REDUCTION OF INFRA-RED (IR) HEATING CYCLE TIME IN PROCESSING OF THERMOPLASTIC COMPOSITES

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This paper deals with increasing the speed of the Infra-Red (IR) heating cycle in the processing of thermoplastic composites. A constraint on the heating process is that all parts of the material must be within the recommended processing temperature range before forming can start. A mathematical model is used to predict the transient temperature distribution through the thickness of flat consolidated panels of APC-2 during heating. The model includes (i) natural convection (ii) medium and longwave radiation and (iii) 1-D conduction through the material. Experimental validation of the model is conducted using an IR test rig. The following process parameters are varied to obtain optimum process conditions (i) heater power (ii) heater-to-composite distance (iii) composite thickness (iv) degree of oversizing of heater area compared to surface area of composite and (v) one or two sided heating.

Results presented show that reduction of heater-to-composite distance from 100mm to 50mm increases the steady state temperature rise of the composite by 88% whereas a doubling of the heater power density from 25.6 kW/m^2 to 47.3 kW/m^2 increases the composite temperature by only 17%. Using one-sided heating, experimental results shows that upward facing heaters produce a more even temperature distribution across a panel surface than downward facing heaters. Model results showing IR heating times for composite panels of thickness 0.5mm to 9mm are also presented. For example, a 1mm thick consolidated APC-2 panel can be heated to its process temperature in less than 20 seconds using two-sided heating.

Keywords: optimisation; infra red; heat transfer; thermoplastic composite; press forming; model; experiment

1. INTRODUCTION

1.1 General

The future growth of the thermoplastic composite industry depends on developing manufacturing processes with short cycle times. Press forming is seen as one method which is commercially viable in the high speed production of composite parts. Press forming is classified as a thermoforming process where the thermoplastic composite is heated to its processing temperature and pressure is applied to form the part into a mould. Heating the composite requires a substantial part of the overall process time. Infra Red (IR) radiant heating is regarded as the most effective method of heating thermoplastic composites due to its potential for short heat-up times.

However, problems associated with infra-red heating include (i) hot and/or cold spots on the material due to a non-uniform surface temperature distribution and (ii) large temperature differences through the thickness of the material. At high energy densities, this may lead to the heated surface of the composite being burned while the remainder of the composite is below processing temperature. This problem is especially significant for thicker specimens. A lack of knowledge of optimum heating rates verses specimen thickness leads to inefficient use of IR heating and increased processing costs.

The objective of this paper is to make general recommendations to manufacturers in producing optimum processing conditions in the heating of consolidated composite panels and by doing so, reduce the heating cycle time. The approach is to undertake an optimisation study using a mathematical model developed by the authors to investigate process parameters to obtain optimum process conditions by varying (i) heater power (ii) heater to composite distances (iii) composite thickness (iv) degree of oversizing of heater area compared to surface area of composite (v) one or two sided heating. APC-2[1] is the thermoplastic material selected for the study and the use of a mathematical model allows for a *predict and verify* approach rather than an expensive *trial and error* approach.

In this paper, different heating strategies, which simultaneously bring all parts of APC-2 sheets into a "process window", are investigated.

1.2 Review

IR Heating of Plastics Panels

Radiant heating of a plastic panel has been investigated by Progelhof *et al*[2] and Miyanaga and Nakano[3] and of a thermoplastic composite laminate by Scobbo[4]. In all three models, a simple radiation model has been used to determine the one-dimensional temperature distribution through the absorber. Results are presented making model against experimental comparisons. No significant work has been carried out on the optimisation of the IR heating of plastic panels.

Scobbo[4] determined optimum heating and forming times for thermoforming a panel of Radel-C/T-500 graphite reinforced composite. Results are presented showing the transient temperature profiles through the thickness for one specimen thickness of 2mm using one heater power density.

APC-2 - Process Window

Güçeri[5] defines the processing window as a temperature range having a lower limit below which there is unsatisfactory forming and an upper limit beyond which material degradation occurs due to excessive temperatures maintained over a period of time. Cattanach and Cogswell[6] indicates that the preferred processing temperature of APC-2 is 380°C with a recommended process window of 360°C to 400°C. Processing below 360°C may result in an non-homogeneous melt, while above 400°C chemical changes in the resin may occur.

O'Bradaigh and Mallon[7] have shown that processing composite materials at temperatures outside the optimum temperature range may affect the mechanical and physical properties of the end product. However, these processes involved maintaining high temperatures for long periods and the resulting thermal degradation causes these defects. Philips *et al*[8] have worked on the thermal degradation of PEEK-based composites in air. They defined a limit for thermal exposure for APC-2/AS4 and APC-2/S2 at different processing temperatures which will still allow for good processability. For example, APC-2/AS4 may be maintained at a temperature of 370°C for 1900 seconds. However, at higher process temperatures, e.g. 420°C, only 360 seconds is permitted to allow for good processability.

APC-2 - Effect of Rapid Heating on Mechanical and Physical Properties

Cogswell[9] has stated that it is possible to use flash heating such as flame, laser or hot gas in some rapid processing without adversely affecting the properties of the composite. Berlin *et al*[10] found that no deterioration in mechanical properties of APC-2 was observed before visible defects appeared on the composite laminates.

Conclusion from Literary Review

(1) Process Window for APC-2 is between 360°C and 400°C[6].
(2) Rapid heating of APC-2 has negligible effect on mechanical and physical properties[9].
(3) Overshooting the upper processing temperature limit is permitted for short periods[8].

2. APPROACH

2.1 Introduction

A mathematical model along with a graphical user interface is developed in order to simulate the IR heating cycle of thermoplastic composites. To validate the model, experimental tests are carried out on flat consolidated panels of APC-2 using an IR test rig. After validation, the model is then used to investigate varying process parameters in order to make recommendations on how to reduce the IR heating cycle time in the process of thermoplastic composites.

2.2 Mathematical Model

Figure 1 shows the mechanisms of heat transfer that occur between the IR heaters and a heated panel of APC-2.

The heat transfer mechanisms are:

(1) Radiation from the IR heaters to the panel and surroundings.
(2) Natural convection from IR heaters to the panel.
(3) Conduction through the panel.
(4) Natural convection from the top and bottom surfaces of the panel to the surroundings.
(5) Long wave radiation from the top and bottom surfaces of the panel to the surroundings.

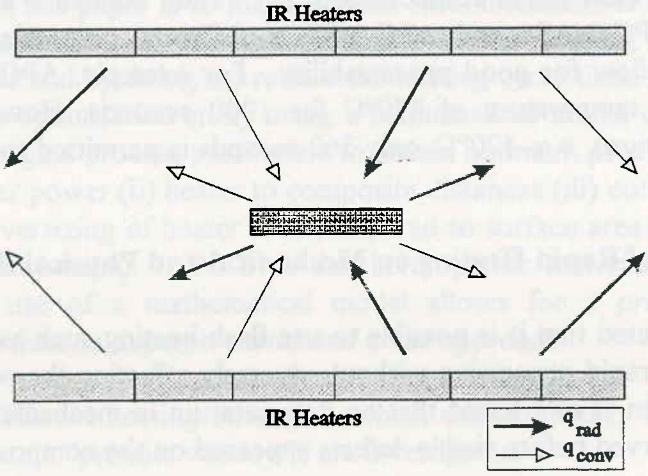

Figure 1: Heater Transfer Mechanisms

A mathematical model has been developed to simulate the above heat transfer mechanisms to determine the heat flux at the surfaces of the composite. Radiant heat transfer occurs between the panel, the heaters and side walls if present or the surrounding room if no side walls are present. The radiation exchange between the surrounding surfaces and the panel is calculated using a conventional enclosure analysis[11]. This assumes that the surfaces that form the enclosure are (i) isothermal, (ii) opaque, (iii) diffuse and (iv) grey. Natural convection is calculated using empirical correlations[11]. The net heat flux to the surfaces of the composite is then used by the model to predict the transient 1-D temperature distribution through the thickness. For detailed description of the mathematical model see Brogan[12].

The model was developed to simulate various IR heating processes (e.g. press forming, diaphragm forming). The user may specific a composite lay-up of a number of layers with each layer having different material properties. Other process parameters which the model may simulate include:

(i) IR heating above/below or both.
(ii) Processing inside or outside an autoclave.
(iii) Varying heater-to-composite distance.
(iv) Degree of oversizing of heater area compared to surface area of composite.
(v) Time dependent IR heating temperature.
(vi) Temperature dependent properties.

Material properties for the density, specific heat capacity and conductivity for APC-2 are obtained from Blundell and Willmouth[13]. Emissivity value for APC-2 is obtained from Scobbo[4].

2.3 Graphical User Interface (GUI)

A graphical user interface (GUI) was designed and implemented as a front end on the transient conduction model. The GUI enables the user to enter all the different parameters without having to write detailed computer input files. Through use of a GUI for the model, manufacturers can more easily optimise their own process by running the model for different boundary conditions. Figure 2 shows one screen of the GUI.

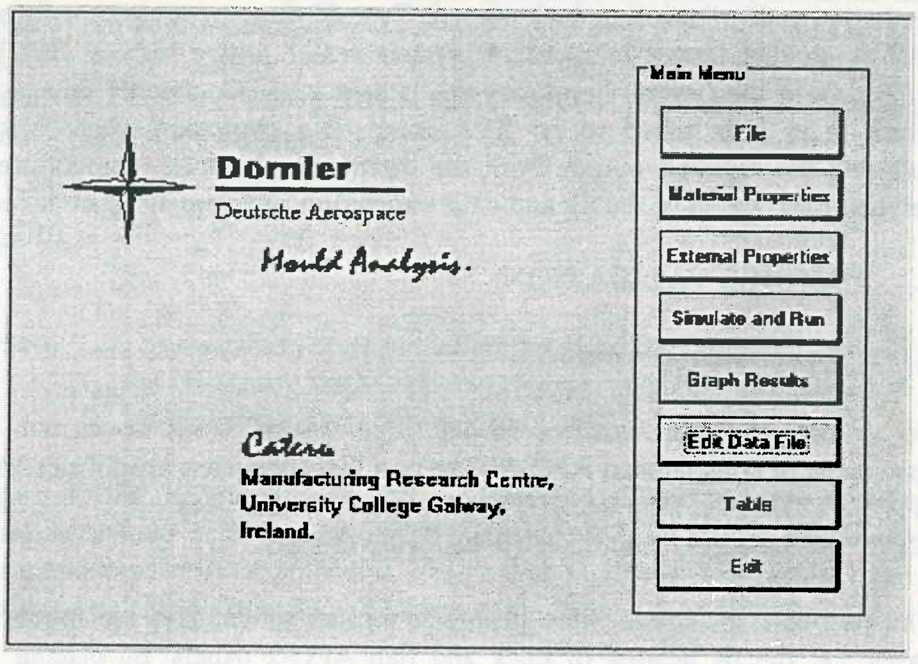

Figure 2: Graphical User Interface (GUI) for one version of Mathematical Model

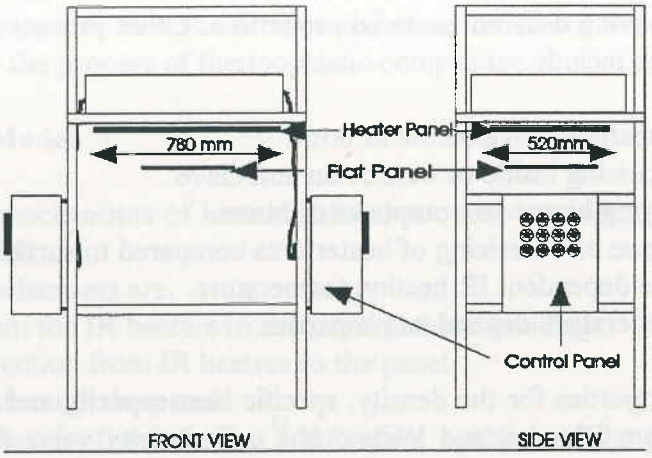

Figure 3 Schematic of an Infra-Red Radiant Oven.

2.4 Infra-Red (IR) Test Rig

The IR test rig used to validate the model was designed and built. Figure 3 is a schematic of the IR rig used in this study. The IR bank consists of 48 medium wave quartz heaters[14], each with 400W power, arranged in a 12x4 grid giving an overall heater bank size of 780x420mm. The bank has been designed so that it may be split in half to allow two sided heating experiments to be undertaken. The heaters are controlled in pairs using manual thyristors located at the control panel. In all, 24 heater zones may be specified by the user allowing the effect of variable heater power distribution on mould surface temperature distribution to be analysed. Type-K thermocouples are fitted to a number of heaters so that heater temperature versus heater power curves may be obtained. The output from the heater thermocouples is sent to a 32 channel data acquisition board[15] which is in turn linked to an IBM compatible computer where a standard program converts the millivolt output from the thermocouples into temperature values. A more detailed description of the rig and data acquisition system may be obtained in Brogan[12].

3. MODEL VALIDATION

3.1 Experimental Approach

To validate the mathematical model, experimental work is carried out on two test specimens of consolidated APC-2. The two test specimens are formed using an autoclave:
(1) (125x125x1)mm thick $(0/90)_s$ test piece with 8 plies.
(2) (125x125x9.5)mm thick $(0/90)_s$ with 76 plies.

The two test specimens were primarily formed to validate the model for two extreme cases, i.e. the IR heating of thick and thin APC-2 panels, by placing each specimen at various distances from the heaters and by varying the heater power density. The (125x125x1)mm specimen can demonstrate that very fast uniform one-sided heating can be achieved while the (125x125x9.5)mm piece demonstrates that only two-sided heating can produce a uniform temperature distribution through the thickness.

A type-K thermocouple is embedded in the (125x125x1)mm panel between the second and third layer to obtain a better temperature reading close to the bottom of the panel. Two type-K thermocouples are embedded in the (125x125x9.5)mm panel, one between the second and third ply from the top of the panel and the second thermocouple is embedded between the second and third ply from the bottom.

Experimental work is carried out on both test specimens by (i) varying heater-to-composite distance from 100mm to 30mm and (ii) using three different power densities 25.3 kW/m^2, 38.4 kW/m^2 and 47.3 kW/m^2. Using these process parameter variations, experiments are conducted using

(i) One-sided heating with equi-sized (i.e. 125x125)mm upward facing IR heaters for both specimens.
(ii) Two sided heating with equi-sized IR heating for the (125x125x9.5)mm panel.
(iii) One-sided heating with over-sized (i.e. 250x250)mm upward facing IR heaters for both specimens.
(iv) Both specimens were heated up as fast as possible using maximum heater power density of 47.3kW/m^2, at 30mm from one-sided upward facing equi-sized heaters for the (125x125x1)mm specimen and 50mm from two-sided equi-sized heaters for the (125x125x9.5)mm.

3.2 Model Validation Results

Figure 4 shows how the mathematical model compares against experimental data for the (125x125x9.5)mm consolidated APC-2 panel placed 50mm from upward facing equi-sized heaters with a power density of 25.3 kW/m^2. The model results compare well with experimental data. To compare steady state model temperature versus experimental temperature a percentage difference is defined by:

$$\%Diff = \frac{T_{\text{mod}} - T_{\text{exp}}}{T_{\text{exp}} - T_{start}} * 100$$

where T_{mod} is the steady state model predicted by the model
T_{exp} is the steady state temperature experimentally measured and
T_{start} is the initial temperature of the panel

From Figure 4, the %Diff between the model top temperature and experimental top temperature at steady state is only 1.7% whereas the %Diff for the model bottom temperature and experimental bottom at steady state is 4.5%. The results from a total of 15 experimental validation runs, like in Figure 4, are summarised in Tables 1-3.

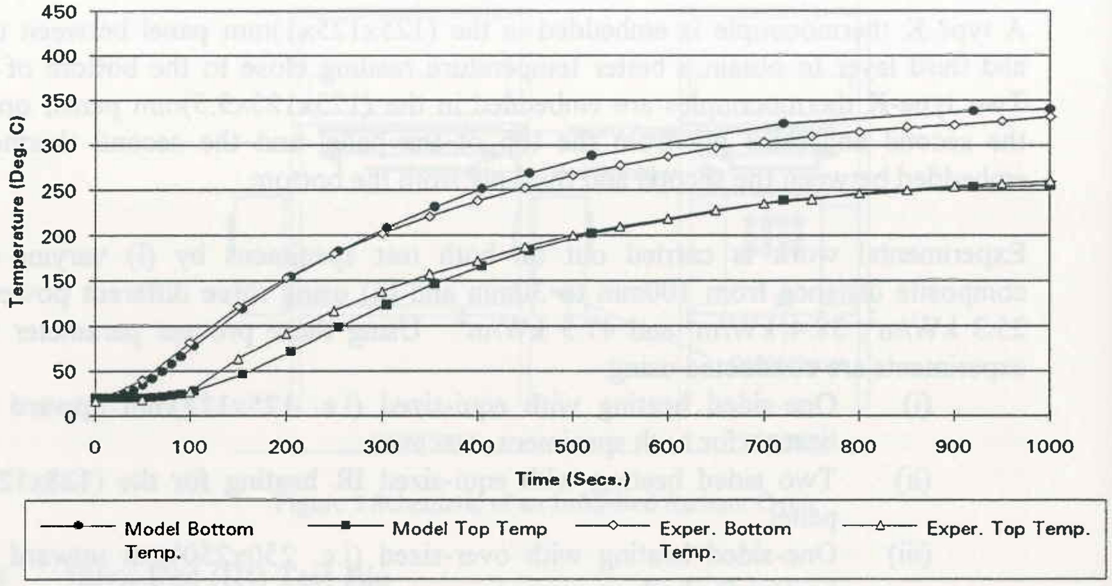

Figure 4: Comparison of predicted model temperature against experimental data for top and bottom surfaces of (125x125x9.5)mm consolidated APC-2 panel positioned 50mm from upward facing equi-sized IR heaters with a power density of 25.3kW/m^2.

Table 1 shows the percentage difference at the steady state temperature between the predicted model results and the experimental data for the (125x125x1)mm piece of APC-2 positioned at different distances from equi-sized (i.e. 125x125)mm upward facing heaters. As shown the model is capable of predicting the average panel temperature quite well.

Table 2 shows the percentage difference at the steady state temperature between predicted model results and the experimental data for the (125x125x9.5)mm piece of APC-2 positioned at different distances from both equi-sized one-sided upward facing heaters and equi-sized two-sided heaters.

Table 3 shows the percentage difference at the steady state temperature between predicted model results and the experimental data for the (125x125x1)mm and the (125x125x9.5)mm specimens of APC-2 positioned at different distances from the one-sided over-sized (i.e. 250x250)mm upward facing heaters.

Heater-to-panel distance, mm	Heater Power, kW/m^2	APC-2 Steady State Temperature °C		
		Model	Exper	%Diff
100	25.6	217	192	14.5
75	25.6	250	233	7.2
50	25.6	310	344	-10.4
125	38.4	213	193	11.5
100	38.4	234	224	4.9

Table 1 Percentage difference between the model prediction steady state temperatures and experimental data for the (125x125x1)mm consolidated panel of APC-2 using upward facing equi-sized (125x125)mm heating.

Heater-to- panel distance, mm	Heater Power kW/m^2	APC-2 Steady State Bottom Temperature °C			APC-2 Steady State Top Temperature °C		
One Sided Heating with Upward Facing Heaters							
		Model	Exper	%Diff	Model	Exper	%Diff
50	25.6	342	327	4.5	257	253	1.7
100	25.6	231	194	21.2	178	162	11.2
100	38.4	251	212	20.3	193	176	10.8
Two Sided Heating							
100	25.6	311	289	8.1	293	293	0

Table 2 Percentage difference between the model prediction steady state temperatures and the experimental data for the (125x125x9.5)mm consolidated panel of APC-2 using both one and two sided equi-sized (125x125)mm IR heating.

Over-sized (250x250) Upward Facing IR Heaters of (125x125x9x1)mm Consolidated APC-2 Panel				
Heater-to- panel distance, mm	Heater Power kW/m^2	APC-2 Steady State Temperature °C		
		Model	Exper	%Diff
100	25.6	311	295	5.8
100	38.4	359	344	4.6
50	25.6	379	386	-1.9

Over-sized (250x250) Upward Facing IR Heaters of (125x125x9.5)mm Consolidated APC-2 Panel							
Heater-to-panel distance, mm	Heater Power kW/m^2	APC-2 Steady State Bottom Temperature °C			APC-2 Steady State Top Temperature °C		
		Model	Exper	%Diff	Model	Exper	%Diff
100	25.6	360	305	19.2	270	227	20.7
100	38.4	404	359	13.2	300	259	17.1
50	25.6	429	399	7.9	315	275	15.6

Table 3 Percentage difference between the model prediction steady state temperatures and the experimental data for the (125x125x9.5)mm and (125x125x1)mm consolidated panel of APC-2 using one-sided over-sized (250x250)mm upward facing heating.

Finally, both specimens are heated using a maximum IR heater power density and by placing the consolidated APC-2 panels very close to the heaters. The (125x125x1)mm consolidated APC-2 panel was heated using upward facing equi-sized heaters with a maximum power density of 47.3 kW/m2 and by placing the panel 30mm from the heaters.

Figure 5 shows a comparison of the model prediction to the experimental data. The model under-predicts the steady state centre temperature of the (125x125x1)mm panel by 10°C.

The (125x125x9.5)mm consolidated APC-2 panel was heated using upward and downward facing equi-sized heaters having a maximum power density of 47.3 kW/m^2. The panel is positioned 50mm from both the top and bottom heaters. Figure 6 is a comparison of the experimental data against predicted top and bottom temperatures. As in the case for the 1mm panel, the model under-predicts the top and bottom temperatures by %Diff of -8.5% and -2.8% respectively after 200 seconds.

The general conclusion on validation is that the model predicts the temperature distribution through the thickness of the APC-2 with some accuracy. For equi-sized one/two sided and over-sized heaters and for thick and thin consolidated APC-2 panels, the model is particularly good (-10.4% to +7.9% at 50mm or less except for oversized heating of thick panel at 50mm where %Diff of top temperature is +15.6%) for panel positions close to the heaters. Model result also compare well (from +4.6% to +21.2% at greater than 50mm) for panels positioned far from the heaters. Experimental tests with the fastest heating rates for both (125x125x1)mm and the (125x125x9.5)mm consolidated panels are in good agreement (-2.8% to -9.8% after 200 secs.) with the mathematical model. Therefore, it may be concluded that the model gives realistic predictions of APC-2 panel heating under a wide range of conditions of interest to manufacturers.

4. RESULTS

4.1 Layout of Optimisation Studies

Optimisation results using the validated model are now presented. This study is primarily conducted by using the model. However, important experimental findings are also reported. The results presented in this section are divided into two sub-sections:

Section 4.2 Experimental Results.
Section 4.3 Model Results.

In the sections 4.2 and 4.3, a detailed discussion of the main factors affecting the reduction of IR heating process times of flat consolidated APC-2 panels is made.

The experimental results section consists of two parts, i.e. the effect of:

(i) Using upward facing heaters.
(ii) Varying heater-to-composite distance.

The final part of the study using the mathematical model is a presentation of results that compares the temperature profiles of various thicknesses of APC-2 panels ranging from 0.5mm to 9mm heated from one-side and two-sides. To demonstrate how the model may reduce IR heating cycle times, each simulation is run by placing the panel of consolidated APC-2 30mm from the heaters and the power density of the heaters are set to their maximum of 47.3kW/m^2. The model results section consist of four parts; i.e. the effect of:

(i) Increasing IR heater power density.
(ii) One-sided or two-sided IR heating on the temperature distribution through APC-2 panels of different thicknesses.
(iii) Cutting back heater power density during one-sided IR heating.
(iv) One-sided or two-sided IR heating in producing shorter IR heating cycle times.

4.2 Experimental Results

4.2.1 Effect of using Upward Facing Heaters

Some processes require heating from only one side. Experiments on the heating of blackened brass plates carried out, show that upward facing heaters produce a more even temperature distribution on the surface of the plates. Figure 7 shows that by using downward facing heaters placed 100mm from the IR heaters set at a power density of 38.6kW/m^2, the steady state temperature difference between the corner and centre temperature is 45°C. However, using upward facing heaters the steady state temperature difference between the corner and centre temperature is only 10°C. This finding suggests that a more even temperature distribution across the surface is obtained by using upward facing IR heaters. The authors believe that this is due to the different convection flows that occur.

4.2.2 Effect of varying Heater-to-Composite Distance

Heater-to-composite distance has a dramatic effect on the steady state temperature of the composite panel. Figure 8 shows the experimental centre temperature heat-up curves of the (125x125x1)mm consolidated APC-2 panel placed 100mm, 75mm, and 50mm from upward facing equi-sized heaters using a constant heater power density of 25.3kW/m^2 in all three cases. By moving the APC-2 panel from 100mm to 50mm from the heaters, the experimental steady state centre temperature increases by a %Diff of 88.2%.

4.3 Model Results

4.3.1 Effect of increasing IR Heater Power Density

The significance of increasing the power density of the heaters has not a dramatic effect on the temperature of a composite panel. Figure 9 presents model results for the (125x125x1)mm consolidated APC-2 panel placed 100mm from the equi-sized upward facing IR heaters. Almost doubling the power density of the heaters from 25.43kW/m^2 to 47.3kW/m^2, increases the panel steady state temperature by only a %Diff of 17.1%.

4.3.2 Effect of one-sided or two-sided IR heating on the temperature distribution through APC-2 panels of different thicknesses

Figure 10 shows the (125x125x9)mm consolidated APC-2 panel heated from one side and two sides. In this case, it is evident that one-sided heating is not sufficient to heat the panel to its process temperature. At 200 seconds, the temperature difference between the top and bottom surfaces of the panel using upward facing IR heaters is 160°C. However, use of two-sided heating produces a more even temperature distribution through the thickness and hence processing can be achieved using this arrangement.

The main criterion resulting from the literature review is that the process window for APC-2 is 360°C to 400°C. In general, with one-sided heating, it is very difficult to achieve processing temperature for thicker specimens, due to the resulting large temperature distribution through the thickness. For process conditions used in this study, to bring the temperature of 3mm and 4mm thick APC-2 panels within the process window, sudden heater power reduction is required (see Section 4.3.3). Two-sided heating is recommended for specimens thicker than 4mm.

4.3.3 Effect of cutting back heater power density during one-sided IR heating

Figure 11 shows that by cutting back on the temperature of the IR heaters from 745°C to 645°C in 20 seconds, the temperature of the (125x125x3)mm consolidated APC-2 panel can be brought to fall inside the process window. The bottom temperature overshoots the upper process temperature limit of 400°C, but by reducing the heater power, the top and bottom temperatures of the panel quickly fall within the process window. For a short time, after the reduction in heater power density, the bottom temperature of the panel drops from 412°C to 403°C while the top temperature of the panel actually increases from 364°C to 369°C for the same time period. This finding is significant because by reducing the IR heater power, the temperature difference through the thickness of thicker consolidated APC-2 panels can be reduced and therefore, processing of 3mm and 4mm thick panels using one-sided heaters could be feasible.

4.3.4 Effect of one-sided or two-sided IR heating in producing shorter IR heating cycle times

Figure 12 is a comparison of short heating cycle times taken for each panel thickness of APC-2 required for all the material to fall within the process window range of 360°C-400°C for consolidated APC-2 panels. From Figure 11, the processing temperature for the 3mm thick APC-2 panel, using one-sided upward facing heaters, is achieved after 158 seconds. This result is shown in Figure 12 represented as one data point. Similarly, the other heating cycle times for various specimens thicknesses are obtained and plotted in Figure 12.

It is evident from Figure 12 that increasing the thickness of the panel increases the heating cycle time. The heating cycle times for one-sided IR heating are shown for APC-2 panels of 4mm thickness or less, as it is very difficult to heat thicker specimens using one-sided IR heating under the process conditions set out for this study. It is important to mention that two-sided IR heating produces much shorter heating cycle times. For example, a 3mm thick consolidated APC-2 panel may be heated to its process temperature in 42 seconds using two-sided heating whereas it takes 158 seconds using one-sided. Also, for thicker specimens, a more even temperature distribution through the composite thickness is achieved using two-sided heating.

5. CONCLUSIONS

A number of conclusions apply to the numerical results presented:

(1) Heater-to-composite distance has a significant effect on the temperature of the composite (see Figure 8).

(2) Heater power density increase is not as important as the reduction of heater-to-composite distance (compare Figures 8 and 9).

(3) A more even temperature distribution across the surface is achieved using upward facing heaters as opposed to downward facing heaters (see Figure 7).

(4) Using lower power densities e.g. 25.6 kW/m^2 and placing the composite closer to the heaters achieves the same results as using high power densities and placing the composite far from the heaters.

(5) It is possible to heat with IR heaters closer to the composite than has previously been recommended by the manufacturers of composites[16].

(6) IR heating will be very important in the high speed production of composite parts using press forming techniques. Using two sided heating, a 1mm panel of APC-2 can reach its processing temperature in less than 20 secs.

(7) Using the processing conditions for the study, the processing temperature can be achieved using one sided IR heating for consolidated panels 4mm or less. Due to the large temperature distribution through the thickness of the APC-2 greater than 4mm, two sided heating is recommended.

(8) Cutting back power density for 3mm and 4mm consolidated panels of APC-2 during the IR heating process may bring the temperature distributions of these panels inside the process window (see Figure 11).

A significant finding is that the validation studies prove that the model is suitable for use to predict composite temperature in real IR processes. The validated model together with the graphical user interface opens the door for manufacturers to use this modelling technique to optimise IR heating processes for a wide range of composites and polymers. This cuts down on expensive trial and error approaches at production facilities.

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REFERENCES

1. *Aromatic Polymer Composite, APC-2,* Fiberite Europe GmbH, Erkelenzer Strasse 20, D-4050 Möchengladbach, Germany

2. Progelhof, R.C., Quitiere, J. and Throne, J.L., "Temperature distribution in semitransparent plastic sheets exposed to symmetric, unsymmetric and pulsed radiant heating and surface cooling", *Journal of Applied Polymer Science*, Vol. 17, 1973, pp. 1227-1252

3. Miyanaga, T. and Nakano, Y., "Analysis of infrared radiation heating of plastics", *Trans. Heat Transfer - Japanese Research*, Vol. 21, 1993, pp. 631-647

4. Scobbo Jr., J.J., "Radiative heating of thermoplastic/graphite fiber composites", 22nd Int. SAMPE Technical Conf., 1990, pp. 39-49

5. Güçeri, S.I., "Transport phenomena in on-line consolidation of thermoplastic composites", *Proc. of 28th ASME Heat Transfer Conf.*, San Diego, Vol. 196, 1992, pp. 11-21

6. Cattanach, J.B. and Cogswell, F.N., "Processing with aromatic polymer composites", *Developments in Reinforced Plastics - 5*, ed. G. Pritchard, Elsevier Applied Science Publishers, 1986, pp. 1-38

7. O'Brádaigh, C.M., Mallon, P.J., "Effect of forming temperature on the properties of polymeric diaphragm formed thermoplastic composites", *ASCM/CCM Joint Symposium on Composite Materials Science and Engineering,* University of Delaware, USA, 23-25 September 1987

8. Phillips, R., Johnsson, G. and Månson, J. E., "Thermal stability of PEEK composite in air: dynamic rheological analysis", *proc at ICCM-9*, Madrid, 1993

9. Cogswell, F.N., *Thermoplastic Aromatic Polymer Composites,* Butterworth-Heinemann Ltd, London, 1992

10. Berlin, P., Dickman, O. and Larsson, F., "Effects of heat radiation on carbon/PEEK, carbon/epoxy and glass/epoxy composites", *Composites*, Vol. 23, No. 4, July 1992, pp 235-243

11. Incropera, F.P. and DeWitt, D.P., *Fundamentals of Heat and Mass Transfer*, 2nd Edn., Wiley and sons, New York, 1981

12. Brogan, M.T., "Heat transfer analysis of thermoplastic composite materials", *Ph.d. thesis*, University College Galway, Ireland, 1994

13. Blundell, D.J. and Willmouth, F.M., "Crystalline morphology of the matrix of PEEK/carbon fibre aromatic polymer composites Part III Prediction of cooling rates during fabrication", SAMPE Quarterly, Vol. 17, No. 2, 1986, pp. 50-58

14. *Vulcatherm quartz heater product sheet*, Vulcan Refractories Ltd., Brookhouses Industrial Estate, Cheadle, Stoke-on-Trent, Staffordshire ST10 1PN, England

15. *Data acquisition and control catalogue*, Amplicon Liveline Ltd., Centenary Industrial Estate, Hollingdean Road, Brighton, East Sussex BN2 4AW, England

16. *Data Sheet 5: Fabricating with aromatic polymer composite, APC-2*, Fiberite Europe GmbH, Erkelenzer Strasse 20, D-4050 Möchengladbach, Germany

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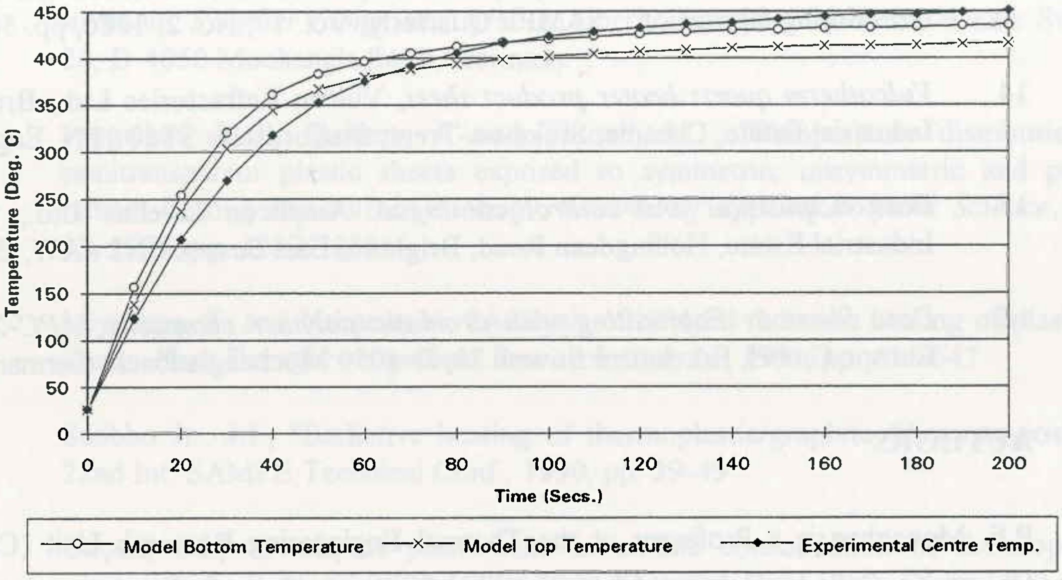

Figure 5 Comparison of model prediction to experimental data for (125x125x1)mm panel of consolidated APC-2 positioned 30mm above equi-sized (125x125)mm upward facing IR heaters of power density 47.3 kW/m^2.

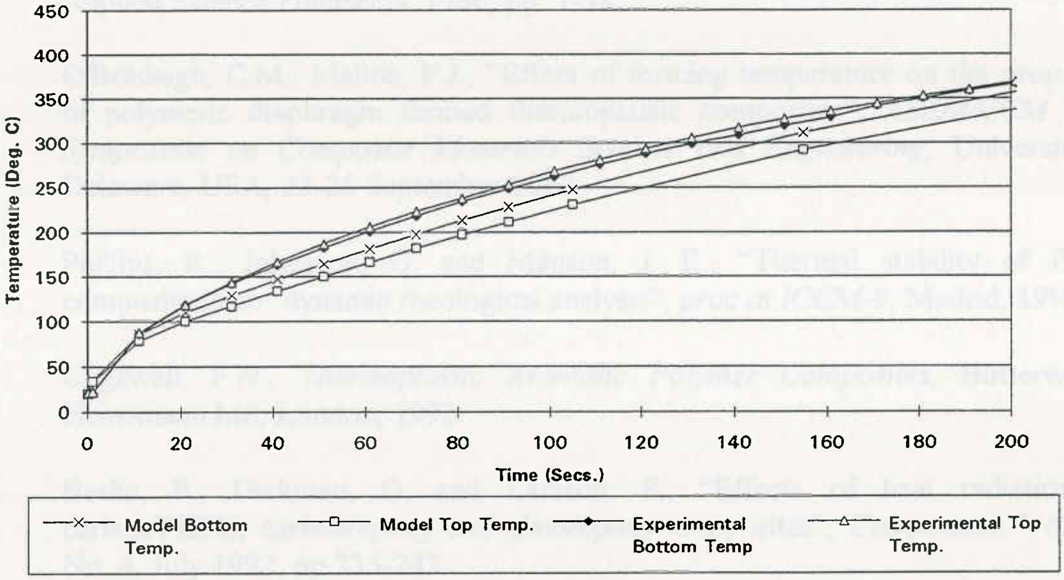

Figure 6 Comparison of model prediction to experimental data for (125x125x9.5)mm panel of consolidated APC-2 positioned 50mm above and below equi-sized (125x125)mm IR heaters of power density 47.3 kW/m^2.

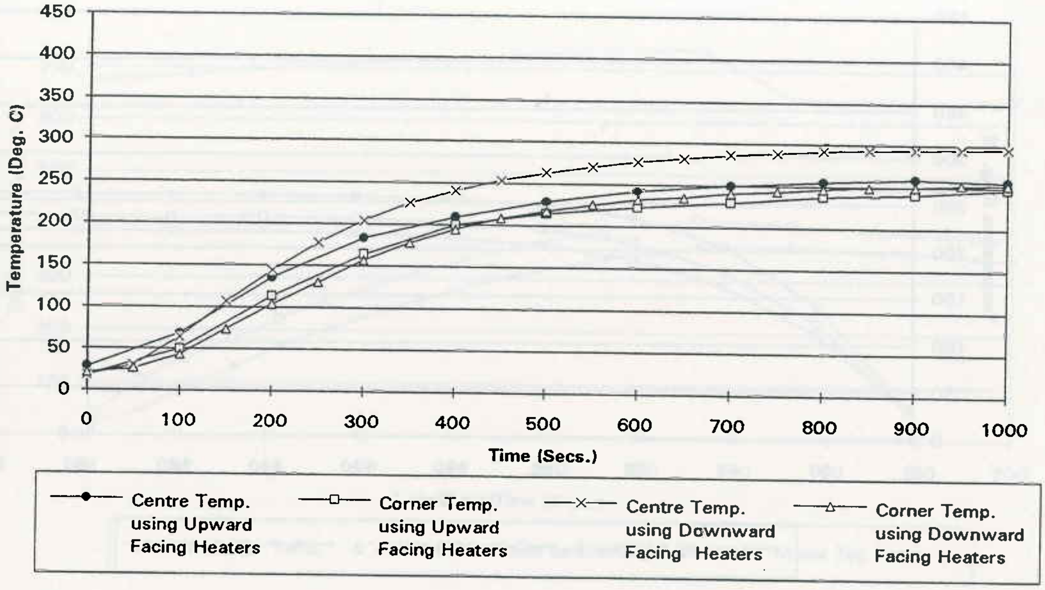

Figure 7 Comparison of experimental corner and centre temperatures for (395x395x3)mm blackened brass plate positioned 200mm (i) above equi-sized (395x395)mm upward facing IR heaters and (ii) below equi-sized (395x395)mm downward facing IR heaters with both cases using power density 38.6kW/m^2

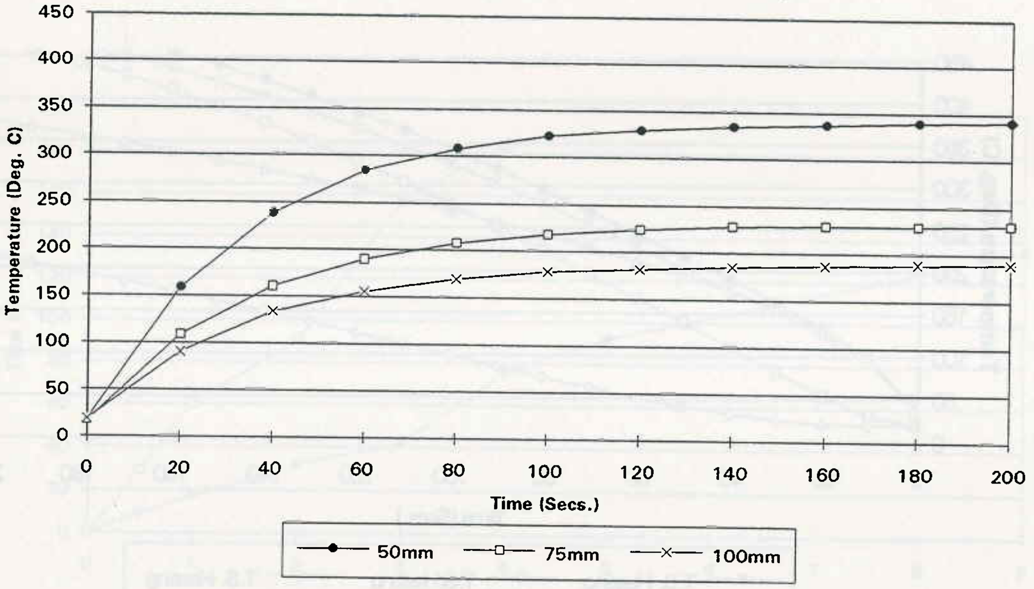

Figure 8 Comparison of experimental data (125x125x1)mm panel of consolidated APC-2 positioned 100mm, 75mm and 50mm above equi-sized (125x125)mm upward facing IR heaters of power density 25.6 kW/m^2 showing the effect of varying heater-to-composite distance.

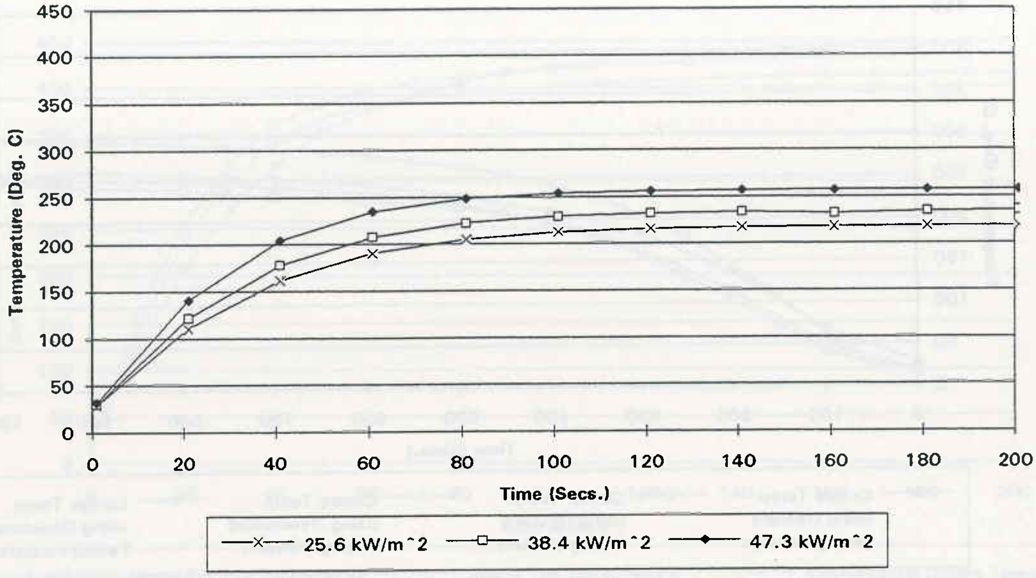

Figure 9 Comparison of model data of the average top surface temperature of a (125x125x1)mm panel of consolidated APC-2 positioned 100mm above equi-sized (125x125)mm upward facing IR heaters of power densities 25.6 kW/m^2, 38.4 kW/m^2, 47.3 kW/m^2 showing the effect that varying heater power density has on composite temperature.

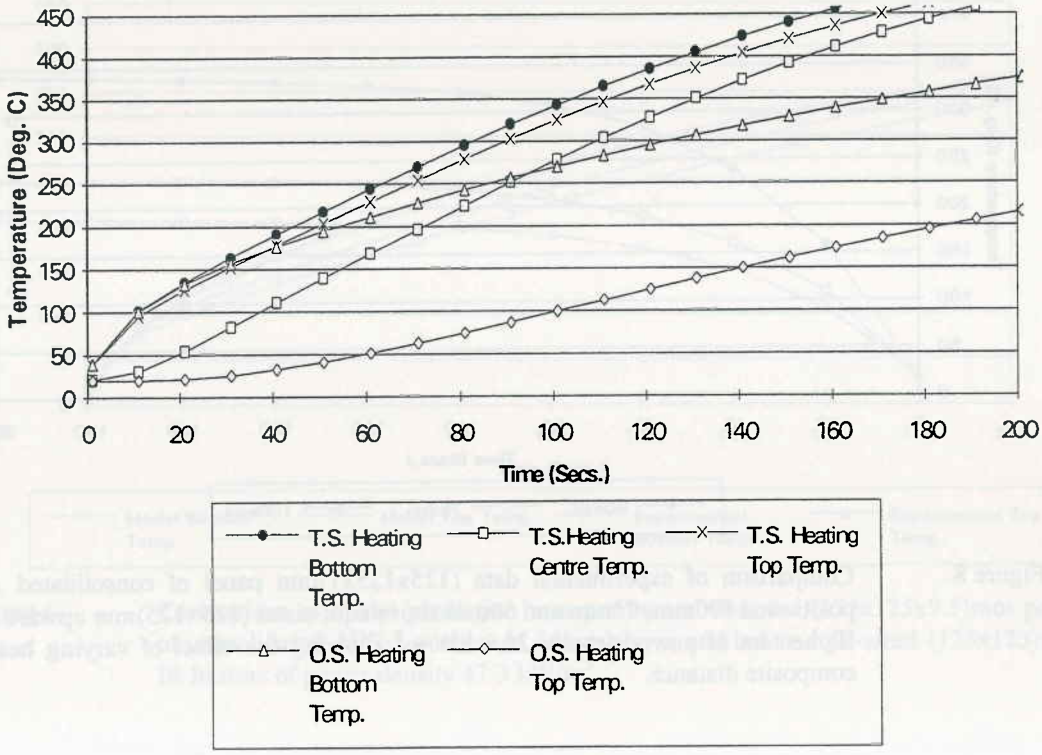

Figure 10 Model prediction of (125x125x9)mm consolidated panel of APC-2 showing the top and bottom temperature using one sided (O.S.) IR heating and showing the top, bottom and centre temperature using two sided (T.S.) IR heating placed 30mm from equi-sized heaters having a maximum power density of 47.3 kW/m^2 in both cases.

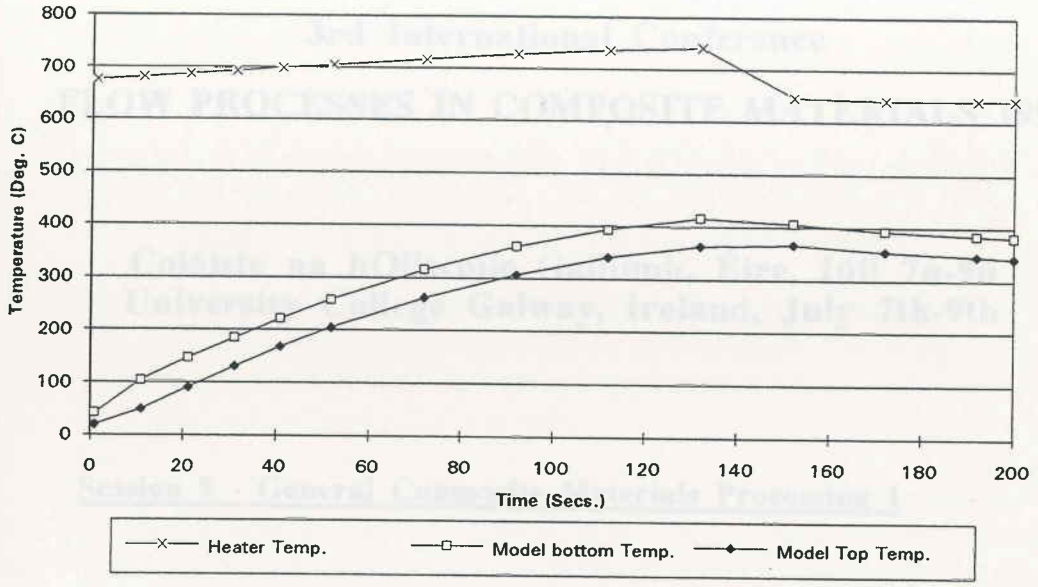

Figure 11 Plot showing model results of the top and bottom average surface temperature of a (125x125x3)mm panel of consolidated APC-2 positioned 30mm above equi-sized (125x125)mm upward facing IR heaters of power densities 47.3kW/m^2, demonstrating that a panel of thickness 3mm can be processed using one-sided heating by reducing the heater power density during the heating cycle.

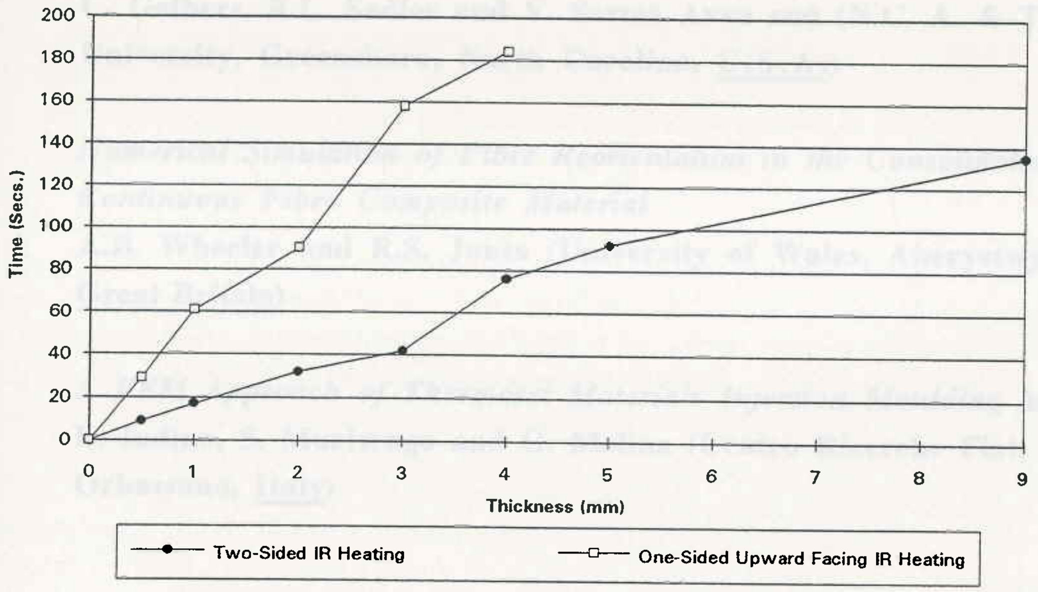

Figure 12 Comparison of model predictions for shorter IR heating cycle times required for all the material to fall within the process window range of 360°C to 400°C, for consolidated APC-2 panels of varying thickness from 0.5mm to 9mm using one-sided upward facing IR heating and two-sided IR heating with the panels placed 30mm from equi-sized (125x125)mm IR heaters having a maximum power density of 47.3 kW/m^2.