EFFECT OF LASER IRRADIATION ON KEVLAR FABRIC TREATED WITH NANOPOROUS AEROGEL

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Abstract

LASER is defined as an intense beam of coherent monochromatic light (or other electromagnetic radiation) by stimulated emission of photons from excited atoms or molecules. It can propagate in a straight line and occur in a wide range of wavelength, energy/power and beam-modes/configurations. They find wide applications in academic, commercial and scientific domains ranging from very simple to complex applications. This research provides an overview of the application of lasers for thermal protection from the laser irradiation for protective clothing. In this work, aerogel particles in granular form were embedded between glass and kevlar fabric and the impact of laser irradiation on the samples was studied. 150 Flexi Marcatex laser instrument was used for this experiment with the new experimental set-up. Samples with different mass of aerogel was sandwiched between the glass and kevlar fabric and its resistance to thermal radiation from laser rays was studied. The surface temperature of kevlar fabric was recorded from the backside and it was observed from the results that the surface temperature of kevlar fabric decreased with the increase in mass of aerogel. All data was statistically analysed in Matlab and Linear fit model was plotted with residuals to see the difference from observed and fitted datas.

Keywords: Laser, Thermal Irradiation, Aerogel, Kevlar

1. INTRODUCTION

Laser stands for "Light Amplification by Stimulated Emission of Radiation", is a coherent, convergent and monochromatic beam of electromagnetic radiation with wavelength ranging from ultra-violet to infrared [1]. It can deliver very low (mW) to extremely high (1-100kW) focused power with a precise spot size/dimension and interaction/pulse time (10^{-3} to 10^{-15s}) on to any kind of substrate through any medium [1-4]. It is different from other electromagnetic radiation because it is coherent, pure spectrally and propagate in a straight line. It is used for commercial, scientific and futuristic healthcare and defence applications. Laser's differentiating properties that justify its use in a wide spectrum of applications are (a) spatial and temporal coherence (i.e., phase and amplitude are unique), (b) low divergence (parallel to the optical axis), (c) high continuous or pulsed power density, and (d) monochromaticity [1-10]. Accordingly, a host of lasers capable of delivering a wide variety of wavelength, energy, temporal/spectral distribution and efficiency have been developed over the last several decades[1]. Power levels should be adequate for any application because any different either shortage or higher amount may can damage the fabrics. Thermal damage by Infra-red lasers like CO_2 can be overcome by the use of pulsed-mode CO_2 lasers, which are easier to control than lasers operating in the continuous wave mode. Aerogel is a niche material known for its unique properties such as low density, low thermal conductivity, high specific surface area, and excellent thermal insulative [11]. The thermal conductivity of aerogel is from 0.004 to 0.03 W/m·K [12]. It is being employed in varied applications such as construction, aerospace, and defense [13]. A few usages of Aerogel in clothing are: (a) NASA used aerogel to produce space suits in 2002 [14]. (b) US Navy evaluated aerogel undergarments as passive thermal protection for divers [15] (c) Corpo Nove and Hugo Boss have designed and produced an 'Antarctic Jacket' using aerogel as insulation materials in extreme conditions down to minus 50 °C [16] and (d) McFarlane Enterprises has produced a cold weather garment that is insulated with encapsulated aerogel [17]. From those applications, it can be understood that aerogel was mainly used to keep warmth in low temperature situations.

Therefore, the purpose of this study was to embed aerogel into the thermal barrier layer of kevlar and glass fabric to determine its thermal protective performance. In order to provide protection from laser devices with adequate protection against accidental laser irradiation of the skin, different mass of aerogel embedded between kevlar and glass fabrics have been investigated. CO_2 laser treatment was conducted in different experimental conditions.These solutions can be used for personal protective clothing. The passive solutions are constructed as multilayer systems (Kevlar-aerogel-glass) with high passive protection levels with respect to laser radiation. The incorporation of silica aerogel into the multilayer structure is able to increase the protection level significantly by providing the ability to deactivate the laser source upon irradiation above a threshold.

2. METHODOLOGY

2.1. Materials

In this study, glass fabric with density - 75 g/m^2 , Thickness (50 kPa) - 0.3 mm and air permeability (200 Pa)- 40 l/m^{2}s, Kevlar 49 T 968 oder T 968 TG with density - 1.45 g/cm^3, Thickness - 0.60 mm and Silica aerogel in granular form with pore diameter - 20 nm, particle density - 120-150 kg/m^3 were used. The fabrics were cut to 5 × 5 cm and sequentially placed. The thermal barrier layer with kevlar and glass fabric sample is shown in ***Fig. 3***. The mass of all the layers was measured by an analytical balance respectively.

2.2. Methods

Thermal Irradiation was carried out using a commercial pulsed CO_2 laser (MARCATEX 150 FLEXI, EasyLaser), used for cutting and marking textiles, providing a laser beam of wavelength 10.6 μm. The thickness of the evaporated layer starts in the micrometer range. Laser beams interact with fibres by local evaporation of material, thermal decomposition or changing the surface roughness. Different experimental conditions concerning laser radiation were tested in order to select the most adequate situation or situations for the thermal protection of kevlar fabric. Laser instrument is illustrated with a detailed description is shown in **Fig. 1**. CO_2 lasers are frequently used in a lot of industrial applications. The main laser characteristics are mentioned are; Model Marcatex 150/250 flexi, Average output power 150/250 watts, Peak output power 230/400 watts, Working frequency 50/60 Hz, Wavelength of laser beam 10.6 micrometre, Polarisation linear, Time mode pulse.

Fig. 1 Image of 150 FLEXI MARCATEX laser instrument

The experimental equipment consists of three parts: the sample holder, IR thermometer and laser instrument. The IR thermometer was connected to the Optris software to record the temperature on the surface of the fabric. The sample holder was largely composed of thermal insulation board with the size of 760 mm × 760 mm × 50 mm. There was a 5 × 5 cm square opening located in the center of the insulation board where the sample was placed. The experimental set up with exposed surface of the sample holder and IR thermometer fixed to a holder facing the sample surface is shown in **Fig. 2**. The camera was laid behind the sample holder, so the temperature field of the back surface of the kevlar sample can be recorded. **Fig. 3** shows the schematic diagram of the fabric/aerogel arrangement for thermal experiment. From the laser instrument, the "duty cycle" was constant for all the pixel time which is synonymous with the power applied and represents the ratio of the laser time on (pulse width) and laser time off. Its maximum value is 50% for the equipment used. The pixel time is the time used to mark each pixel of the image (in microseconds) which was varied for all the different proportion of aerogel content.

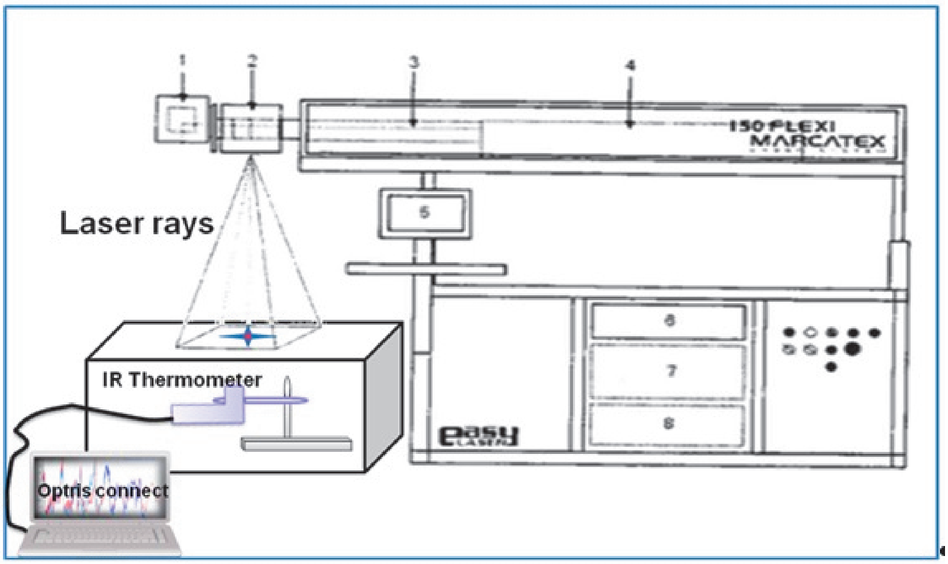


Fig. 2 Schematic diagram of Laser System

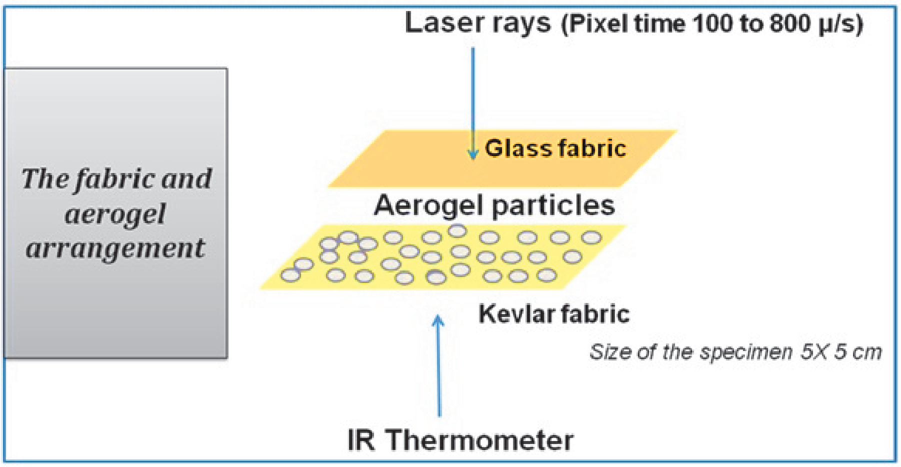


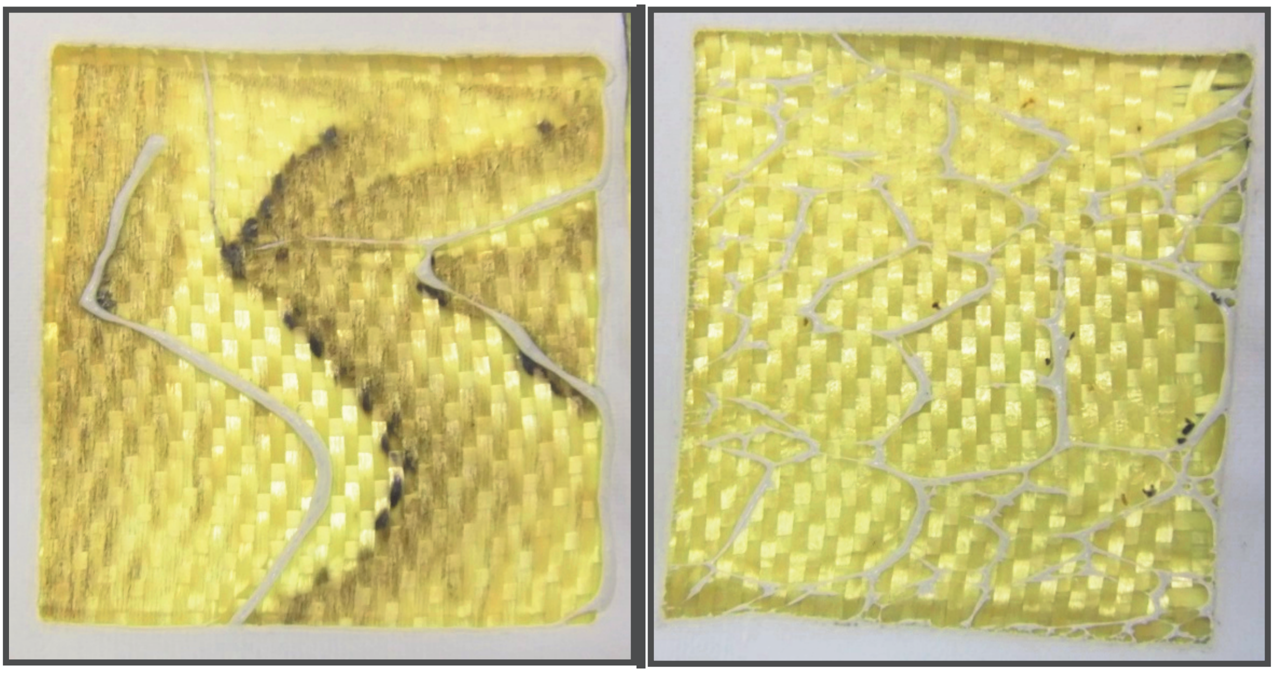
Fig. 3 Schematic diagram of fabric/aerogel setup

3. RESULTS AND DISCUSSIONS

The maximum temperatures without aerogel and the temperatures with the varied mass of aerogel content for four pixel times on the back surface of the kevlar sample are shown in **Table 2**. The mass of aerogel plays a vital role on the surface temperature of the kevlar fabric. From the **Fig. 4** (a) & (b), it is obvious that with the higher mass of aerogel content (0.5 g) the kevlar fabric was protected from the laser radiations. Whereas, the surface of the kevlar fabric was burnt due to the lower aerogel content (0.05 g).

Table 1 Results of laser experiment

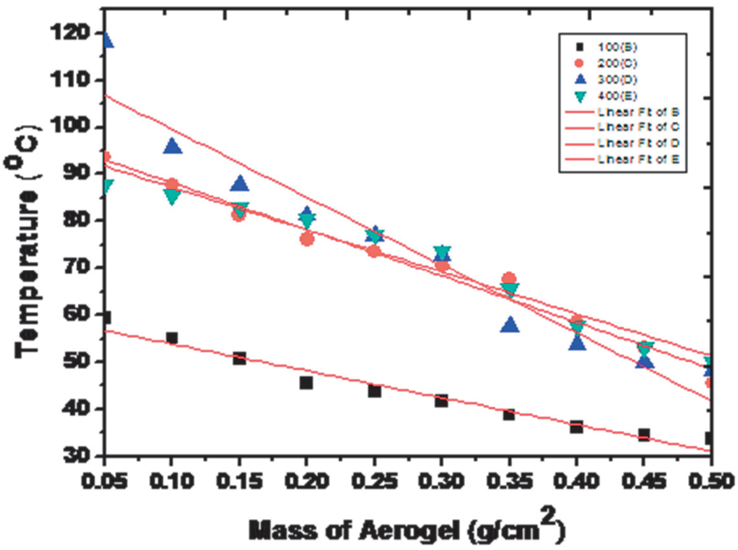
Pixel time (µs)	**100**	**200**	**300**	**400**
Maximum IR temperature without aerogel	**74.9**	**132**	**158.7**	**176.2**
Mass of aerogel (g/cm²)	**IR Temp (°C)**	**IR Temp (°C)**	**IR Temp (°C)**	**IR Temp (°C)**
0.05	59.3	93.6	111.1	87.9
0.10	55.0	87.7	95.6	85.7
0.15	50.6	81.4	87.7	82.9
0.20	45.5	76.2	81.3	80.6
0.25	43.8	73.6	76.9	77.2
0.30	41.7	70.5	72.8	73.7
0.35	38.7	67.4	57.7	65.6
0.40	36.1	58.7	53.7	57.7
0.45	34.4	53.1	50.0	53.2
0.50	33.6	45.5	48.2	50.0



(a) (b)

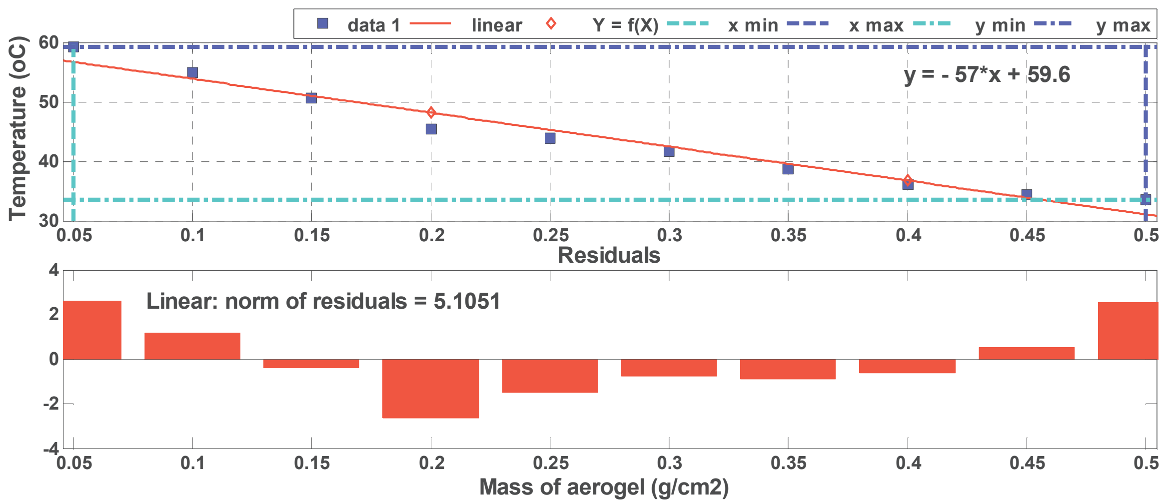
Fig. 4 Images after laser experiment
(a) Mass of aerogel **-** 0.05 g (at 400 µs)
(b) Mass of aerogel **-** 0.5 g (at 400 µs)

Fig. 6 to **9** shows clearly the temperature history of the tested sample. The temperature of the kevlar samples was lower when the mass of aerogel was increased. From the **Fig. 5** the linear fit model for all the samples were analysed and found that the adjusted R^2 was near to 0.9 which means that the temperature from backside of Kevlar fabric decreases linearly with the increase in mass of aerogel. This phenomenon of each sample was analysed for residuals and the linear fit in MATLAB and found that the observed data was very near to the fitted data which is shown in **Fig.s 6** to **9**.



Pixel Time (µs)	y = a + b*x	Value	Standard Error	Residual Sum of Squares	Adj. R-Square
100	Intercept	59.5533	1.233	26.06206	0.9579
	Slope	-57.03	3.97432		
200	Intercept	98.04	1.49074	38.09673	0.9793
	Slope	-99.164	4.80509		
300	Intercept	113.973	3.94576	266.8981	0.9345
	Slope	-144.63	12.71835		
400	Intercept	96.22	2.01695	69.73891	0.955
	Slope	-90.073	6.50123		

Fig. 5 Linear fit model for all samples



Linear model Poly1:

f(x) = p1*x + p2

Coefficients (with 95% confidence bounds):

p1 = -57.03 (-66.2, -47.87)

p2 = 59.55 (56.71, 62.4)

Goodness of fit:

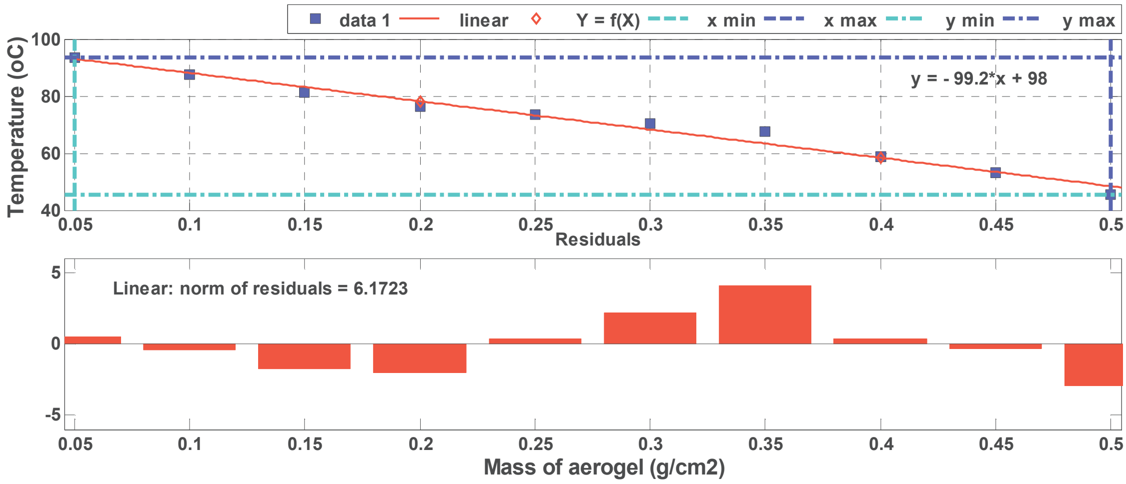
SSE: 26.06

R-square: 0.9626

Adjusted R-square: 0.9579

RMSE: 1.805

Fig. 6 Linear fit model for Pixel time = 100 µs



Linear model Poly1:

f(x) = p1*x + p2

Coefficients (with 95% confidence bounds):

p1 = -99.16 (-110.2, -88.08)

p2 = 98.04 (94.6, 101.5)

Goodness of fit:

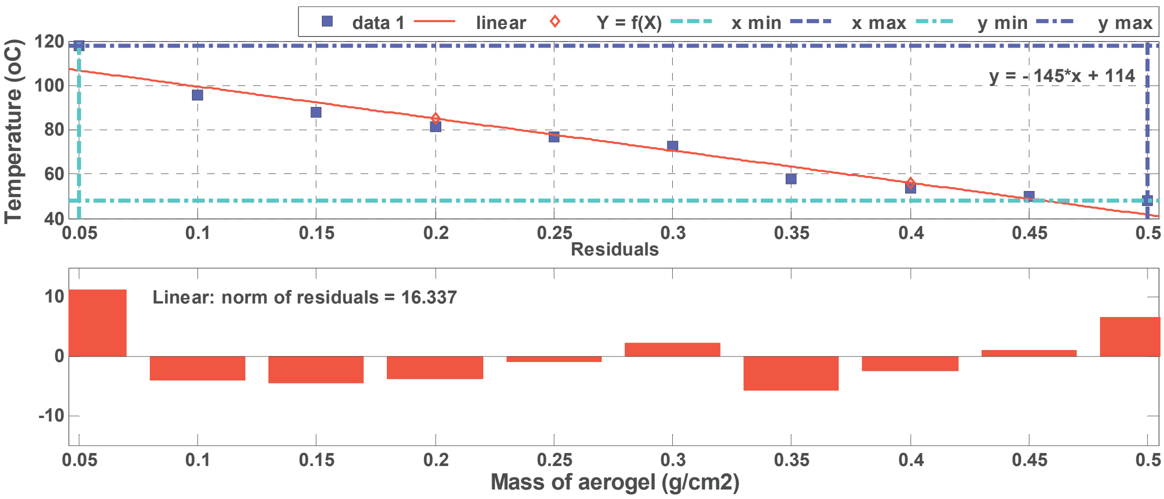
SSE: 38.1

R-square: 0.9816

Adjusted R-square: 0.9793

RMSE: 2.182

Fig. 7 Linear fit model for Pixel time = 200 μs



Linear model Poly1:

f(x) = p1*x + p2

Coefficients (with 95% confidence bounds):

p1 = -144.6 (-174, -115.3)

p2 = 114 (104.9, 123.1)

Goodness of fit:

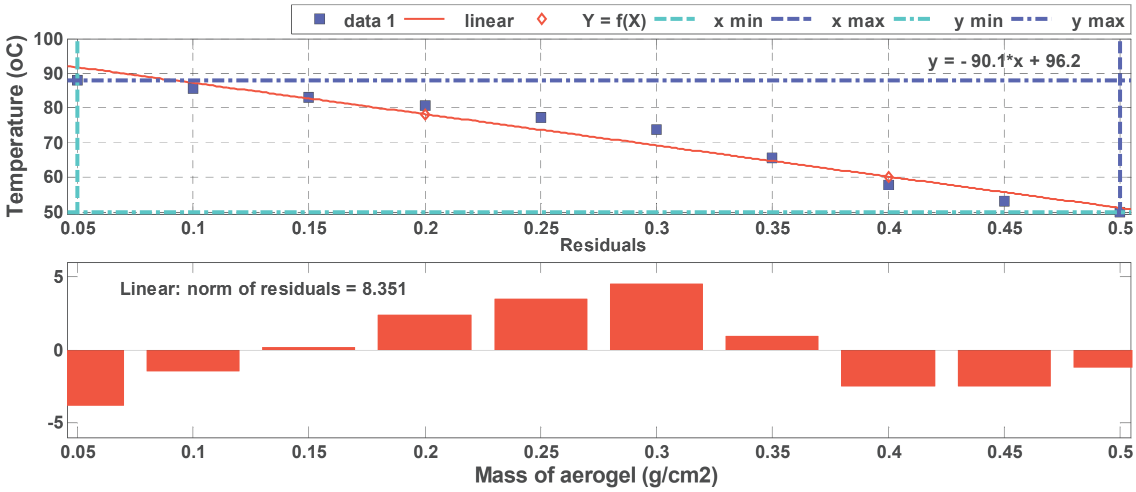
SSE: 266.9

R-square: 0.9417

Adjusted R-square: 0.9345

RMSE: 5.776

Fig. 8 Linear fit model for Pixel time = 300 μs



Linear model Poly1:

f(x) = p1*x + p2

Coefficients (with 95% confidence bounds):

p1 = -90.07 (-105.1, -75.08)

p2 = 96.22 (91.57, 100.9)

Goodness of fit:

SSE: 69.74

R-square: 0.96

Adjusted R-square: 0.955

RMSE: 2.953

Fig. 9 Linear fit model for Pixel time = 400 μs

The above results show that the Galss and Kevlar fabrics that used aerogel as a thermal barrier layer is excellent most of the time, except during the very low mass of aerogel content. The temperature difference from each sample differs due to the different pixel time from 100 **-** 400 μs. The heat transfers mainly through three ways: conduction, convection and thermal radiation. As a high porosity material, the solid volume ratio of the aerogel is extremely low. Also, the aerogel's solid-state thermal conductivity is only about 0.002 W/m·K. For the air convection inside the aerogels, it is usually very small as the pore size of the aerogel is smaller than the mean free path of air (about 70 nm). Thus, with the increase of temperature, thermal radiation becomes the main form of heat transfer in aerogels [13]. The radiative heat transfer in aerogel strongly depends on the wavelength of the incident radiation, λ, as the absorption coefficient is a function of λ. As shown in **Fig. 10**, the absorption coefficient reaches its maximum value when λ= 9.5 μm, and gets its minimum value when λ locates between 3 and 5 μm. At room temperature (e.g. 290 K), the peak wavelength is calculated by Wien's displacement law as:

$$\lambda_m = 2.898 \times 10^3 \text{ K·μm} / 290 \text{ K} = 9.99 \text{ μm} \quad (1)$$

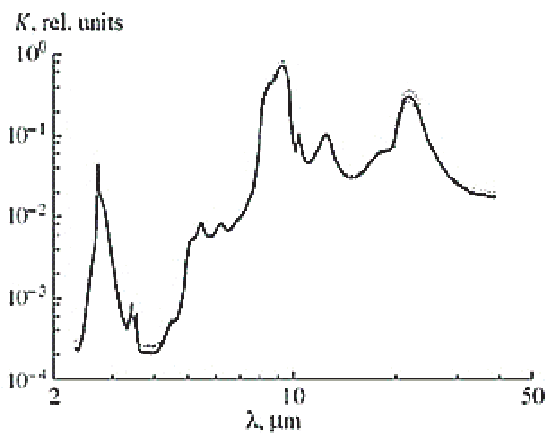


Fig. 10 The IR absorption coefficient of aerogel as a function of wavelength

4. CONCLUSION

As aerogel has the characteristics of low density and low thermal conductivity, it was embedded as a thermal barrier layer between glass and Kevlar fabric, and the thermal response was tested with the different proportion of aerogel content. When exposed to radiant heat, the backside temperature of the kevlar samples with aerogel was about 40 - 100 °C lower than that of the samples without aerogel depending on the different pixel time. From the results we can conclude that Kevlar/glass embedded with aerogel has the advantages of lighter garment and better thermal protection.

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