NOVEL HEAT-DIRECTED CARBON/CARBON COMPOSITES REINFORCED WITH HYBRID UNIDIRECTIONAL CARBON FABRICS

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Abstract

In this research, a novel unidirectional carbon/carbon composite reinforced with hybrid carbon fabrics, consists of PAN-based and pitch-based carbon fibers in each fabric of the composites, were fabricated and examined experimentally and numerically. The suggested composite has the ability to direct or guide the transferred heat by conduction to the proper direction or area of the thermal structure. This unique "heat-directed" property was mainly attributed due to the difference of thermal conductivity of the PAN-based and pitch-based carbon fibers.

1 Introduction

Carbon fiber reinforced carbon matrix composites or the so called carbon/carbon composites (C/Cs) have received increasing attention in recent years as potential ultra-high-temperature materials. Some of the most important and useful properties of C/Cs are light weight, high strength at high temperature up to 3000 ^{o}C in non-oxidizing atmospheres, low coefficient of thermal expansion, high thermal conductivity, high thermal shock resistance and low recession in high pressure ablation environments[1-6]. One of the unique properties of C/Cs is the mechanical strength of C/Cs increases with temperature [8-10], in contrast to the strength of metal and ceramics, which decrease with increasing temperature. These extraordinary properties of C/Cs have made these materials extremely useful right for aerospace and defense applications such as rocket nozzles, leading edges of re-entry space vehicles, thermal management components in space vehicles, brake discs, furnace heating, etc.

Recently, a practical research was carried out to use C/Cs in the near future as load bearing or long term components for primary applications of ATREX engine of Japanese Horizontal-Take-Off-Launching/Two-Stages-To-Orbit (HTOL/TSTO) space plane, e.g. tip turbine blades, heat exchanger, combustion chamber, air intake, plug nozzle [5]. ATREX is a precooled jet engine that works as a turbojet at low speeds and a ramjet up to mach 6.0 using liquid hydrogen as not only a fuel but also a coolant.

The undesirable heat energy either heat loss (e.g. in the heat exchangers) or excessive heat (e.g. in the thermal protection systems of re-entry space transportation vehicles) not only reduces the heat transfer efficiency but also make the system needs some additional requirements (e.g. cooling systems) to recover the resulted effects of this undesirable heat energy. As will Known, the light weight and efficiently consuming of the limited amount of energy are very important design requirements in the aerospace technology. Figure 1 Shows the lost and gain heat of heat exchanger as an example.

Therefore, in this research, novel heat-directed or heat-controlled materials were introduced. These materials have the ability to direct or guide the heat transferred by conduction to the proper direction or area of the thermal structure by changing the in-plane thermal conductivity functinoally. Figure 2. shows a comparison between the concepts of heat transfer in traditional materials and heat transfer in the suggested heat-directed materials.

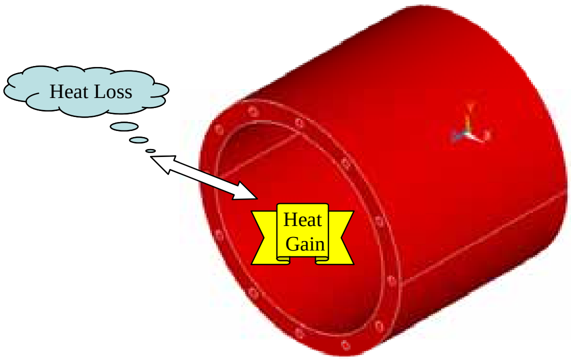

Fig. 1. The heat loss and heat gain of a heat exchanger as an example of heat transfer applications

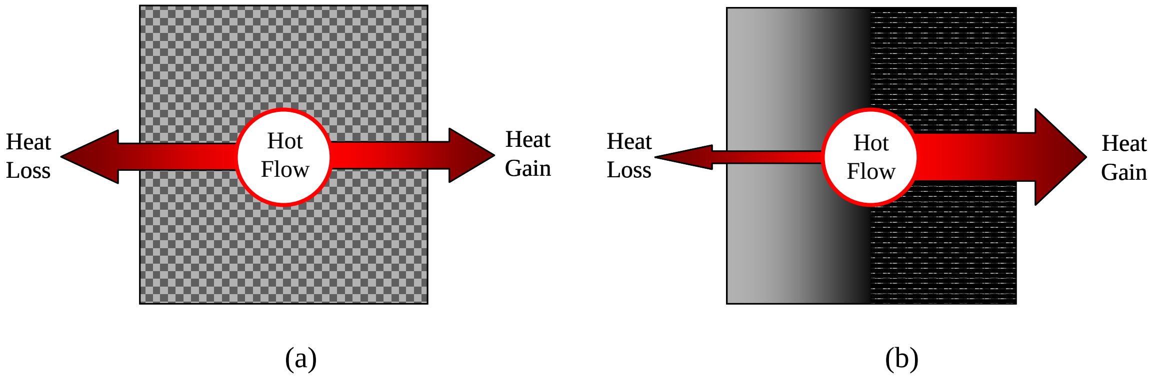

Fig. 2. (a) Concept of heat transfer in traditional materials; and (b) Concept of heat transfer in the suggested heat-directed materials

2 Materials Processing

In order to attain the above-mentioned objective, an unique fabric perform consisting of PAN-based carbon fibers (T300, 7μm, 6K, Torayca, Japan) and pitch-based carbon fibers (XN-80, 10 μm, 3K, Nippon Graphite Fiber Corp., Japan) with thermal conductivities 6.3 W/Km and 320 W/Km, respectively. This hybrid fabric was made from unidirectional prepreg reinforced with PAN-based carbon fibers via replacement about 50% of carbon fibers of the right side by the Pitch-based carbon fibers. Figure 3 shows the structure of one of these hybrid fabrics.

Sixteen of these unique fabrics were stacked uni-directionally then two PAN-based plies with plain woven were plied as external fabric surfaces for the composites as shown in Figure 4. Then, carbon fiber reinforced phenolic composites were fabricated using the above-mentioned hybrid reinforcement.

The carbon matrix of the C/C composites was positioned via conducting pyrolysis and re-impregnation processes for the phenolic resin as carbon precursor in an inert gas. These pyrolysis and re-impregnation processes were repeated sequentially five times to maximize the carbon matrix density in the suggested heat-directed C/C composites. Finally, unidirectional C/C composites have been fabricated.with fiber volume fraction about 57% and dimensions of 140, 140 and 6 mm for length, width and thickness, respectively.

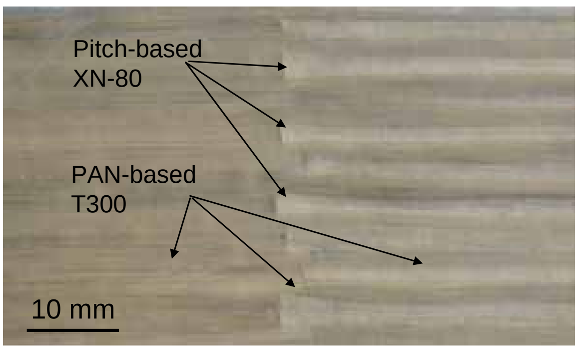

Fig. 3. Hybrid unidirectional carbon fabric

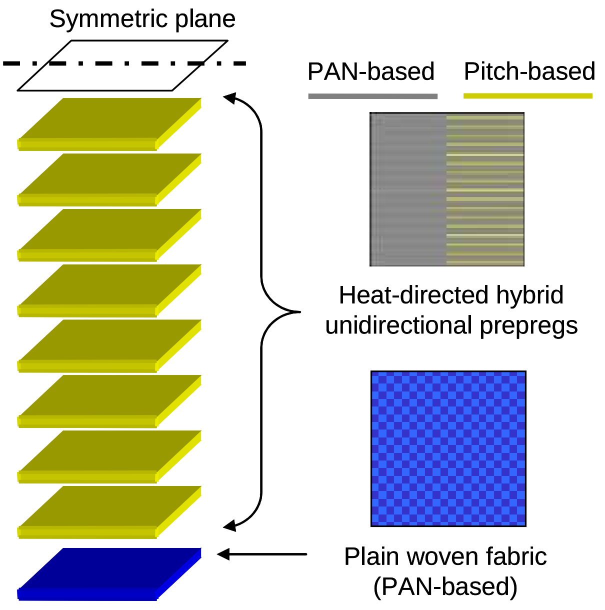

Fig. 4. Schmetic of [(0,90)F/0_8]s lay up of the suggested heat-directed C/C composites

3 Results and Discussions

3.1 Non-Destructive Inspections

The pulsed thermography is an useful technique for quantitative prediction of defect depth within composite materials [11]. Therefore, the pulsed thermography method was used as non-destructive technique to inspect some typical defects which could be found in C/C composites and to ensure the quality of the processing route of the suggested C/C composites. One such defect is delamination or lateral crack that may be present in and is of critical concern for C/C composites. Delaminations between the plies can significantly reduce the strength and performance of the ceramic matrix composite components [12-13]; therefore, they must be detected and evaluated.

Figure 5 is a schematic diagram of a thermography setup for detection of a delamination or lateral crack within a specimen. The flash lamps provide the thermal impulse, and the infrared camera monitors the surface-temperature decay on the heated surface. When the heat flux reaches the delamination or the subsurface defect, which is filled by air with higher thermal resistance, the heat transfer rate is reduced in the region above the defect. Therefore, the surface above this region will register a higher temperature than the surrounding areas, i.e., it is seen as a local “hot spot.” The hot spot appears earlier during the transient if the delamination is shallow and later if the delamination is deep. Figure 7 illustrates the time evolution of the surface temperature at eight surface regions with square of 15 mm^2 marked in Fig. 6, where the square regions 3, 4, and 5 are located at the side with Pitch-based and PAN-based carbon fibers and square regions 7 and 8 are located at the other side with only PAN-based carbon fibers while square regions 1, 2 and 6 are located at the middle region.

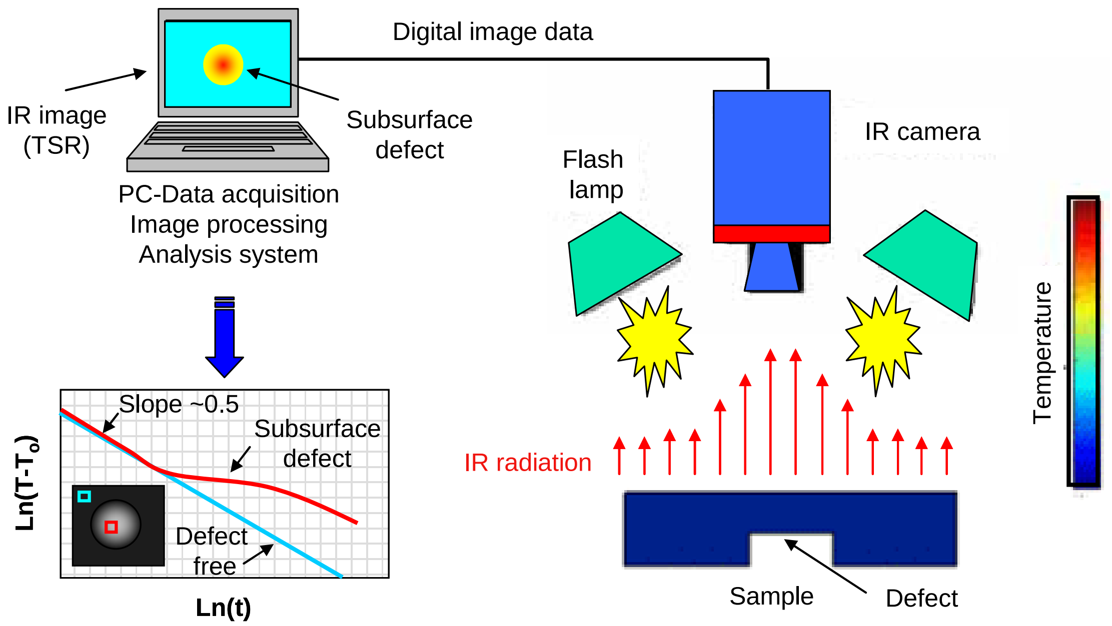

Fig. 5. Schmetic digram of the pulsed thermography setup

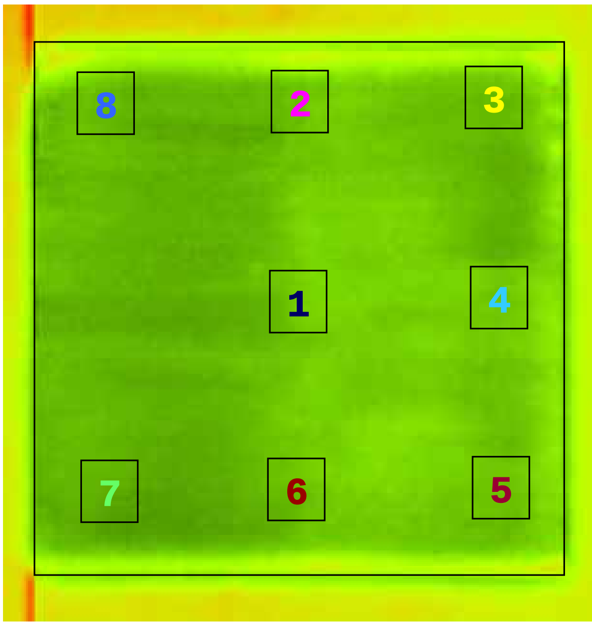

Fig. 6. Thermal wave imaging of the heat-directed C/C composites

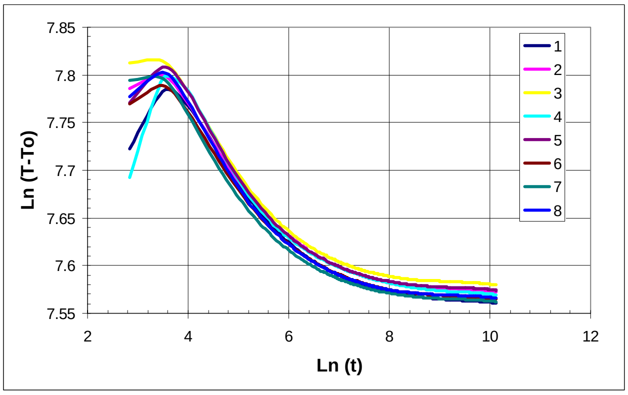

Fig. 7. Logarithmic time evolution of the surface temperature

In this pulsed thermography system, Thermographic Signal Reconstruction (TSR) method was adopted to take advantage of the physics of heat diffusion, in order to remove noise (e.g. noise of the IR camera) and extraneous non-thermal signal components from the raw signal, and to accentuate signals that deviate from typical cooling behavior [14-16]. The overall result of the TSR process is a significant increase in sensitivity to low aspect ratio features, as well as an order of magnitude reduction in RAM and storage space requirements.

From the above-mentioned results, the fabricated heat-directed C/C composites showed that there are no significant defects such as delaminations observed in the thermal weave image (see Fig. 6) and that the temperature decay is linear with slope about -0.5 until heat flow is obstructed by the boundary back wall as shown in Fig. 7.

3.2 Experimental Evaluation of Heat-Directed Property

To evaluate the in-plane heat transfer by conduction of the fabricated heat-directed C/C composites reinforced with unidirectional hybrid carbon reinforcement, a setup consists of controlled hot plate, infrared camera, data acquisition system, image processing system using Thermographic Signal Reconstruction (TSR) method, temperature logger and thermocouples was assembled Figure 8 demonstrates a schematic diagram this built-up infrared system with local heating source. A aluminum cylinder with diameter of 25 mm, contacts the controlled hot plate from one end while the another end of it contacts the composites, was used to apply local heating at the center of the bottom surface of the fabricated heat-directed C/C composites reinforced with unidirectional hybrid carbon reinforcement. In addition, insulation plate was inserted between the fabricated heat-directed C/C composites and hot plate to prevent the heat transfer by convection. In situ full field measurements of temperature prorogation and distribution of the upper surface of the heat-directed C/C composites reinforced with unidirectional hybrid carbon reinforcement were carried out up to 120 ^{o}C (the maximum reading temperature of the infrared camera).

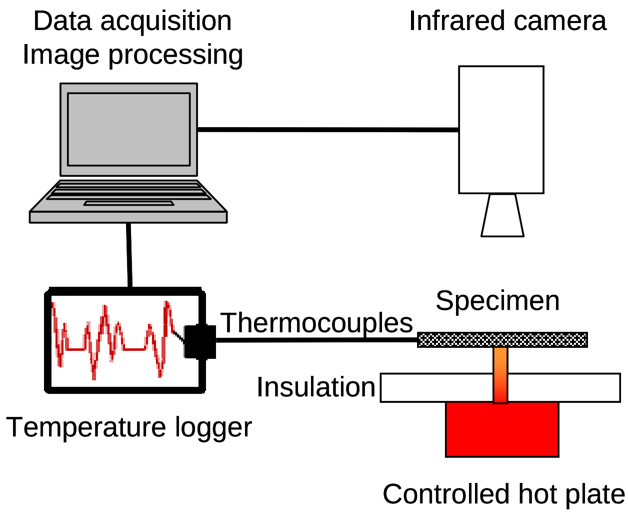

Fig. 8. Schmetic digram of the setup of evaluation of the heat-directed property

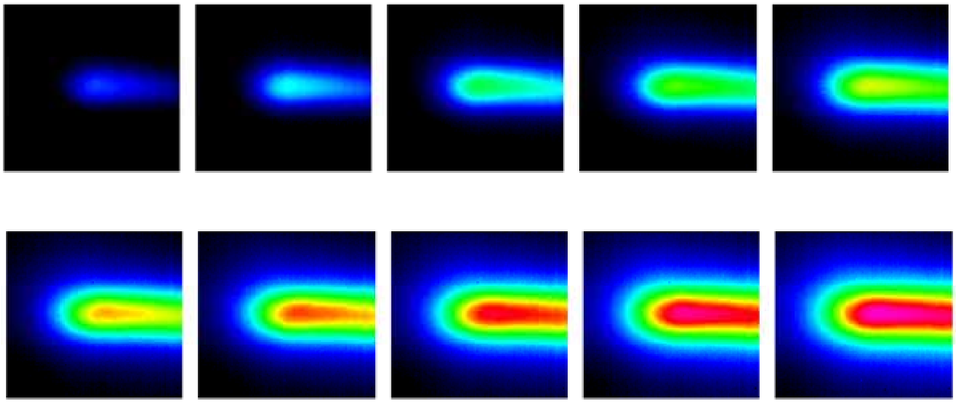

Fig. 9. Sanp shots of the temperature propagation of the upper surface of heat-directed C/C composites reinforced with unidirectional hybrid reinforcements

The built-up system was adjusted to achieve the steady state condition of maximum temperature of 115 °C for the upper surface of the composites within 800 seconds. Figure 9 shows the in-situ full-field infrared experimental measurements in form of sanp shots with interval time of 80 sec for the temperature propagation until achieving the steady state condition of the upper surface of heat-directed C/C composites reinforced with unidirectional hybrid fabrics. Figure 10 is an in-situ full-field infrared observation of temperature distribution of upper surface of suggested heat-directed C/C composites. From Figures 9 and 10, the full-field infrared experimental results of the fabricated composites showed that the heat transfer direction was significantly controlled by reinforcing the C/C composites with unidirectional hybrid fabrics

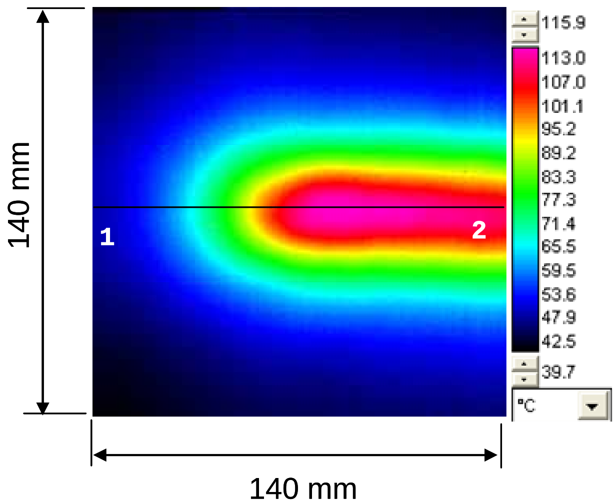

Fig. 10. Experimentally full-field infrared measurements of temperature distribution of upper surface of heat-directed C/C composites

Figure 11 demonstrates the temperature distribution along the line 1-2 which marked on Figure 10. From this result also we can see the influence of using the unidirectional hybrid carbon fabrics with carbon/carbon composites in the heat transfer process obviously. The temperature propagation of point 1 which located in the side that has PAN-based carbon fabrics and point 2 which located in side of hybrid carbon fabrics (PAN-based and Pitch-based) were monitored until reaching the steady state condition as illustrated in Figure 12.From this figure we can see clearly that not only the temperature of point 2 is much higher than point 1 but also the temperature variation of the two points during 800 sec of local heating exposure time is increasing substantially.

From the above-mentioned results, the suggested C/C composite showed ability to control the transferred heat by conduction to the designed direction. This unique “heat-directed” property was mainly attributed due to the difference of thermal conductivity of the PAN-based and pitch-based carbon fibers.

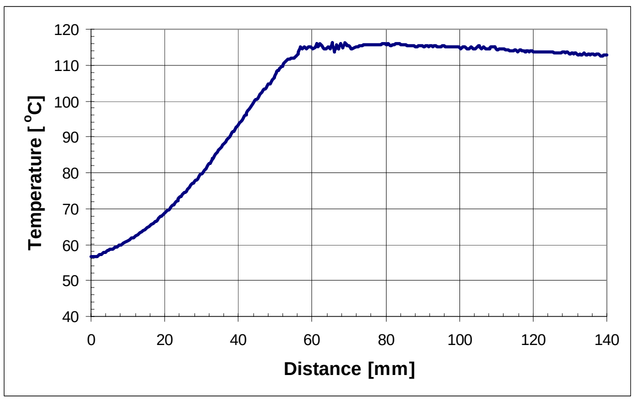

Fig. 11. Temperature distribution along line 1-2

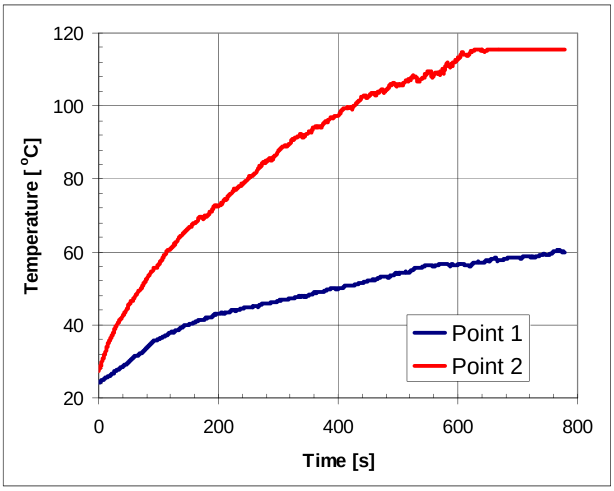

Fig. 12. Temperature propagation versus time of points 1 and 2 of the upper surface of heat-directed C/Cs

3.3 Numerical Evaluation of Heat-Directed Property

Nonlinear transient thermal finite element, FEM, analysis was carried out using ANSYS code version 9.0 with solid thermal element with 20 nodes to evaluate the heat-directed property and to predict the thermal behavior at high temperature to overcome the experiment limitations (e.g. maximum temperature of IR camera, oxidation of C/C composites in air, etc.). The longitudinal, transverse and through-thickness thermal conductivities which used in the modeling were determined by Hatta and Taya model [17], Equation 1 and 2 respectively.

$$K_L = V_f K_{fL} + V_m K_{mL} \quad (1)$$

$$K_T = K_m + \frac{K_m (K_{fL} - K_m) V_f}{K_m + (1 - V_f)(K_{fL} - K_m)/2} \quad (2)$$

Where:

K_L is the longitudinal thermal conductivity of the composites
K_T is the transverse or through-thickness thermal conductivity of the composites
K_{fL} is the longitudinal thermal conductivity of the fibers
K_m is the thermal conductivity of the matrix

Figure 13 illustrates the numerically calculated temperature distribution of the heat-directed C/C composites reinforced with unidirectional hybrid carbon fabrics. The experimental measurements and FEM simulation of the temperature distribution, Figures 10 and 13 respectively exhibited good agreement not only in the temperature distributions but also in temperature propagation of the suggested C/C composites reinforced with unidirectional hybrid carbon fabrics.

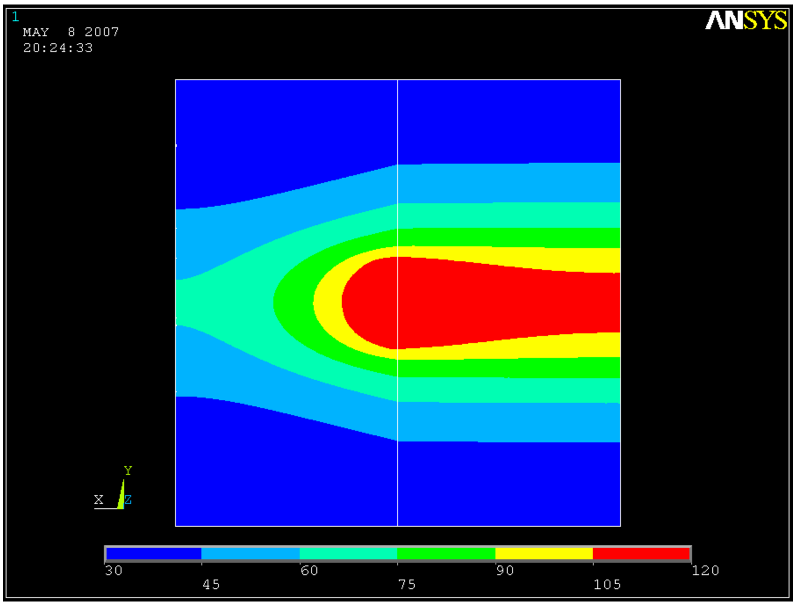

Fig. 13. the numerically calculated temperature distribution of the heat-directed C/C composites

Conclusions

In this research, a novel hybrid carbon fabric approach leads to new generation of materials with unique 'heat-directed' property which can play a significant performance improvement in heat transfer process as well as helping to decrease the heating up of the Earth, global warming, due to the escaped heat of many engineering applications. This new generation of materials has the ability to direct or guide most of the transferred heat by conduction to the desired direction or area of the thermal structure via changing the in-plane thermal conductivity of the material. To attain this unique property, a novel unidirectional carbon/carbon composite reinforced with hybrid carbon fabrics, consists of PAN-based and pitch-based carbon fibers in each fabric of the composites has been fabricated and examined. The full-field infrared experimental results of the fabricated C/C composites showed that the heat transfer direction can be substantially controlled by using the suggested hybrid reinforcements.

The suggested heat-directed C/C composite can fit in some aerospace applications such as heat exchangers, combustion chambers, plug nozzles, turbines, thermal protection systems, etc. where the light weight and efficiently consuming of the limited amount of energy are very important design requirements in these applications.

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