Infrared thermography in material research – A review of textile applications

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With the development of high resolution infrared cameras, thermography is gaining increased attention of the researcher not merely as a non-contact tool to measure surface temperature of the objects, but also as a tool in fine physical experiments to analyze thermo-physical phenomena. Apart from their regular application in condition monitoring and preventive maintenance, the infrared cameras are slowly finding application in research and development. In the field of textile research, the application of thermal imaging is still at its infancy. Most of the present applications are for qualitative observations of surface temperature profile of the object. In the present paper, various applications of thermography in textiles and allied fields have been reported with a projection of potential future research where thermography may play crucial roles.

\textbf{Keywords:} Comfort, Fracture analysis, Heat transfer, Non-destructive testing, Thermography

1 Introduction

Infrared thermography or the thermal imaging is rapidly gaining popularity amongst the researchers in various fields like medicine, biology, material science, civil engineering etc. Many researchers have explored the potential of thermal imaging not only as a non-contact two-dimensional temperature measurement tool, but also to investigate several thermo physical phenomena like heat transfer, measurement of thermal properties, non-destructive testing (NDT), greenhouse gas exchange, diagnosis of diseases, etc. In fact, any process that leads to a variation in temperature of the object can be subjected to thermographic investigation. With the present generation infrared cameras and fast data processing abilities of computer systems, infrared thermography has the potential to explore many scientific processes in experimental physics and engineering.

The researchers in the field of textiles have tried to utilize the potential of infrared thermography in different avenues encompassing fibre spinning, clothing comfort, and insulation property of textiles to NDT of textile reinforced composites. Based on the information available in research domain, the application of infrared thermography has been grouped into six different areas of textile research as shown in Fig. 1.

2 Principle of Infrared Thermography

Developed in the 1960s, infrared imaging technology is used for real-time measurement of two-dimensional surface temperature field. Infrared thermography basically includes a camera, a data acquisition and a processing computer. The infrared detector of the camera absorbs the IR energy emitted by the object under investigation and converts it into electrical signal. Any object above absolute zero temperature emits radiation that is proportional to its...
surface temperature. This radiation may be detected with the help of an infrared camera. However, the energy really detected (by the infrared detector) depends on the emissivity coefficient of the surface under measurement. Temperature measurement of infrared imaging technology is based on the following Stefan-Boltzmann law:

\[ E_b = \sigma T^4 \]

where \( E_b \) is the total blackbody hemispherical emission; \( \sigma \), the Stephan-Boltzmann constant; and \( T \), the absolute temperature of the object. Real bodies do not exactly obey this blackbody radiation law. A real body generally emits only a fraction of the radiation emitted by a blackbody at the same temperature and at the same wavelength and hence a correction factor (\( \varepsilon \)) must be included in the above equation, as shown below:

\[ E = \varepsilon \sigma T^4 \]

where \( \varepsilon \) is known as the emissivity of the object surface. It can be seen from the above equation that for any temperature \( T \) of an object, there is a corresponding energy signal which may be detected, processed and represented in a pseudo-colored image by an infrared camera. Infrared instruments are sometimes classified as total-radiation radiometers and thought to be based on the Stefan–Boltzmann law even if their detectors sense radiation in a limited bandwidth of the IR spectrum. Measurements are generally performed in two different windows, namely short wave (SW) i.e. 3-6 \( \mu \)m and long wave (LW) i.e. 8-14 \( \mu \)m. These two windows are selected based on the available transmission window of the atmosphere.

### 3 Applications

#### 3.1 Measurement of Thermal Properties of Textile Materials

In the textile research, the thermal properties of the material are of utmost importance. Michalak \textit{et al.} \cite{1,11,12} reported a series of studies that applied thermography as a non-contact method for the measurement of thermal properties and heat transfer in textile products. A custom designed set-up enabled to heat the sample on one part and observe the surface temperature distribution on both sides of the sample on the other part where it was not directly heated. From the observation of the temporal temperature evolution on both sides of the sample, it was possible to infer about the thermal conductivity of the sample both in-plane and cross-directional. The technique was used to measure the thermal barrier properties of the textile products\cite{11,12} as well. From the shape and mutual position of the time-temperature characteristics, different modes of heat transport i.e. conduction, convection and radiation were identified for the first time. In a similar study\cite{13}, the measurement of cross-directional thermal conductivity of nonwovens and nonwovens with phase change materials was reported. The technique was based on an optimization procedure that minimizes the temperature difference obtained through analytical modelling and thermography measurements. A pulse of heat was given to the material and temperature distribution was calculated during heating and cooling using 3D thermal model. Michalak \textit{et al.}\cite{6} also studied the thermal parameters of nonwovens manufactured from hemp fibres, chemical fibres and with an addition of electrically conducting fibres. In textile, such investigations using the pulse thermography method were applied for the first time. The surface of the studied nonwoven sample was exposed to infrared radiation during 100s. Distribution of temperature on the other surface of the sample was recorded during the exposure and thereafter. Results of this experiment were compared with the results of temperature distribution measurements obtained at registration of temperature distribution on the exposed surface. Analysis of the obtained results proved that the hemp fibres have better barrier properties than the studied chemical fibres. From the decay of temperature during the cooling down process it was possible to differentiate materials with different thermal conductivities and diffusivities. Another study reported thermography for the measurement of thermal properties of textile product and visualization of heat flow in textile materials and in garment design\cite{14}. To investigate the thermal effects on textile material by digital inkjet printing, Novakovic \textit{et al.}\cite{15} used thermovision camera to observe the surface temperature distribution of the sample. The printed material was subjected to a thermal load by a heating element to a desired temperature. The exact value of thermal efficiency is determined by thermovision camera. The thermovision method was also used to estimate the heat stream permeation in composite materials as a function of the distribution of the distances between
reinforcing fibres. The method was used for identifying the thermal conductivity changes in the polymer matrix and its dependence on the geometrical distribution of the reinforcing fibres.

The temperature distribution on the surface of an object in response to an incident energy flux is a function of material thermal property. If the prevailing boundary conditions are known or measured, the thermal parameters can be estimated from the transient temperature data using suitable mathematical models. An infrared camera has proved to be a very useful tool in the measurement of thermal properties of textile materials as it can measure the two dimensional temperature distribution non-destructively and with reasonable accuracy.

3.2 Measurement of Drying, Heat and Moisture Transport Property

Drying is a very important physical phenomenon for several applications and energy considerations. Heat and mass transfer during drying plays a very important role both in designing of the product as well as in deciding its final application. Therefore, a clear understanding of heat and moisture transfer in textile products is of utmost importance. Infrared thermography has been successfully applied in this direction of research. Michalak et al. studied the heat transport in nonwovens manufactured from polypropylene and electro-conductive fibres using infrared thermography. Morphological, electro-physical, and comfort properties of the produced textiles were studied simultaneously with thermographic measurements. Thermograms of the two opposite sides of the sample were recorded at the same time on an indigenous experimental stand. The results obtained indicate the possibility to determine two mechanisms of heat transport in the textiles, the radiation and the conduction. This problem is utmost important for modelling products, which should secure physiological comfort of the user, especially as thermographic methods are non-invasive investigations, and can be carried out in the on-line mode directly on the user. In order to evaluate heat conduction performance of carbon-fibre, Yunhong et al. used an infrared imaging system to analyze and measure the temperature distribution of carbon-fibre fabric, and to compare the different heat conduction performance of carbon-fibre fabric under the different temperature processing based on the changing trend of temperature against time behaviour of such fabric.

Three dimensional heat conduction in solids were analyzed and thermography measurements were used to calculate thermal properties in an inverse analysis.

Banerjee et al. applied active thermography for the validation of heat transfer model in thin porous fibrous material. A mathematical model based on finite volume method was developed to model the heat transfer in a paper sheet when it was subjected to an incident heat flux. The temporal temperature distribution on surface has been numerically calculated considering all possible modes of heat transfer and compared with experimentally measured values by active thermography. Such a model is very helpful in understanding the dynamics of heat transport in porous media. Another advantage of the thermography is the high spatial and temporal resolution. Hence, it may provide spatially resolved measurements of thermal properties and heat transfer parameters during drying. This means that not only a single thermal parameter is measured, but its distribution over time and space is also investigated. In a very interesting study of drying of textile substrate, thermal imaging has been used to find the direction of water movement and to explain the drying mechanism. In this paper, improvement in the drying rate of polyester-cotton knitted fabric samples has been shown by internal movement of water from polyester to cotton portion by surface wicking. This has been observed by tracking the surface temperature of the knit hoses during drying through thermography. Thus, thermography can give a better insight of the moisture mobility during drying and the mechanism of drying of textile materials. Since moisture mobility and its management is a very important aspect in the designing of textile products, infrared thermography could be a very useful tool in product design and development.

Another very important application of thermography has been in the development of simultaneous heat and mass transfer model in hygroscopic textile materials. It is a process characterized by coupled heat and moisture transfer process which involve vapor diffusion, fibre moisture sorption, condensation/evaporation and liquid transport by capillary. A dynamic model of liquid water transfer coupled with moisture sorption, condensation and heat transfer in porous textiles was developed by incorporating the physical mechanism of liquid diffusion in porous textiles into a coupled heat and moisture transfer model. Thermography
helped to understand such complex couplings of heat and moisture transport and may be regarded as an experimental tool for the validation of mathematical models. These models have many applications in the study of clothing comfort and processing techniques for textiles and clothing manufacture where liquid water transport is significant.

3.3 Application in Product Development and Functional Textiles

Infrared thermography has been successfully employed for the product development research, particularly in developing functional textiles. As infrared thermography is concerned with the real time visualization of surface temperature and its variation, the research on functional textiles especially in thermal application have been benefitted. Furuta et al. reported the characterization of a solar energy absorption and its retention in fabric by thermography back in mid-nineties. In an attempt to develop a warm-up suit, zirconium carbide (ZrC) compound was incorporated into the core of filaments. Park et al. developed a similar warm up suit for winter climate by incorporating ceramic powders like zirconium and magnesium oxide into the textile substrate. The effect of incorporating such active materials into textiles on body heat transfer was evaluated by infrared thermography. The heat storage capabilities and performance of such ceramic coated fabrics were confirmed by qualitative observation of thermogram data.

In the materials research, phase change materials (PCM) have found extensive application in developing smart and intelligent textiles. Phase change materials are inorganic or organic compounds which store and release latent heat through phase transition. Onofrei et al. made a nice review of different applications of textile integrating PCMs, the methods of their integration into textiles and the methods of their performance evaluation. Due to the thermo-regulating properties of the PCMs, such textiles have found plenty of applications in sports, automotive, building materials, medical, aerospace, agro and geo-textiles. Paraffin hydrocarbons and polyethylene glycol (PEG) are the examples of organic PCM suitable for textile application due to the temperature of their transition being close to human body temperature and they have a high latent heat. Infrared thermography was preliminary employed for the measurement of thermo-regulating properties of the textiles containing PCM. When PEG is cross-linked and insolubilized with tetra functional agents, in the presence of fibrous polymers, it is chemically and/or physically bound to the fibres, retains much of its PCM behaviour and creates intelligent textiles with a thermal memory that is reversible with changes in temperature. Thermal analysis of woven cotton fabrics containing bound polyols has been carried out using thermography. This has established the potential of the application of thermography in thermo-regulating textile material development. In a similar study, Chung et al. tried to develop a thermally adaptable, vapor-permeable water-repellent fabric for active wear. In this study, the authors treated a vapor-permeable water-repellent fabric with octadecane-containing (PCM) microcapsules to develop active wear with dual functions. They reported the vapor-permeable water-repellent properties as well as the thermal storage/release properties in the microclimate inside the clothing and the subjective thermal comfort sensation. The surface temperature and thermal performance of such a fabric were measured with thermography before and after exercise to compare their performance. In another study to improve the thermal conductivity of wool fabrics with conductive coating, Wang et al. reported the thermal conductivity measurement techniques, influence of synthesis parameters on the thermal conductivity of polypyrrole (PPy)-coated wool fabrics, and the relationship between electrical conductivity and thermal conductivity of PPy-coated wool fabrics. In the experimental part, an infrared camera measured the surface temperature of the hot plate and the fabric placed on the heat source till the fabric comes to thermal balance to calculate thermal conductivity. Thus, the development of thermo-regulating textiles has shown quite a few numbers of applications of infrared thermography for the characterization of the developed material.

Thermography had also found application in the area of technical textiles like electro-conductive, protective and fire resistant textiles research. Electro-conductive textiles are gaining popularity in different applications like antenna and electrodes in various novel applications. To model the operations of the electro-conductive textiles, it is necessary to know their internal current distribution which is a very difficult problem due to the anisotropy of the textile material. A sheet of textile is not a uniform and isotropic conductor due to contact resistance between fibres and interlacing yarns. Banaszczyk et al. tried
to infer the contact resistance of electro-conductive textile material by thermography. They inferred the contact resistance by computer simulation of the power distribution in the textile materials with their corresponding infrared images. A current was fed to electro-conductive textile and heat distribution was observed by infrared camera. Thus, an indirect method to find out the contact resistance of electro-conductive textiles was developed. Koncar et al. used conductive polymer composites (carbon black) for the development of electro-conductive sensors (strain) and a textile based heating elements. The heating effect was monitored using a thermal camera.

The use of infrared radiometry for the development of extreme weather protective clothing has been reported long back. A comparative performance of the fabrics was carried out without the knowledge of surface emissivity and the areas of heat loss by radiation were determined. Thermography has also been used for the evaluation of the protective textiles. Using lock-in thermography, Kevlar® based multi-layered composite consisting of 16 layers of Kevlar® fabric reinforced with formaldehyde resin were tested non-destructively for implanted delamination defects. In a study by Gandhi et al., the smoldering property of upholstery fabrics was investigated using thermal imaging to measure transient temperature field to study smoldering ignition in upholstery. Surface temperature distribution is measured during ignition and smoldering on cotton duck and commercial upholstery fabrics to explain the mechanism. The spatial distribution of surface isotherms helped to analyze smoldering propagation rate. Infrared thermography and digital image processing calculates the changes in surface thermal gradient with the advantage of high spatial, temporal and thermal resolution.

3.4 Application in Analysis of Mechanical Property and Failure

The deformation of solid material is almost always accompanied by heat release. The heat wave, generated by the thermo-mechanical coupling and the intrinsic dissipated energy during mechanical loading of the sample was easily detected by the thermal camera. Infrared thermography can also be successfully employed for non-contact, non-destructive and real time analysis of progressive damage process and failure mechanism of materials. Heat generation in the material due to intrinsic dissipation caused by anelasticity and/or inelasticity have been successfully exploited to determine parameters like the onset of damage process, stress distribution and concentration and heat dissipation localization of metals, alloys, composites, etc.

During tensile tests of textile materials i.e. fibres, yarns and fabric, fibre-to-fibre friction takes place with simultaneous fibre stretching which leads to a change in internal energy of the fibres. This phenomenon increases the surface temperature of the material which may be detected by a present generation high resolution thermal imaging system. Tensile testing methods applied hitherto consist of stretching the textile product in a quasi-static, dynamic, cyclic or any other way, and determining the load and elongation-at-break. These methods ignore the phenomena occurring in the textile material during deformation, though the knowledge of load and elongations during breaking is used for assessment of work done at sample breaking. Mikolajczyk et al. conducted the measurements of strength of textile products with thermography monitoring. A correlation has been found between the temperature at the place of break and elongation and tensile strength. The results obtained showed that the methods hitherto used for testing the tensile strength of textile products were imperfect. They provided only the boundary values of material destruction and do not take into account the processes that occur during building-up of stress. Berger et al. carried out measurements to observe natural cooling phenomena of polyester fabric through an infrared camera after heating the specimen to 60°C to calculate the total heat exchange coefficient. They also recorded thermograms during tensile testing of the polyester fabric to see the effect of test speed and cyclic loading on the maximum temperature rise during application of load. In another very interesting study, the anisotropic behaviour of the nonwoven geotextile materials was studied by Gautier et al.

Experimentally, the surface temperature of the needle punched and thermo bonded nonwovens was measured during uniaxial tensile tests. The intention was to study nonwoven structures, with an aim to link their macroscopic (fabric) behaviour during uniaxial tensile testing to their mesoscopic behaviour (phenomena that occurs at an intermediary scale between macro and microscopic behaviour) e.g. fibrous tangle, friction, movement between fibres and extension of fibres. In this study, thermography has been used to demonstrate
 thermo-mechanical coupling in solid materials loaded over their yield point. The authors did not correlate the observed temperature field and the developed strain field at different points of the specimen which could be a very interesting study to explain the thermo-mechanical couplings.

To assess the size of the damage zone and to follow its change in glass-mat-reinforced (GMT) thermoplastic polypropylene, Kocsis et al.\textsuperscript{42} employed infrared thermography. The fracture of GMT-PP was studied \textit{in situ} i.e. during loading by infrared thermography (IRT). IRT helped in determining process zone i.e. mat rearrangement stage (mesh type deformation stage), crack initiation stage and crack propagation stage. IRT was also found very helpful in understanding the fracture mechanism in such materials. Hansen\textsuperscript{43} studied the initiation of damage and its growth in an impacted woven fabric composite in tension-tension fatigue. In contrast to results from static testing, the effects of low energy impact damage in a fatigue environment were found to be the critical factor leading to the failure of the element. This emphasizes the need to identify and understand the fatigue damage mechanism. It was found that by analyzing the temperature of the external surface during the application of cyclic loading, it was possible to evaluate damage\textsuperscript{44}. IRT was found to be very useful in detecting damage initiation, growth and propagation. It also provides valuable information to the characterization of the operating fatigue damage mechanism and a faster prediction of fatigue life of materials.

3.5 Application in Comfort of Clothing
Thermal comfort is regarded as an element of clothing utility comfort. Thermal comfort refers to the maintenance of a proper relationship between body heat production and loss. Heat exchange between the human organism and its surroundings is a complex phenomenon that depends on many factors connected with the human organism, climatic conditions of the environment, and the properties and structure of clothing. In most of the cases, an infrared camera was used to observe the change in temperature due to interaction of human body with clothing. The temperature in the close proximity of human body and its variation due to its interaction with fabric has a great influence on the sensation of comfort. Ishikura \textit{et al.}\textsuperscript{45} studied the effect of skin-reflex of clothing pressure upon skin temperature by using a thermography. In this study, the physiological effects of the compression of the lower-limbs upon the changes in skin temperature were investigated on subjects wearing different kinds of elastic support knitwear and the skin temperature was measured using thermography. Zimniewska \textit{et al.}\textsuperscript{46} studied the physical parameters such as temperature, electrical resistance and thermal resistance of fabrics made from natural and synthetic fibres to find out the changes on human body caused by the cloth itself. The temperature distribution and coefficient of heat transmission were measured by thermovision on a specially designed experimental stand. A qualitative thermogram analysis showed that the heat exchange between skin and environment was much easier in case of linen than in polyester fabric leading to a sense of uncomort in polyester fabric. Gasi and Bittencourt\textsuperscript{47} tried to evaluate the physical performance improvement during physical activities due to the use of clothing made of high technology fabrics. The body surface temperature was measured by IRT and it was found that if the temp variation is less, it gives higher thermal efficiency. A higher thermal efficiency allows a better local peripheral blood circulation. The paper also described how the performance of cotton and polyamide 6,6 affects the sport performance. A modified PA allows the fabric to interact with human body by emitting an infrared, retarding muscle fatigue and improving skin elasticity.

Matusiak\textsuperscript{48} developed a thermal comfort index (TCI) as a method of assessing the thermal comfort of textile materials considering the heat exchange between the human body and its surroundings. Irrespective of the thermal resistance of clothing material, a key role in heat exchange is played by the size of air layers closed between the human body and the surface, as well as between the particular layers of clothing. In the case of one-layer clothing, thermal comfort depends on the clothing cut and fitting to the figure of the clothing user. The difference in temperature between the extreme points on the surface of the shirt may be higher than 5°C. The thermogram of human body with clothing of different materials and fitting patterns showed the temperature distribution. Such information could be very useful in designing of the comfortable clothing. Dorning \textit{et al.}\textsuperscript{49} employed infrared camera for the comfort testing of various clothing and found that the method was well suited for recording the temperature profiles of
multilayer textiles or combinations of different types of clothing. It was also observed that the results accord well with practical wearer experience. The relationship between coolness and sensation of comfort was also investigated when aerosol spray was applied to the skin\textsuperscript{50}. The distribution of skin surface temperature before and after spraying was photographed using thermography. Effect of pressure stimulation to the waist on the skin temperature of the hand was examined by thermography in two women subjects\textsuperscript{51}. It was observed that analysis of the skin temperature is useful to examine the effect of weak pressure on the human body. Wang \textit{et al.}\textsuperscript{52} developed a system to measure the clothing surface temperature distribution without interfering the air gap state using an infrared camera to investigate the effect of different air gap size on comfort sensation. Borelli\textsuperscript{53} used thermography in the analysis of the temperature of the hot tool in the cut of woven fabric. In hot cutting, the contact temperature between the cutting tool and the fabric is the most important parameter which has successfully been measured by non-contact thermography. Thus, infrared thermography has shown great applications in clothing comfort research due to its non-invasive measurement advantages.

3.6 Application in Synthetic Fibre Spinning

Infrared camera found its application in the measurement and prediction of the temperature of fine polymer filaments in many fibre production processes like melt spinning, melt blowing, and wet spinning. For these processes, experimental measurements of fibre properties along the spinline are useful for understanding the process of fibre formation. Furthermore, these measurements can serve as valuable data for testing against the predictions of mathematical models for the processes. The most successful application of infrared thermography was in the online measurement of surface temperature and diameter of fibres in the melt spinning process. Measurement of temperature in melt spinning is of utmost importance as it is required for the modelling of fibre formation, its cooling behaviour and in other rheological investigations (apparent extensional viscosity) of polymers. The techniques for measuring the polymer temperature are either contact or noncontact techniques. The usual contact technique involves use of a small metal plate with a fine thermocouple probe embedded in the plate. Such contact techniques disturb the fibre and this disturbance can affect the fibre temperature or may even cause a fibre break. Hence, a noncontact technique like infrared thermography was found very suitable.

Lu and Spruiell\textsuperscript{55} used Barnes infrared microscope to measure the temperature of the filament in melt spinning by using a null-balance technique where the radiation from a filament was compared with a known heater temperature. But they did not consider the filament emissivity and assumed the emissivity of the heater and filament to be the same. For temperature measurements on fibres during melt blowing, Bressee and Ko\textsuperscript{55} used a digital IR thermometer with adjustable emissivity. They inserted the thermometer probe into the fibre stream and measured the temperature of the fibres as the fibres collected on the probe surface. Golzar \textit{et.al.}\textsuperscript{56} carried out an online measurement of temperature along the spinline. They also proposed a new approach to measure the fibre diameter by the evaluation of the measured temperature. The principle of diameter detection is based on the difference in temperature between fibre and the environment or the ambient temperature. In the same study, they emphasized the importance of including the emissivity correction factor for the accuracy in measured temperature and also proposed two experimental techniques to measure the correction factor. However, due to the limitations of the infrared camera in spatial resolution, diameter below 25 µm could not be resolved spatially. Bansal and Shambaugh\textsuperscript{57,58} and de Rovere and Shambaugh\textsuperscript{59} used a slit response factor curve to account for the spatial resolution of their IR camera while measuring the temperature of fibres in the melt spinning and melt-blowing processes. The slit response factor curve corrected the errors involved in measuring the temperature of fine fibres where the fibre diameter has a size that was on the order of a pixel. This helped to improve the spatial resolution of the measurements. In a similar direction, Marla \textit{et al.}\textsuperscript{60} compared the temperature of polymer filaments held in a stream of hot air by a thermal camera and a thermocouple held close to the filaments. Under certain conditions, the air temperatures determined by the thermocouple closely approximate the temperatures of the polymer filaments. In this way, they developed a calibration curve for the infrared camera and used the same calibration curve for the online measurement of fibre temperature. Their study also addressed two very
important aspects relating to the use of infrared thermography to measure fibre temperature. Firstly, the emissivity of the polymer filament must be accurately known and secondly, the effect of the small dimension of the filament relative to the detector array of the infrared camera must be considered for the accuracy of results. In yet another reporting by Marla et. al., online measurements of fibre temperature and diameter were carried out for both the melt-spinning and the melt blowing processes. The fibre temperature was determined by infrared thermography, and the fibre diameter was determined by high-speed photography. These measurements were then compared with predictions made with mathematical models for melt spinning and melt blowing. A very good agreement between the models and the experimental results was observed, and the agreement was best when heat-transfer correlations developed specifically for fine cylindrical fibres were considered.

3.7 Non-destructive Testing of Multi-layered Structures

Recently the textile fibre, fabric or nonwoven materials are being used as reinforcing material in composites and multi-layered laminated structures. Such materials are gaining huge popularity due to their high strength to weight ratio and corrosion resistance and are finding many industrial applications. Composite materials can be affected by manufacturing process defects e.g. voids due to volatile resin components, bonding defects, delamination, ply cracks, foreign bodies, etc. There could also be defects in-service like fractures of fibres, cracks, ingress of moisture, impact damage, delamination, etc. Infrared thermography is evolving as the most useful method in non-destructive testing (NDT) of materials such as composites, electrical components and building materials. The advantages of this technique are fast, reliable and real time measurement over a larger surface area. Thermography is particularly suitable for non-destructive testing on composite materials providing a global mapping where other methods like ultrasonic gives only local result. Infrared thermography has been used heavily to detect defects in multi-layered structures and a plethora of literature is available which describe different NDT thermography techniques viz. pulsed thermography, lock-in thermography, pulsed-phase thermography, and frequency modulated thermal wave imaging. The complete details of each technique and its application are out of the scope of the present paper and a good number of literatures may be found elsewhere.

4 Future Prospects

As it is evident from the previous discussion, infrared thermography has found a plenty of applications in the textile research. It is also observed that in most of the cases the infrared camera was used to measure the surface temperature of the object i.e. as a non-contact two dimensional thermometer. It must be mentioned here that in most of the previously mentioned applications, the authors did not mentioned about the surface emissivity of the object which is utmost important for quantitative thermography. In very few cases, the measurements of emissivity before quantitative thermography have been reported. Therefore, there is a huge research gap in ascertaining the surface emissivity of different textile products at different infrared frequencies and at different temperatures.

Apart from being used as a non-contact 2D thermometer, infrared cameras have tremendous potential in fine physical experimentation too. Quantitative infrared thermography has also been successfully employed in local heat transfer measurements and in fluid flow visualization. Such techniques rely on the measurement of surface temperature gradient or surface heat flux, or some other scalar, which is a function of surface temperature. The phase relation between the surface heat flux and the subsequent surface temperature depends upon the thermo physical properties of the model, the heat flux driving frequency and the local heat transfer coefficients. Thermal processes in solids, liquids, and living tissues are being studied today with infrared thermography. In a recent investigation, Vainer have shown how a modern focal plane array based high resolution infrared camera can offer a plethora of new possibilities to investigate fine physical experiments. An infrared thermography can be useful in investigating any dissimilar physical phenomena causing thermo-physical effects as thermography combines real time visualization with an opportunity of quantitative analysis. The adsorption kinetics of vapour on fabric surfaces have also been analytically and quantitatively evaluated using an infrared camera.

With a temperature sensitivity of hundredths of a degree that has become available in the FPAs at frame rates of hundreds of frames per second makes FPA-based IR systems very attractive as high-tech
and high performance experimental tool in any kind of thermo physical measurements. In the field of textile research, infrared thermography has huge potential to explore in heat and moisture transfer, mechanical property analysis and enhancement, multi-layered structure investigation, drying and moisture management, development of functional and technical textiles. It may also help in developing engineered textile products like thermo regulating fabric, composites, PCM incorporated material with engineered thermal property, smart and intelligent textiles, such as conductive, protective and comfortable clothing.

5 Conclusion

Based on the above review of literature, it can be concluded that infrared thermography can be a very useful technique in different applications of textile research. Although most of the applications in textile so far have been in the passive observation of surface temperature development, an active thermography has also been ventured in some of the applications. An infrared camera is a single important instrument that may not only be useful in measurement of thermal properties, analysis of mechanical properties, heat transfer, but also may give an important insight into various dynamic phenomena like absorption/desorption, wicking and moisture management, vapour and capillary transport of liquid in textiles. Hence, an infrared camera can be an asset to any textile research laboratory in future. The quantitative thermography needs precise knowledge of surface emissivity of the object. The knowledge of emissivity of textile substrate is not well documented as of now. Surface emissivity is a function of IR wavelength, surface property of material, and temperature, which may vary in individual experimental conditions. Therefore, any quantitative thermography would require prior knowledge of surface emissivity for accuracy. With the continuous development of high resolution infrared cameras, infrared thermography will surely contribute extensively in textile research in future.

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