct were determined. The results were very promising with the curing cycle distributed into three specific zones having a variable temperature gradient. Maintenance of the specified zone temperature was realized effectively with the help of the Proportional Integral Derivative controller employed to satisfactory limits as the results indicate.

Keywords: Composite Materials, Curing, Furnaces, Heat Transfer.

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1 INTRODUCTION

FURNACE (sometimes, retort furnace) is a device in which the subject material is isolated from the heating source. After the development of high-temperature electric heating elements and widespread electrification in developed countries, new furnaces quickly moved to electric designs. Today, a furnace is usually a front-loading box-type oven or kiln for high-temperature applications such as fusing glass, creating enamel coatings, ceramics, soldering and brazing articles. They are also used in several research facilities. The term furnace may also be used to describe another oven constructed on the same principles as the box type kiln mentioned above, but takes the form of a long, wide, and thin hollow tube used in roll manufacturing processes. The following research papers are the guidelines for this work; [1] Neil D. Rowe and Martin Kisel designed and built a Multi-Zone Muffle-Tube Furnace and tested for the purpose of providing an in-house experience base with tubular furnaces for materials processing in microgravity. As such, it must not only provide the desired temperatures and controlled thermal gradients at several discrete zones along its length. [2] Wei-Hsin Chen, Optimal refer to heating slabs in a reheating furnace and the investigations aid in managing energy consumption of the reheating furnace in a hot strip mill, where an arc tangent function is applied as the heating curve. Particular attention is paid to the relationship among the temperature uniformity, discharging target temperature and retention time of the slabs. [3] Damian Rivas et al. refer to the heating of cylindrical compound samples in multi zone resistance furnaces study. A global model is considered where the temperature fields in the sample and the furnace are coupled through the radiation exchange between them; the input thermal data is the electric power supplied to the heaters. By changing this parameter different surface temperature distributions in the melt are obtained, which in turn define different thermo capillary flow patterns. [4] Man Young Kim (2007) defined a mathematical heat transfer model for the prediction of heat flux on the slab surface and temperature distribution in the same for considering the thermal radiation in the furnace chamber and transient heat conduction governing equation respectively. The furnace is modeled as radiating medium with spatially varying temperature and constant absorption coefficient. Comparison with the experimental work show that the present heat transfer model works well for the prediction of thermal behavior of the slab in the reheating furnace. [5] Francisco P.et al. (2008) work stresses on Composite curing, a rapidly developing industry process, generating heavy costs when not properly controlled. Curing autoclaves require tight control over temperature that must be uniform throughout the curing vessel. This paper discusses how agent-based software can improve the robustness and reliability of the curing process by pushing control logic down to the lowest level of the control hierarchy into the process controller (i.e. PLC). These improvements are achieved by an architecture that defines a partition of the agent-based and control system components. [6] F. Boey et al. work focuses on the two main process parameters affecting the final mechanical properties of thermoset composites i.e., cure cycle and the reduction in void

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content. To affect the former, a conventional thermal process is used normally, with the cycle duration lasting a matter of hours. Recent work by the authors has indicated that this can be significantly shorter by using a microwave curing process. In order to apply the same microwave process industrially, reduction in void content must be accomplished.

2. EXPERIMENTAL SET UP AND TESTING PROCEDURE

As shown in Fig.1 the set up consists of resin measuring and mixing unit with weigh scales, fiber glass reinforcement roll feed unit into resin bath, stepper motor control, twin rolling system and continuous resin curing. Once the cured profile comes out of the third furnace if left alone, a long profile will keep forming. To restrict the length to reasonable limit, it is imperative to have a cutting machine, which form basic necessities in this project.

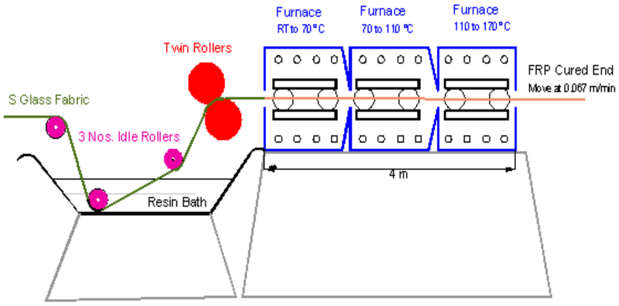

Fig1. FRP Manufacturing

2.1 Idler Rollers

Proper wetting of fiber glass reinforcement strands is a major need because the final strength is directly proportional to the adequate bonding between fibers as a result of resin.

2.2 Design of Stepper Motors Controller

Precise control of the quantity of resin, without air entrapment, on the fiber plays a crucial role in preventing defects (delaminating, air bubbles, resin build up) which adversely affect the properties of the final product. This forms the central theme of the present investigation. Since the speed of roller is a main factor, its precise feed rate control becomes essential. Hence it is important to have a stepper motor control where it is easy to have a wide range of precision speed control through PLC. Stepper motor as shown in Fig.3 is integrated to the rollers. This stepper motor rotates the rollers using Programmable Logic Controller shown in Fig.4 by integrating with drive mechanism as indicated in Fig.2.

Fig 2.Stepper Drive

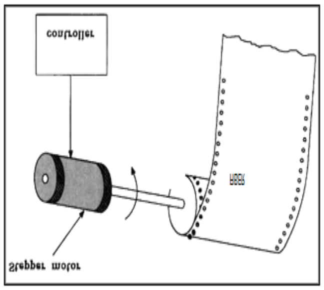

Fig 3. Stepper moter

Fig 4. PLC Display

2.3 Design of Metal Tray with Dummy Rollers

The proper control of resin composition will affect fiber glass reinforcement wetting. Total storage capacity of the metal tray shown in Fig.5 is calculated as, Total storage capacity of metal tray = **35liters.**

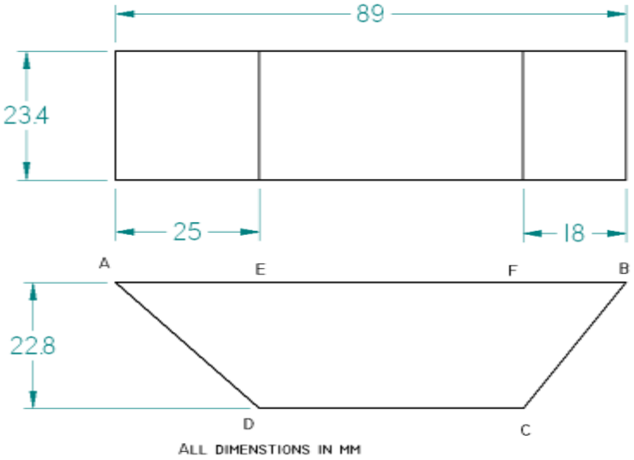

Fig 5. Metal Tray

2.4 Design of a Multi- Zone Furnace

The heating has to be on a gradually increasing gradient for curing the Fiber Reinforced Polymer Composite Laminate. A three stage curing furnace with temperature control (RT to 70^{o} C; 70 to 110^{o} C and 110 to 170^{o} C) is necessary to achieve the desired result. These furnaces are custom made with top part of furnace having facility to swing open easily. At least three temperature monitors and recording facilities suffice the need.Fig.6& 7 shows the geometry of the multi-zone conveyor furnace.

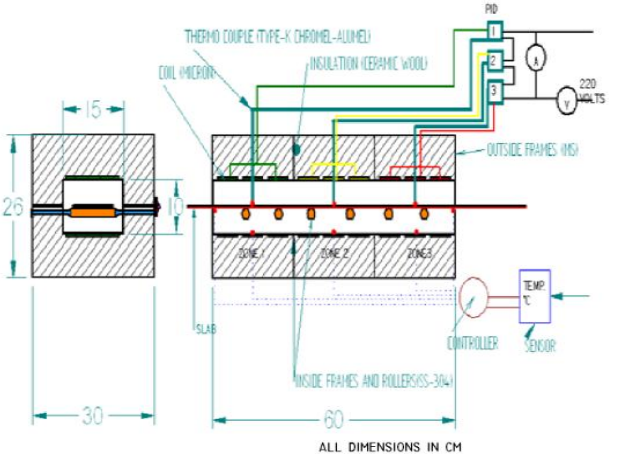

Fig 6. Geometry of the Furnace

Fig 7. Different Views of the furnace

2.5 Specifications

Following information describes the salient features of the furnace.

Table 1 Furnace materials

Part Name	Material
Inside frame	Stainless steel 304/304l
Outside frame	Mild steel
Insulation material	Ceramic wool
Heater Coil	Microme
Thermocouple	Type k (chromel-Alumel)

2.6 Description

An inherent feature of this type of furnace is the continuous, un-interrupted length of the tube which forms its core. This provides a uniform heating configuration without steps or differences in contour, material composition, tube wall thickness, and surface finish. The core requires support along its entire length and on the ends due to mechanical and thermal loads imposed on it during furnace operation. The end components provide the closures which reduce the axial heat loss and serves to support a rugged encapsulated structure. The pieces immediately surrounding the core are of a "split-ring" design to facilitate furnace assembly and dis-assembly and to provide a means for installing heater and thermocouple wires. An important design consideration that was adhered to as the design progressed was accessibility and replace ability of internal components, especially the heater wire sub-assemblies and the thermocouples, which tend to degrade or burn out after a period of use. With this design the heater wires (Kanthal-Al) are not permanently potted in place but are merely wrapped around the core tube into spiral grooves machined into the outer surface of the tube. Each zone is wrapped separately and has its own "in" and "out" leads. In this way, power to each individual zone can be regulated as desired. Also, the heater wires for each zone can be replaced without disturbing the heater wires from the other zones. The thermocouples can also be easily replaced since they are only held in place by thin wire bands and sheet metal tabs. The leads of the heaters and the thermocouples are "Sandwiched" between the insulation components and brought out along the split to "Micarta" terminal blocks attached to the outer steel housing of the furnace.

Other Unique features of this design are:

- The outer rectangular shell consists of two halves split along a horizontal centerline. The "clamshell" construction is formed by casting in a mold around flattened stainless steel tubes.
- Coiled springs at each end of the tube provide enough axial support but still allow thermal expansion of the tube during furnace operation.
- Light weight rigid insulation in areas that require structural support and will not need to be replaced and more flexible "blanket" type insulation that will more readily conform to cavities and may need more frequent replacement.
- A fixture useful when assembling or dis-assembling the unit and for replacing, repairing, or re-configuring the inner components is provided.
- Extensive usage of Proportional Integral Derivative (PID) controllers realized maintenance of the temperature zones in all the three stages.

2.7 Temperature PID Control

The third controller type provides proportional with integral and derivative control, or PID. This controller combines proportional control with two additional adjustments, which helps the unit automatically compensate for changes in the system. These adjustments, integral and derivative, are expressed in time-based units; they are also referred to by their reciprocals, RESET and RATE, respectively. The proportional, integral and derivative terms must be individually adjusted or “tuned” to a particular system using trial and error. It provides the most accurate and stable control of the three controller types, and is best used in systems which have a relatively small mass, those which react quickly to changes in the energy added to the process. It is recommended in systems where the load changes often and the controller is expected to compensate automatically due to frequent changes in set point, the amount of energy available, or the mass to be controlled.

How a PID Controller Works: The PID controllers' job is to maintain the output at a level so that there is no difference (error) between the process variable (PV) and the set point (SP). In the diagram shown above the valve could be controlling the gas going to a heater, the chilling of a cooler, the pressure in a pipe, the flow through a pipe, the level in a tank, or any other process control system.

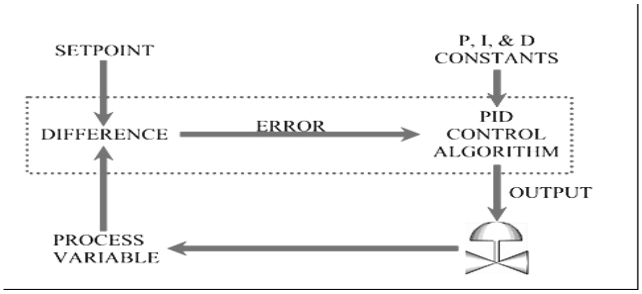

Fig 8.PID Temperature Controller

2.8 Type K Thermocouple

Nickel-Chromium Vs Nickel-Aluminum (Chromel-Alumel); Type K fine wire thermocouples may be used continuously in inert or oxidizing atmospheres at temperatures up to 649°C (1200°F) for .001" diameter bare wire, and up to 982°C (1800°F) for .032" diameter bare couples. These couples have better oxidation resistance characteristics than the other base metal thermocouples and so are widely used at temperatures above 540°C (1004°F). They may also be used temperatures as low as -250°C (-428°F). Type K thermocouples are not suitable for use in the following atmospheres: vacuums; sulfurous atmospheres without a protection tube; reducing, or oxidizing/reducing atmospheres without a protection tube.

2.9 HEATER

Figures.9are photographs showing the components of the integrated heater coils before assembly in three zones for 9 coils top and 9 coils bottom was installed in the furnace. Electric heaters generate heat by passing an electric current through a high-resistance material

- Type-Air heater
- Fuel/Energy Source- Electric
- Maximum operating temperatures-200^{o}C
- Maximum operating power-600watts.

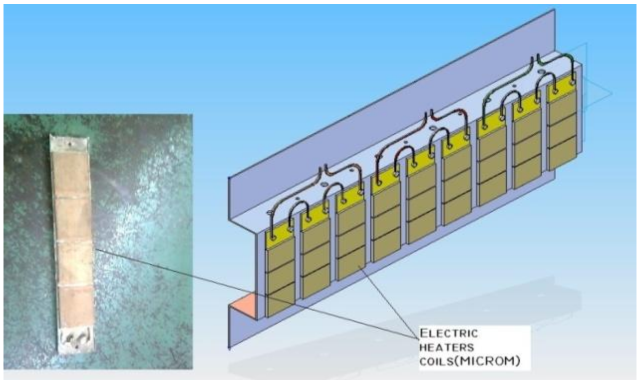

Fig 9.PID Temperature Controller

3. EXPERIMENTAL SET-UP

Fig 10.complete Experimental Set-up

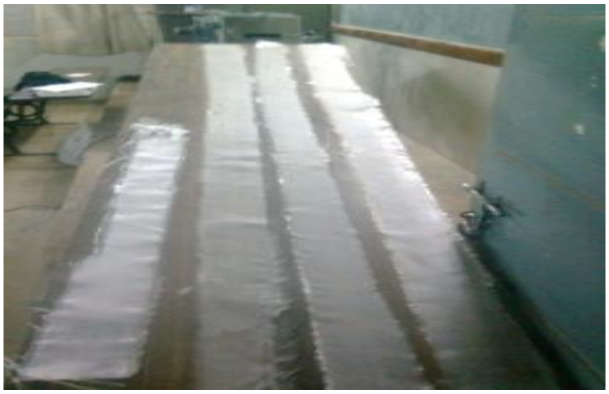

Fig 11.Rolled FRP Laminates on the right side

4. RESULTS AND DISCUSSION

4.1 Thermal Testing For Each Zone.

4.1.1 Room Temperature 27^{o}c and Heater No.1 Setting Temperature is 35^{o}c.

Fig. 12 shows the variation of temperature of three zones over a test period of 30 minutes when the heater in zone 1 is ON. It is observed that the temperature of the zone 1 has reached

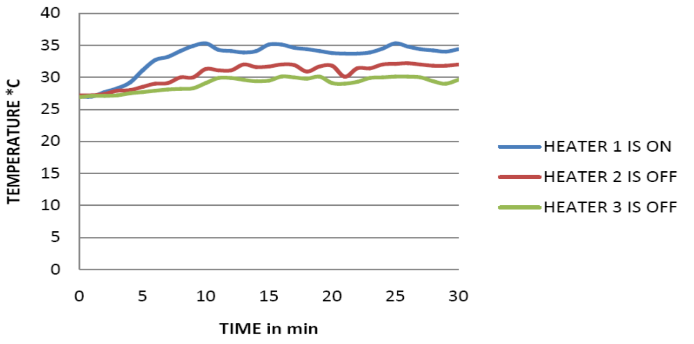

Fig 12.Three zone slab temperature Vs Time

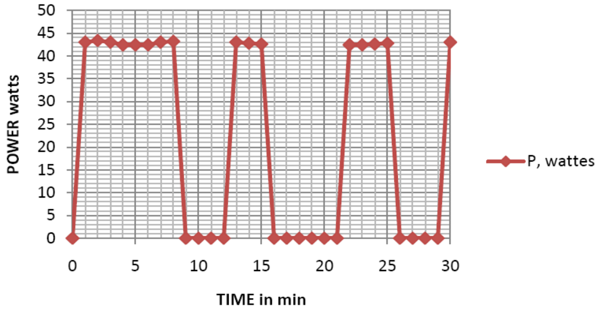

Fig 13.Power Consumption Vs Time

35^{0}C after 10 minutes and remained constant thereafter. This temperature matches with the SET temperature of 35^{0}C. Further, it is observed that the zone 2 has attained a temperature of 32^{0}C while the zone 3 has a temperature of 30^{0}C even though the corresponding heaters are in OFF position. This is mainly attributed to the fact that the zones are not separated by insulations and hence the heat is transferred from zone 1 to zone 2 and 3 due to convection and radiation effects. Fig. 13 shows the variation of power consumption of the heater in zone 1 with respect to time. It is observed that the power consumption is 42 watts when the heater in zone 1 is switched ON and the temperature is maintained at 35^{0}C. Further, it is noted that the heater is switched OFF when the temperature has reached the SET POINT of 35^{0}C. The heater gets switched ON when the temperature drops below the SET POINT. This indicates that the heater is working satisfactorily as per the design.

4.1.2 Room Temperature 28^{o}c and Heater No.2 Setting Temperature is 55^{o}c

Fig. 14 shows the variation of temperature of three zones over a test period of 30 minutes when the heater in zone 2 is ON. It is observed that the temperature of the zone 2 has reached 55^{0}C after 10 minutes and remained constant thereafter. This temperature matches with the SET temperature of 55^{0}C. Further, it is observed that the zone 1 and zone 2 has attained a temperature of 38^{0}C even though the corresponding heaters are in OFF position. This is mainly attributed to the fact that the zones are not separated by insulations and hence the heat is transferred from zone 2 to zone 1 and 3 due to convection and radiation effects.

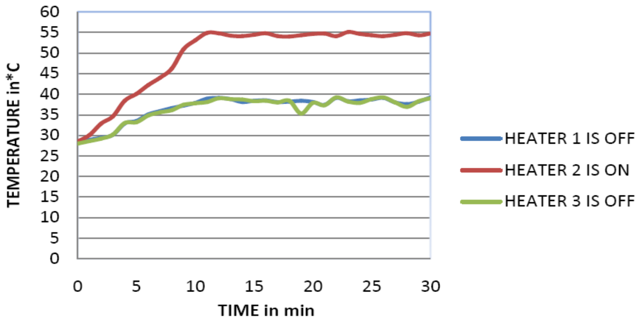

Fig 14.Three zone slab temperature Vs Time

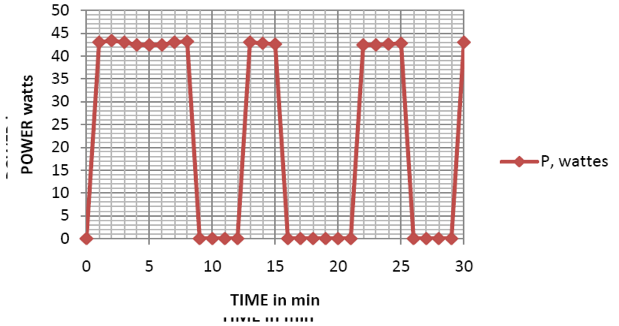

Fig 15.Power Consumption Vs Time

Fig.15 shows the variation of power consumption of the heater in zone 2 with respect to time. It is observed that the power consumption is 42 watts when the heater in zone 2 is switched ON and the temperature is maintained at 55^{0}C. Further, it is noted that the heater is switched OFF when the temperature has reached the SET POINT of 55^{0}C. The heater gets switched ON when the temperature drops below the SET POINT. This indicates that the heater is working satisfactorily as per the design.

4.1.3 Room Temperature 29^{o}c and Heater No.3 Setting Temperature is 75^{o}c

Fig. 16 shows the variation of temperature of three zones over a test period of 30 minutes when the heater in zone 3 is ON. It is observed that the temperature of the zone 3 has reached 75^{0}C after 10 minutes and remained constant thereafter. This temperature matches with the SET temperature of 75^{0}C.

Further, it is observed that the zone 3 has attained a temperature of 45^{0}C while the zone has a temperature of 30^{0}C even though the corresponding heaters are in OFF position. This is mainly attributed to the fact that the zones are not separated by insulations and hence the heat is transferred from zone 3 to zone 2 and zone2 to zone 1 due to convection and radiation effects.

Fig. 17 shows power consumption variation of zone 1 heater with respect to time. It is seen that the power consumption is

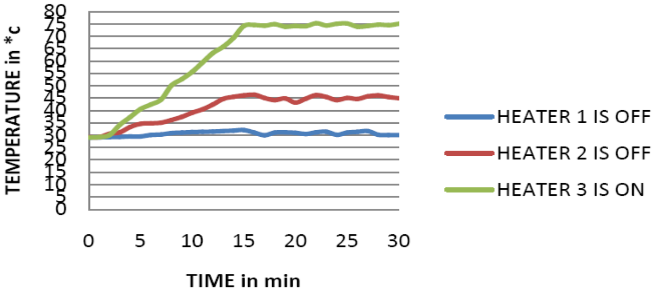

Fig 16.Three zone slab temperature Vs Time

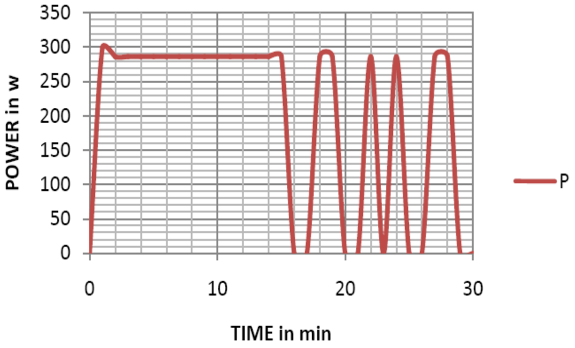

Fig 17.Power Consumption Vs Time

42 watts when the heater in zone 1 is switched ON and the temperature is maintained at 35⁰C. Further, the heater switches OFF when temperature reaches SET POINT of 35⁰C. The heater switches ON when temperature drops below SET POINT indicating that the heater is working as per design.

4.2 Thermal Testing For All Zones.

Room Temperature 27ₒc and All Heaters On. The furnace was tested to determine power consumption as a function of time and temperature and to accomplish a linear gradient profile as shown in Fig.18 and 19. The test scenario was developed to minimize the cycling of the heater wires until all test profiles were complete to avoid damage to the furnace coils. Eight holes were drilled longitudinally to insert thermocouples through the top of the furnace and into the heating zones to estimate an axial thermal gradient. A hole size of 5mm comfortably houses the thermocouples in each zone. The thermal testing was started slowly by switching on the heaters one by one in all the zones. A sudden surge in temperature in the initial stage is noted and after 40 minutes of heating the temperature was held constant for several hours giving a clear indication that power consumption was on a favorable side. This clearly indicates that all the PIDs are active and do not allow any surge in temperature in the respective zones despite continuous heating. As the last zone PID has a higher limit of cutoff, even though the first two zones PIDs are active heat transfer by convection and radiation through the section to these zones results in maintenance of the desired gradient.

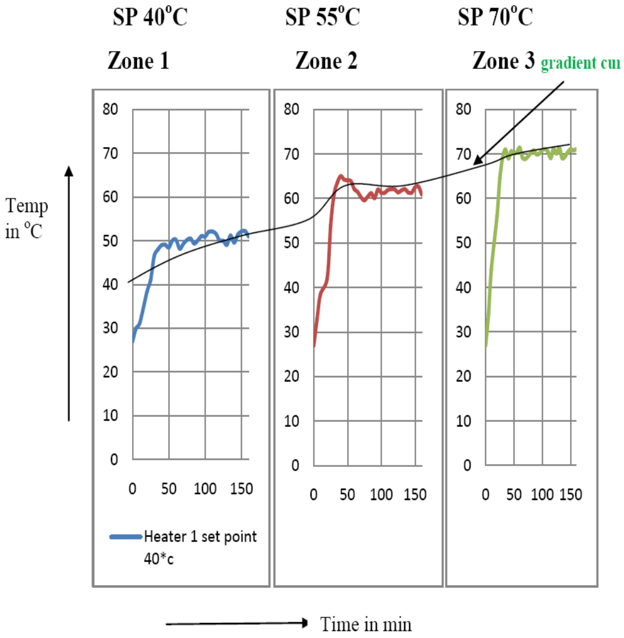

Fig 18 .Ttemperature Vs Time

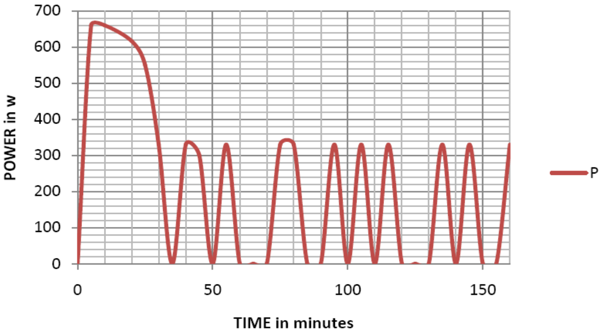

Fig 19.Power Consumption Vs Time

4.3 Furnace Power and Losses Calculations

Table 2.Properties

Polymer Resins, Density	1140kg/m³
Specific Heat	930 J/kg K
SS Steel 304, Emissivity εs	0.8
Thermal Conductivity Ks	0.036w/m ᴼC
Speed , N	1.29 rpm
Slab Moving Velocity inside Oven Vs	0.005 m/s

Table 3.Assumptions

Steady State
Constant Properties
Negligible Changes in KE & PE Energy
Temperatures taking average all three ones

4.4 Calculations

Step-By-Step Procedure for Calculations Shows One Reading.

Data Taking at Time 30 Minutes in Table is considered.
Inlet Temperature $T_i = 30.7^oc$.
Outlet Temperature $T_o = 69^oc$.
Surface Zone 1 Temperature $T_s1 = 46.1^oc$.

Surface Zone 2 Temperature $T_s2 = 68.4^oc$.

Surface Zone 3 Temperature $T_s3 = 119.4^oc$.

Oven Inside Slab Temperature Zone1 $T_z1 = 47.8^oc$.

Oven Inside Slab Temperature Zone2 $T_z2 = 59.1^oc$.

Oven Inside Slab Temperature Zone3 $T_z3 = 69.9^oc$.

Surface Average Temperature $Ts = (Ts1+Ts2+Ts3)/3) +273= 350.96k$.

Oven Inside Slab Average Temperature $Tz = (T_z1+ T_z2+ T_z3)/3) +273 = 331.93k$.

$Ti = 30.7+273 = 303.7^ok$.

$To = 69.1+273 = 342.1^ok$.

The Physical Properties of Atmospheric Air is calculated in 14 to 18.

The fluid is evaluated at the film temperature.

$$T_f = \frac{(Ts + Tz)}{2} = \frac{350.96 + 331.93}{2} = 350.96^ok.$$

Oven Insulation Temperature $T_{ins} = 38^oc = 311^ok$.

The Kinematic Viscosity of the Fluid. $v = 18.635\times10^{-6}\ m^2/s$.

The Thermal Conductivity of the Fluid. $K = 0.0279\ W/m\ ^OC$.

Prandtl Number. $Pr = 0.702$

The Volume Coefficient of Thermal Expansion

$$\beta = \frac{1}{Tf} = \frac{1}{350.96} = 3.09\times10^{-3}.$$

The Grashoff Number.

Area of the Heat Flow$A_f=l\times W_{O}=0.6\times0.15 =0.09\ m^2$

$$\text{Characteristic Length } L = 0.9\sqrt{\left(\frac{4Af}{\pi}\right)} = 0.304m$$

$$Gr = \frac{g\beta(Ts - Tz)L^3}{V^2} = \frac{9.81 \times 3.09 \times 10^{-3}(350.96 - 331.93)0.304^3}{18.635 \times 10^{-6}}$$

$=6.66\times10^{-6}$.

Heat Transfer by Free Convection
For horizontal plate with hot surface up, the average Nusselt number is determined from equation. $GrPr = 3.27\times10^7$ for the Turbulent Flow Condition, We Obtain.

$$Nu_m = \frac{hm \times L}{K} = 0.14(Gr\ Pr)^{1/3} = 0.14(3.27\times10^7)^{1/3} = 44.76.$$

$$\text{Then } h_{m\ Up} = \frac{K}{L}Nu_m = \frac{0.0279}{0.304} \times 44.76 = 4.11 w/m^2.^OC$$

For the horizontal plate with the hot surface facing down, the average Nusselt number is determined from equation. $GrPr = 3.27\times10^7$ for the Laminar Flow Condition, We Obtain.

$$Nu_m = \frac{hm \times L}{K} = 0.27(Gr\ Pr)^{1/4} = 20.41.$$

$$\text{Then } h_{m\ Down} = \frac{K}{L}Nu_m = 1.87 w/m^2.^OC$$

The Rate of Energy Transfer to the Slab.$Q_{Slab} = m\times c_p\times (T_s-T_Z)$

Mass = Density × Area Slab Surface × Velocity

$Q_{Slab}=1140\times0.6\times0.001\times0.005\times930(342.1-303.7) = 122.13\ W$.

Rate of Heat Loss from the Oven.
Conduction. Temperature distribution T(x) and conduction heat flow through a slab.
$Q_{Cond.} = K\ A_S\ (\Delta T\ /L) =$

$$= 2\ K_S\{(W_o H_o) - (T_S W_S)\}\frac{(Tz - Tout\ surf.)}{\Delta L}$$

$=11.14w$.

Convection Hot Surface Up.

$Q_{Conv.} = 7.03\ W$.
Convection Hot Surface Facing Down$Q_{Conv.} = 3.20\ W$.

Radiation.Stefan-Boltzmann Constant

$\sigma = 5.6697\times10^{-8}$ W/ (m^2. K^4)

$Q_{Radi.}$ =28.86 W.

Total energy input = the rate of energy transfer to the slab + conduction + convection hot surface up + convection hot surface facing down + radiation.

Total Energy Input = 122.13 + 11.4 + (7.03+3.2) + 28.28 = 172.04 W

Percentage of Heat Transfer to the Slab = 70.98%.

Percentage of Heat Transfer by Conduction = 6.62%.

Percentage of Heat Transfer by Convection =5.94%.

Percentage of Heat Transfer to by Radiation = 16.43%.

Variation of furnace temperature, time, heat rate and losses. As indicated in Fig.20 there is an initial (first 18 minutes) energy sap by the three modes of heat transfer in the form of losses due to pre-heating of the slab and rollers which is made of good conducting materials. Later on as the materials are saturated with the requisite amount of heat energy the slab and rollers performance substantially improves. Of the three modes of heat losses radiation dominates because of the entry and exit openings which are large enough to facilitate this mode of losses. Improvisations in the design for the entry of FRP composite laminate and the exit of the same may address this issue.

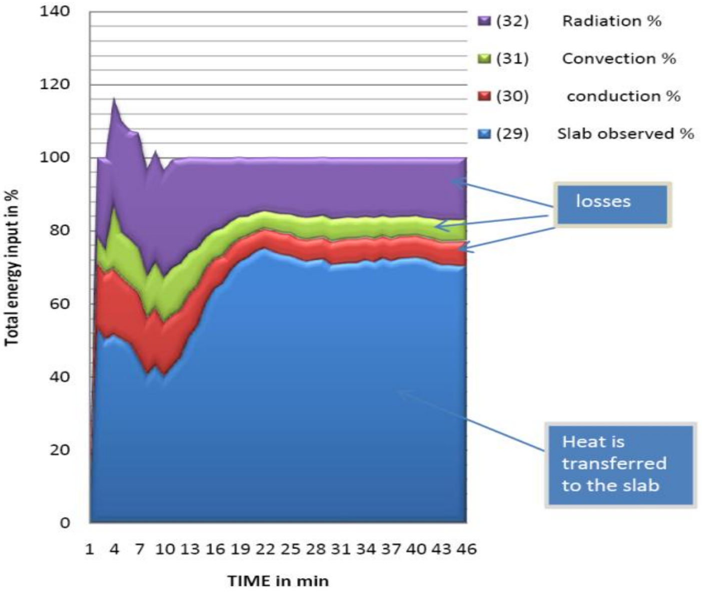

Fig 20.Total energy input Vs Time

5. CONCLUSION

- Multi zone conveyor curing furnace for FRP composites has been designed and fabricated successfully.
- Detailed thermal analysis of the furnace has been carried out.
- The furnace was tested for a period of 30 minutes with the heaters switched ON in sequence.
- Cooling curves for all the three zones have been plotted.
- Results indicated that the heat transfer from one zone to the other has taken place predominantly due to convection and radiation effects.
- The temperature gradient in the zones is maintained as per the SET point.

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