Synthesis of Functional Nanocapsules and their Application to Cotton Fabric for Thermal Management

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Abstract

Smart, phase change materials can provide comfort to the wearer in extreme weather by absorbing heat in hot environment and releasing stored heat in cold environment. The nanocapsules containing mixture of paraffin as phase change materials were synthesized to bring the temperature around 33 °C which is closer to the skin comfort temperature. The developed nanocapsules were applied on a cotton fabric via pad-dry-cure process and the resultant fabric was evaluated using DSC and SEM in comparison with MPCM treated fabric. Furthermore the synthesized nanocapsules were incorporated into polypropylene monofilament to compare their properties with microencapsulated PCM monofilament. The results indicated that nanocapsules showed better durability on cotton fabric than microencapsulated phase change materials. The decrease in latent heat was more for microencapsulated PCM after washing than Nanoencapsulated PCM.

Keywords

Melamine formaldehyde, nanoencapsulation, latent heat, cotton, thermoregualting

Introduction

Thermal management has always been a challenge where high temperature and heat is involved such as steel mills, glass factories and sports activities (Yang et al. 2007). To overcome these

problems, researchers have been working on smart textiles or intelligent textiles. Phase change materials are active smart materials which can sense and react to the environmental stimuli by storing and releasing heat energy (Onofrei et al. 2010). Phase change materials cannot be applied directly on textiles because they melt by absorbing heat or crystallize by releasing the same heat. To prevent phase change materials from leakage, a process called microencapsulation or nanoencapsulation is used for durability and better application (Mondal 2008).

PCMs are attractive for storing energy in all the available heat energy storage techniques due to the high density, compact storage system and high latent heat (Farid et al. 2004; Mondal 2008). The pioneer study of phase change material was applied for space crafts on small scale and then on large scale was applied in buildings and solar energy systems to build thermal energy storage system (Buddhi et al. 1987; Lacroix 1993; Pauken et al. 2007). A large number of inorganic and organic PCMs are available in the temperature range of -5 °C to 190 °C (Agbossou et al. 2010; Alkan 2006; Choi et al. 2001). The organic phase change materials ranging from 18-65 °C are used in textiles and buildings to enhance thermal comfort effect (Tyagi and Buddhi 2007; Zalba et al. 2003). Among all the PCMs, n-octadecane is usually used for the textile application having melting point of 28 °C (Feldman et al. 1986).

Microencapsulation is the process of covering core material such as PCM in a protective shell called capsule. Microcapsules define the particle size in the range of 1µm to 1000 µm while nanocapsules are used to describe the particle size less than 1µm (Sarier and Onder 2012). There are many techniques for microencapsulation such as complex coacervation (Uddin et al. 2002) *in-situ* polymerization (Jin et al. 2008), interfacial polymerization (Chen et al. 2012), and spray drying (Borreguero et al. 2011). *In-situ* polymerization is widely used among all of these synthesis

techniques because of rapid wall formation and also strong capsule formation suitable for textile (Mondal 2008; Zhao and Zhang 2011).

Shin et al. (2005) synthesized microcapsules containing n-eicosane as core material and melamine formaldehyde as shell material by *in-situ* polymerization. They determined that the latent heat of MPCM was 134.3 Jg^{-1} with particle size of 1.89 µm. The maximum latent heat of thermo-regulating textiles after application was determined as 4.44 Jg^{-1}. Sarier and Onder (2007) used urea formaldehyde as shell material and different paraffin; n-hexadecane, n-octadecane and n-eicosane as core materials. The average particle size of microcapsules was found to be 69.1µm with 51.7-54.8 Jg^{-1} of latent heat. Fang et al. (2010) prepared microencapsulated phase change materials using silicone dioxide as encapsulating shell and paraffin as core material via Sol-Gel method. The differential scanning calorimetry results showed that the latent heat of microencapsulated paraffin was 165.68 Jg^{-1}. Li et al. (2011) encapsulated n-hexadecane using urea formaldehyde as shell material. They studied the effect of surfactant on the process of nanoencapsulation and obtained the average capsule diameter of 270 nm. They determined that as the amount of surfactant increases, the particle size of nanocapsules decreases affecting the thickness of wall of particles; latent heat was found in the range of 114.6 -143.7 Jg^{-1}.

Salaün et al. (2009) synthesized microcapsules using melamine formaldehyde as shell material and different paraffin as core material with their binary mixtures. They added 4% wt. tetra ethyl ortho-silicate to enhance latent heat of phase change material. Sánchez et al. (2010) microencapsulated paraffin wax from C_{19} to C_{27} sourced commercially as a mixture using polystyrene as shell material. The melting temperature of MPCM was from 40°C to 45°C. They coated 100% cotton fabric with prepared microcapsules using different commercial binders to characterize the thermoregualting effect of the fabric and 7.6 Jg^{-1} of latent heat was found on fabric containing 35%

wt. of MPCM. The time duration for thermoregualting effect increases with the increase of the amount of latent heat and hence more Jg^{-1} is required where longer time duration of thermoregualting effect is required.

Nanoencapsulation has been paid attention by more researchers now days because of narrow particle size and enhanced surface characteristics when they are applied on textiles for thermoregualting effect (Sarier and Onder 2012).

Sarı et al. (2009) synthesized nanocapsules using PMMA (polymethyl methacrylate) as a shell material and n-octacosane as a core material for thermal energy storage. The melting temperature was measured as 50.6 °C containing latent heat of 86.4 Jg^{-1}. The average diameter of the nanocapsules was 0.25 µm. In 2010, Kwon et al. (2010) developed NPCM (nanoencapsulated phase change materials) with particle size less than 100 nm. They used polystyrene and PMMA as a shell material to encapsulate n-octadecane as PCM. The latent heat measured for polystyrene and PMMA based nanocapsules were 114 Jg^{-1} and 120 Jg^{-1} respectively. Nanocapsules of n-hexadecane with PMMA shell was made by Black et al. (2010) with the particle size between 100 nm and 280 nm. Alay et al. (2010) studied nanocapsules of PMMA shell containing n-hexadecane as core material with an average diameter of 260 nm and 148.05 Jg^{-1} of latent heat at 17.23 °C. They incorporated nanocapsules into the PAN fibre during electrospinning and measured the heat of fusion which was 36.80 Jg^{-1}.

More recently Karthikeyan et al. (2014) made NPCM containing urea formaldehyde as a shell and paraffin wax as a PCM using *in-situ* polymerization technique; the average particle size was 256 nm. They applied nanocapsules on cotton fabric with 20% and 40% on the weight of binder using pad-dry-cure method and the latent heat was found 15.2 Jg^{-1} and 19.1 Jg^{-1} g respectively.

The humans are thermally comfortable when their skin temperature is around 33 °C while in rest and less than 33 °C if any of the physical activity is involved. No research has been focused until now on synthesizing melamine formaldehyde NPCM in the range of 33 °C to target the skin comfort temperature. The synthesis of nanocapsules in this research work focuses on the preparation of nanocapsules using melamine formaldehyde as shell material and mixture of n-octadecane and eicosane as core PCM. Moreover the developed capsules were in nano scale with narrow size distribution suitable for melt spinning process for synthetic filament production to overcome mixing and extrusion problems.

Materials & Methodology

Melamine and formaldehyde were purchased from Alfa Aesar® and used as raw materials to synthesize MF (melamine formaldehyde) capsule shell. Formaldehyde purchased was 37% w/w in aqueous solution. Eicosane and n-octadecane purchased from Alfa Aesar® were used as PCM core material. Sodium dodecyl-benzene-sulfonate (SDS) was used as an emulsifying agent and polyvinyl alcohol (PVA) was used as a stabilizer. Acetic acid and NaOH were used as pH controllers. The synthesized nanoencapsulated paraffin was compared with commercially available MPCM 28 which is pure octadecane containing phase change temperature of 28 °C.

The nanocapsules were synthesized and incorporated in polypropylene yarn through melt spinning process and were applied on cotton fabric via pad-dry-cure technique. The experiments were designed using Minitab and the effect of factors on response has also been studied.

DOE (design of experiments) aimed to identify the processing conditions, parameters and product components that affect the quality of nanoencapsulation and optimize those factors for the best result. DOE helps to investigate the effects of factors (input variables) on response (output

variables) at the same time. The designed experiments were composed of series trials where different levels of input variables were used. Data was collected for each trial in the form of output variables.

In the design of experiment, Box-Behnken method was selected for nanoencapsulation to determine the effect of levels of different factors on response. Box-Behnken design usually has fewer design points than central composite design thus it is less expensive to run with the same number of factors. Box-Behnken design is very useful especially when safe operating zone of a process is known. Box-Behnken design always has 3 levels per factor unlike CCD (central composite design) which has up to 5 levels per factor because of the axial points in the design. The axial points were not desired in the current research therefore Box-Behnken design was adopted.

Table 1 shows the three factors and their levels which were used to study the particle size of NPCM. Using the above lower and upper levels of each factor, experiments were designed using Box-Behnken response optimizer. The estimated range of upper and lower levels was selected based on the knowledge and experience to attain the desired response. Table 2 shows 15 designed experiments in different combination of levels with each factor. All the experiments were randomized by default and were performed according to the run order. The last column shows the particle size against each experiment as outcome.

Table 1. Factors and levels for DOE

Factors	**Lower level**	**Upper level**
Emulsifier [g]	0.7	1.2
Emulsion speed [rpm]	5000	10000

Encapsulation stir speed [rpm]	400	800

Table 2. Design of experiments

		Factors			Response
Std. order	**Run order**	**Emulsifier [g]**	**Emulsion stir speed [rpm]**	**Encapsulation stir speed [rpm]**	**Particle size [nm]**
15	1	0.95	7500	600	610
6	2	1.20	7500	400	1500
5	3	0.70	7500	400	1505
13	4	0.95	7500	600	611
11	5	0.95	5000	800	1398
9	6	0.95	5000	400	1505
1	7	0.70	5000	600	1836
3	8	0.70	10000	600	700
4	9	1.20	10000	600	1168
10	10	0.95	10000	400	589
2	11	1.20	5000	600	2261
12	12	0.95	10000	800	318
14	13	0.95	7500	600	620
8	14	1.20	7500	800	1467
7	15	0.70	7500	800	743

Experimental

In-situ polymerization technique was used for the synthesis of nanocapsules. For oil in water emulsion, (20g of) octadecane and (10g of) eicosane were taken in (150mL of) distilled water containing SDS and (0.1g) stabilizer. The amount of SDS (emulsifier) and emulsion stirring rate were used in different combination and has been shown in Table 1. The emulsion was prepared under high stirring rate using high speed homogenizer at 70 °C for 30 to 40 min. as shown in Figure 1.

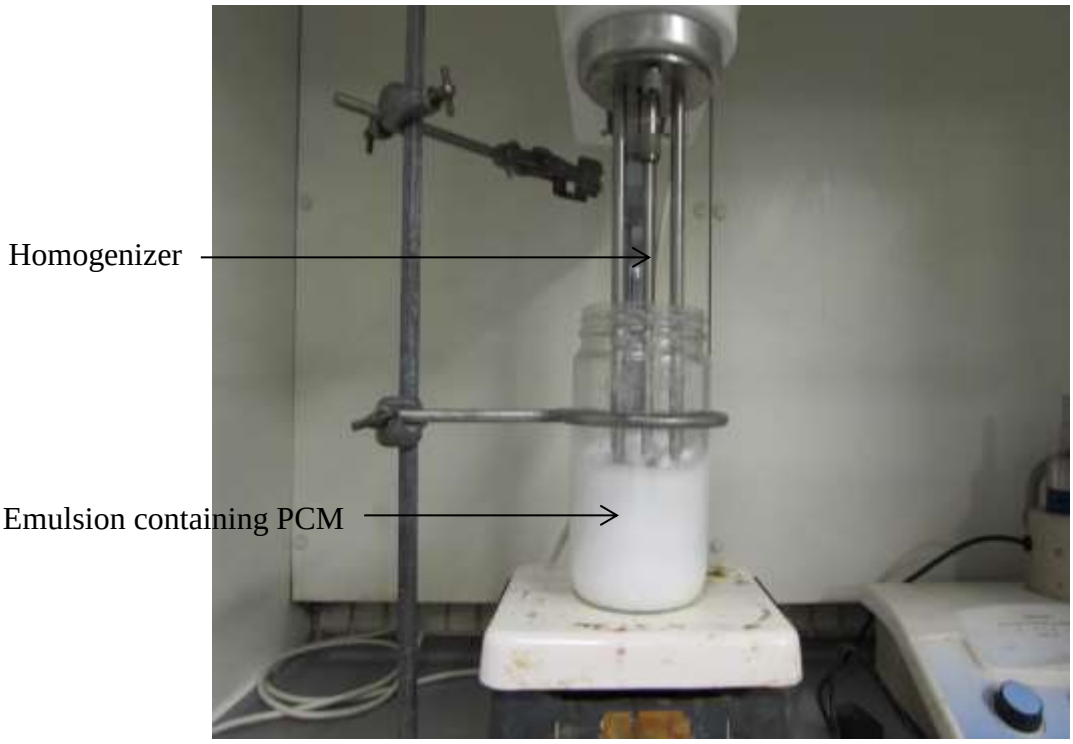


Fig. 1 O/W emulsion using high speed homogeniser

The prepolymer solution was prepared by adding (10g of) melamine and (20g of) formaldehyde in (50g of) distilled water and mixed at 60-65 °C as shown in Figure 2 (a) until a clear solution was obtained as shown in Figure 2 (b).

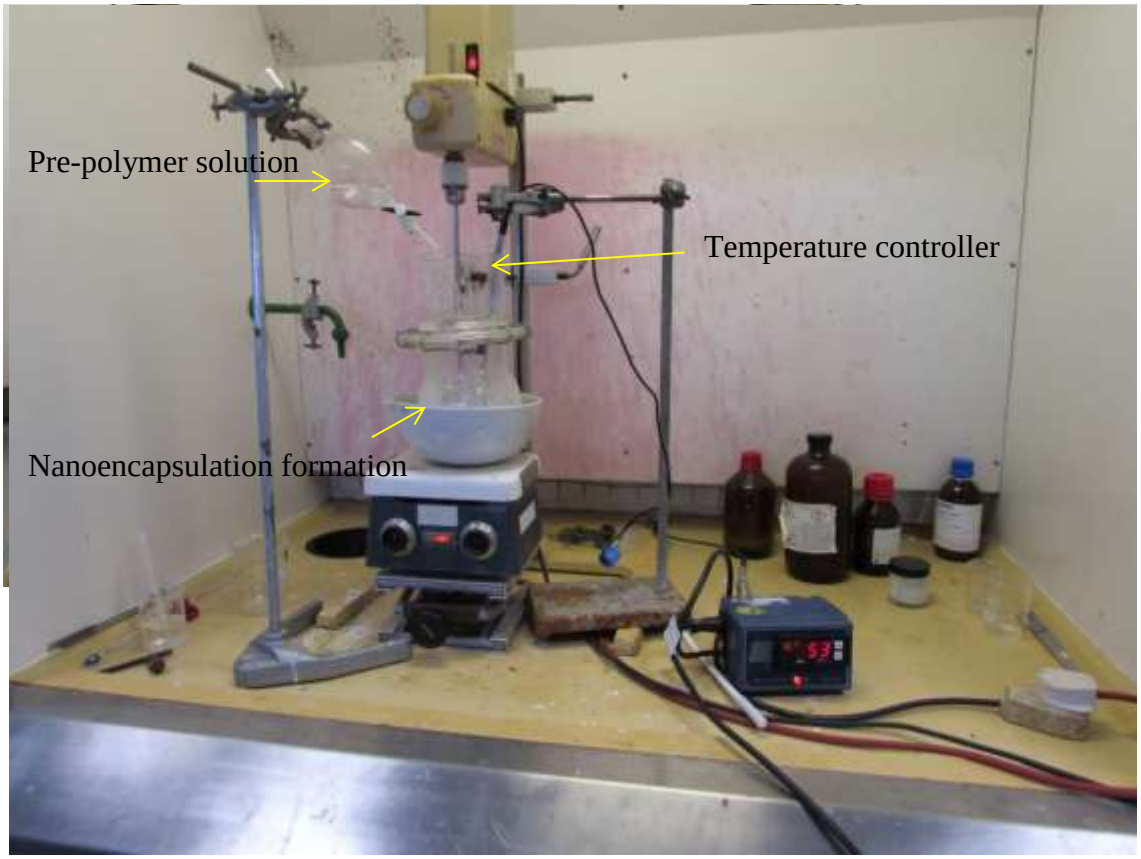
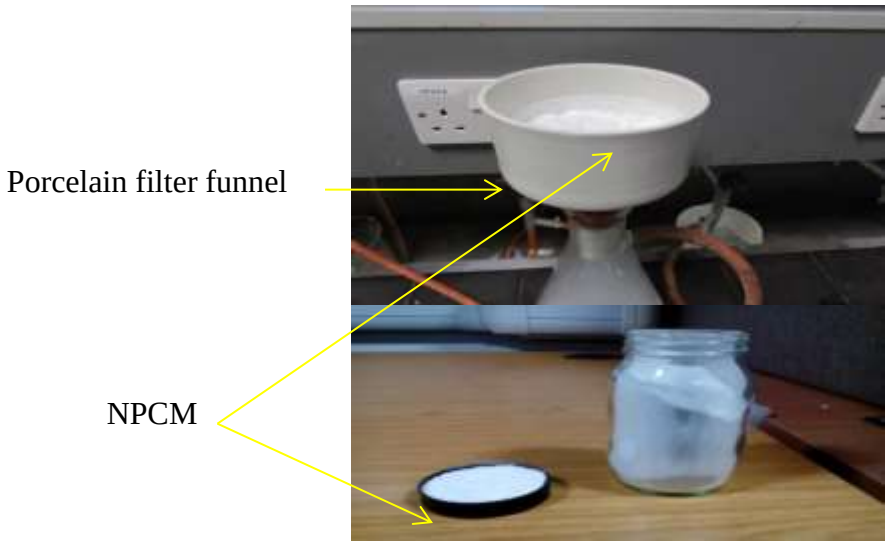


Fig. 2 Pre-polymer formation using melamine and formaldehyde

For nanoencapsulation, the emulsion was poured into three neck flask and prepolymer solution was dribbled into the emulsion drop wise as shown in Figure 3. The temperature of the mixture was increased gradually up to 80 ℃ while controlling pH in the range of 4-4.5 using acetic acid. The mixture was under stirring using different rpm speed as shown in experimental design. The process was held under controlled parameters allowing polycondensation reaction to complete and nanocapsules were washed, filtered and dried to get NPCM paraffin powder as shown in Figure 4.

Fig. 3 Encapsulation of NPCM paraffin in reaction flask



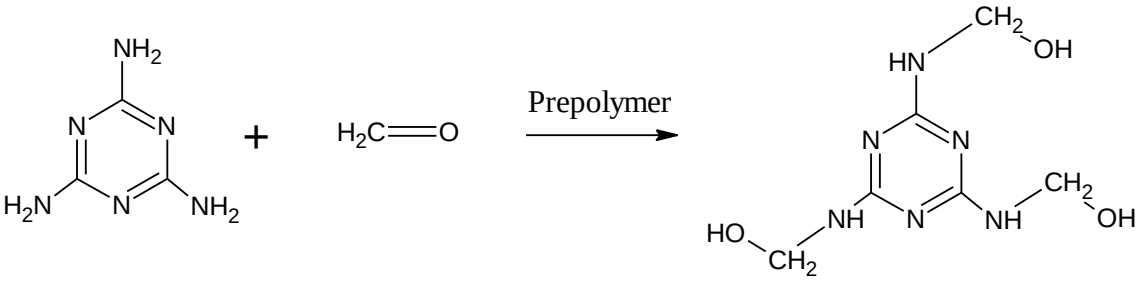
156

157 **Fig. 4** NPCM after filtration and drying

158 Reaction mechanism

159 The first step is the direct reaction between melamine and formaldehyde forming methylolamine

160 prepolymer as shown in Figure 5.



161

162 Melamine Formaldehyde Methylolamine

163 **Fig. 5** Formation of methylolamine

164 The second step shown in Figure 6 is called the condensation reaction step in which methylolamine

165 combines together to form three dimensional network of cross linked melamine formaldehyde with

166 methylene bridges. The condensation reaction takes place between the methylol groups of

neighboring methylolamine with the elimination of water molecules which cross link in three dimensions. The water molecules are shown in Figure 6 by dashed boxes which are eliminated during the polymerization reaction.

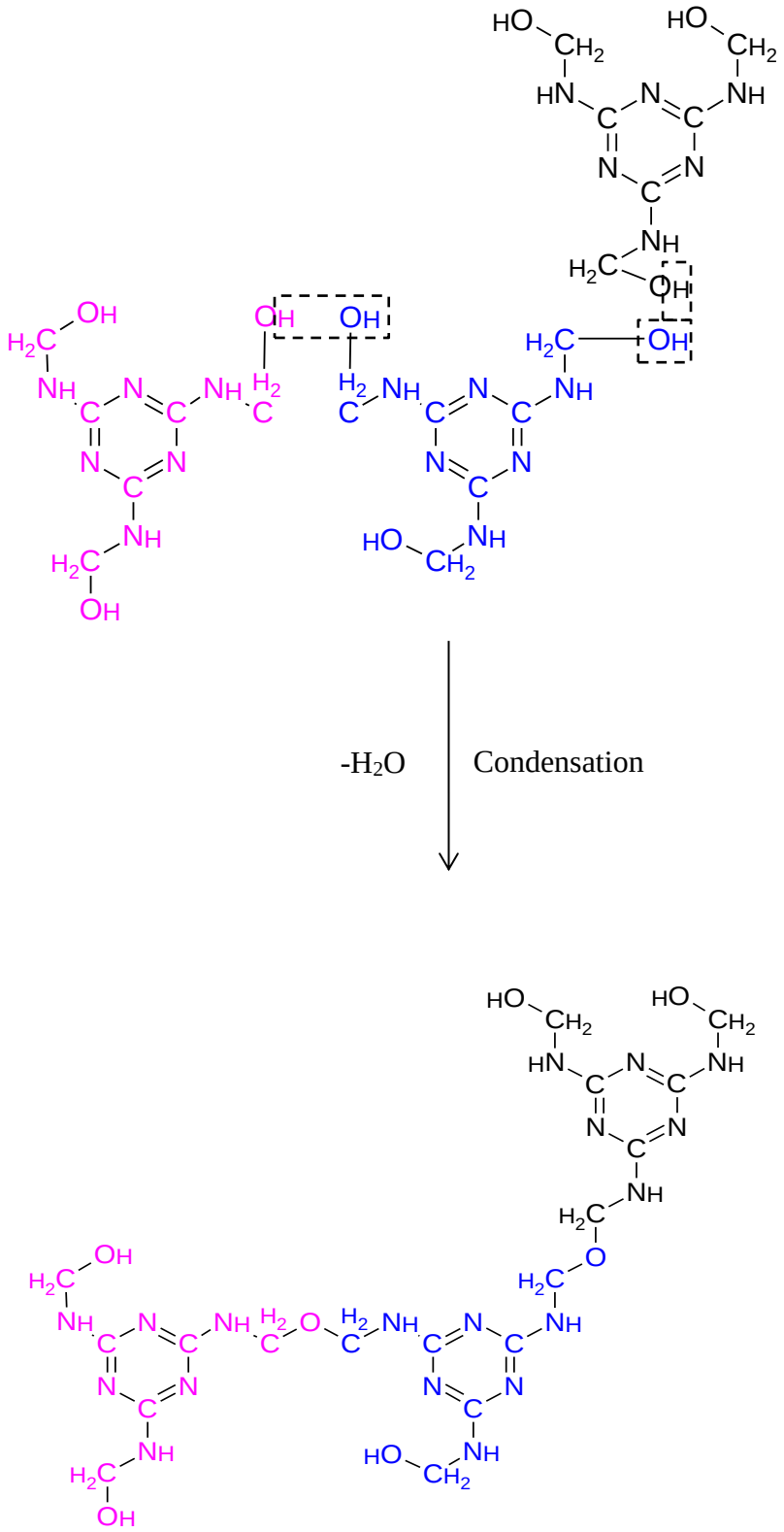


Fig. 6 Condensation reaction of melamine formaldehyde

Application of NPCM paraffin on cotton fabric via pad-dry-cure technique

MPCM 28 and NPCM paraffin were applied on plain woven fabric made of 100% cotton by pad-dry-cure technique. The coating method was not adopted because it makes the fabric stiffer and adversely affects the breathability of fabric which is not ideal for the active smart textile market. The padding solution contained: (60 gL^{-1} of) polyurethane binder ARRISTAN EPD; (50 gL^{-1} of) REAKNITT ZF which is dimethyl-dihydroxyl-ethylene urea, formaldehyde free cross linking agent which enhances the cross linking of binder; (50 gL^{-1} of) TUBINGAL RGH softener which is modified polysiloxane and (8 gL^{-1} of) CHT CATALYST AD, a modified inorganic salt; and MPCM 28 and NPCM paraffin (were used 30% of the weight of binder). The fabric was padded with the pressure of 2 bars between the mangles with speed of 2 $mmin^{-1}$ using two dip two nips. The fabric was dried (at 100 °C) and then cured in a stenter (at 150 °C for 3 minutes).

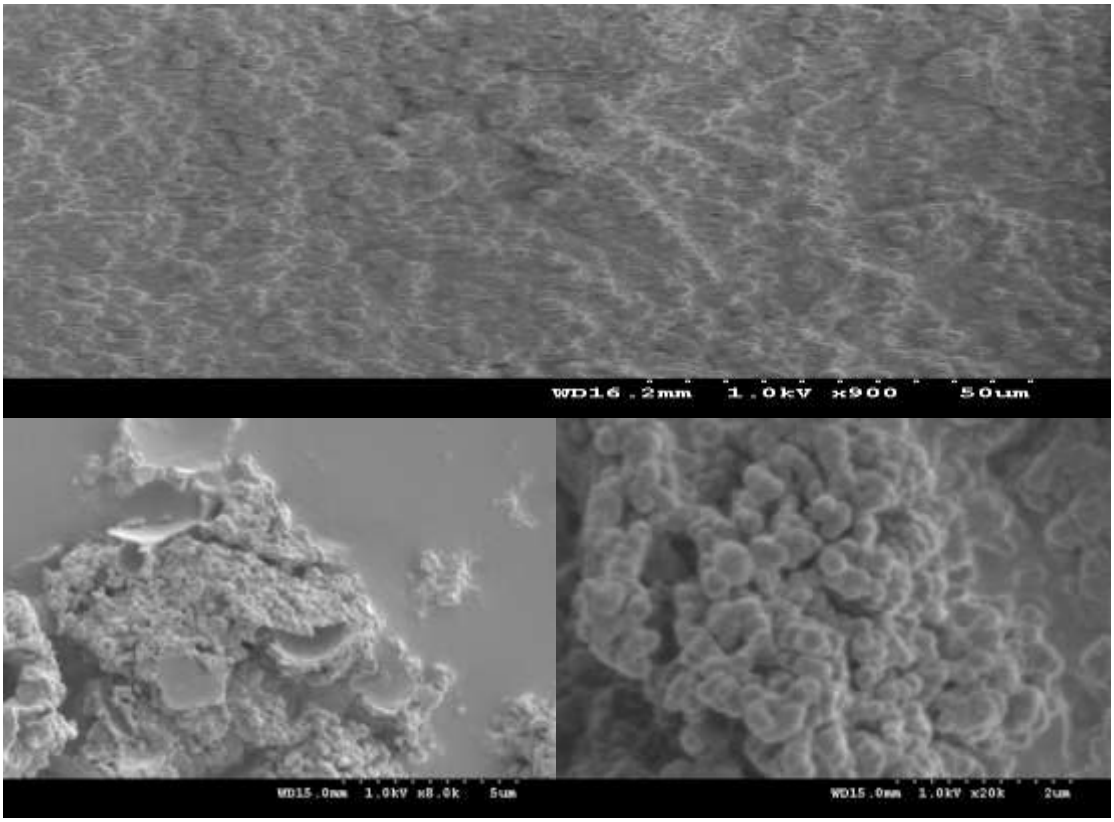
Each sample was then taken for washing (1 wash and 5 washes) to study the durability of the applied PCM capsules. British Standard BS EN 26330: 1994 program 15, 6A 40 °C was followed to perform the washing of samples. SEM and DSC were used to characterize the washed fabrics as comparison to the untreated.

Results and discussion

SEM for nanocapsules

The images of nanocapsules were analyzed using scanning electron microscopy. The images of NPCM paraffin are shown in Figure 7 which indicates that all the images are very consistent in their particle size. The images shown in Figure 7 were taken at lower magnifications to show the aggregates of nanocapsules with narrow size distribution. The images taken at 8000 and 20000

198 magnification in Figure 7 indicates that nanocapsules are very consistent in size and are spherical
199 in shape.



200

201 **Fig. 7** SEM images of NPCM paraffin

202 Figure 8 shows the SEM images at higher magnification of 40K and were used to measure the size
203 of nanocapsules. The size of nanocapsules of one sample measured through SEM was from 300
204 nm to 326 nm as shown in Figure 8.

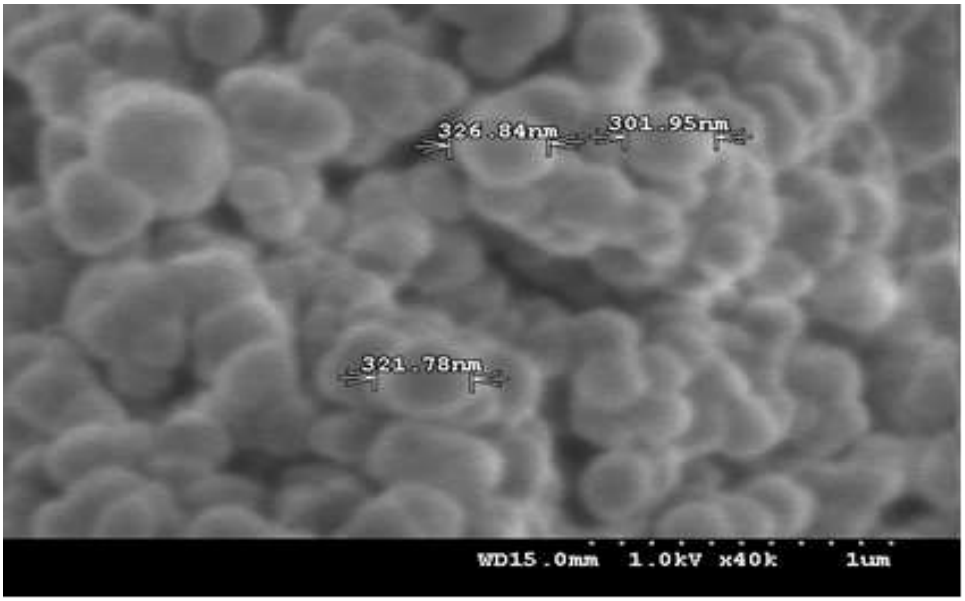
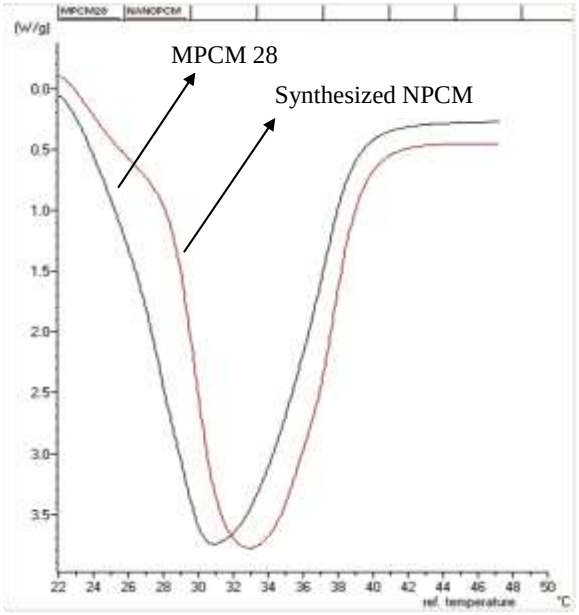


Fig. 8 SEM images at higher magnification

DSC study of NPCM paraffin

The result of latent heat from DSC shows the presence of paraffin in NPCM. The melting temperature of NPCM paraffin was found near the human skin comfort temperature i.e. 33 °C. Figure 9 shows the curves of MPCM 28 (from supplier) and NPCM synthesized in this research. The peak melting temperature of both curves shows clearly that the phase change temperature of the newly developed NPCM is closer to human skin comfort temperature although the curved areas are almost the same. The latent heat of NPCM paraffin is 144 Jg^{-1} as shown in Figure 10.



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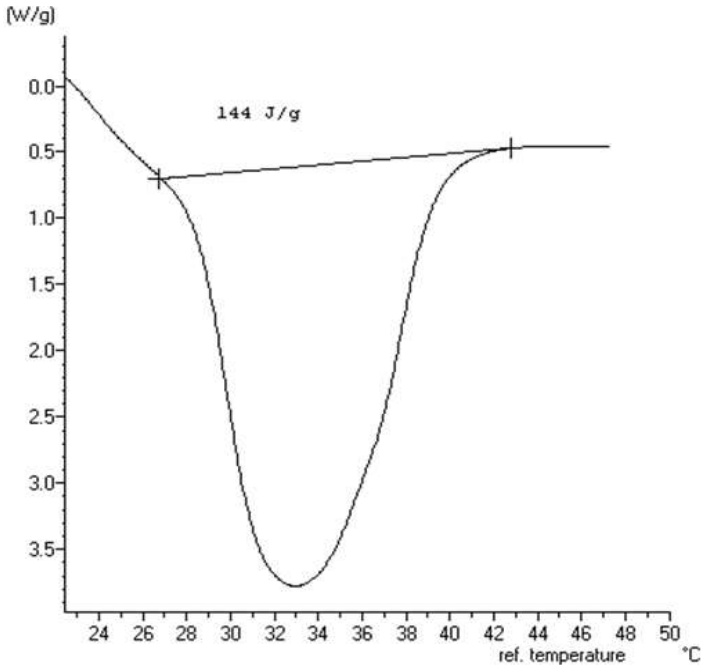
215 **Fig. 9** DSC curves for MPCM 28 and NPCM paraffin



216

217 **Fig. 10** Latent heat for NPCM paraffin

218

Structure of NPCM paraffin

The FTIR spectra of NPCM paraffin is presented in Figure 11. The spectrum shows a strong absorption band at 2850-2930 cm^{-1}attributing to the stretching vibration of aliphatic C-H group of the paraffin. The N-H stretching can be observed at 3300 to 3400 cm^{-1} and N-H bending can be seen at 1320 cm^{-1}. The C-N stretching in the triazine ring can be seen at 1550 cm^{-1} and triazine ring bending is presented by a very sharp peak at 810 cm^{-1}. The peak at 1150 shows the presence of ether group which is the proof the melamine formaldehyde reaction. This proves that the developed nanocapsules indeed are composed of paraffin as core and melamine formaldehyde as shell materials.

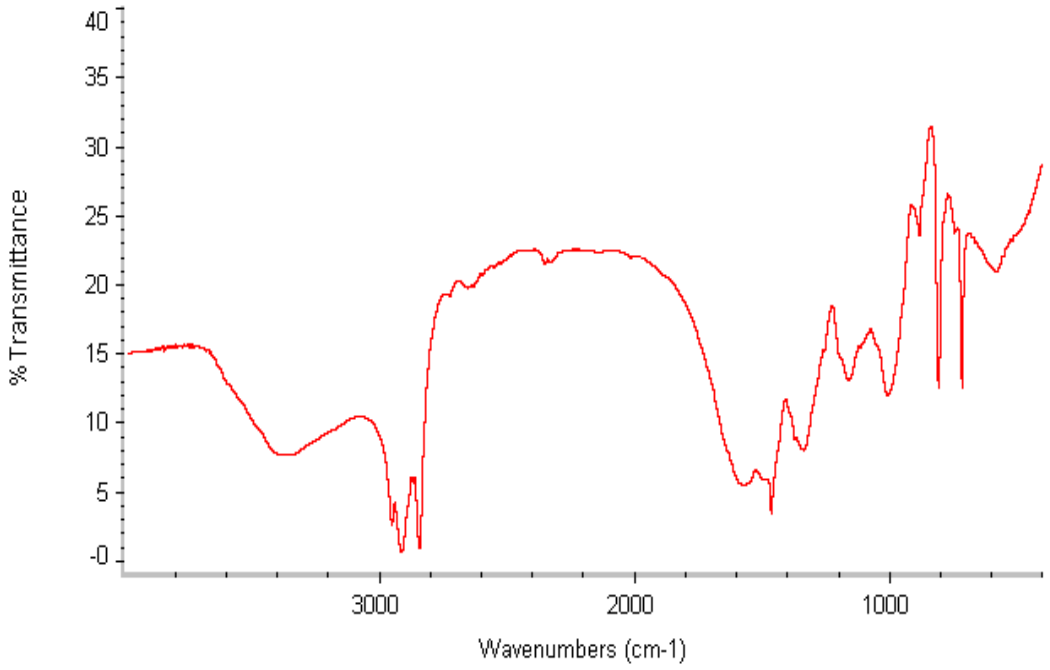


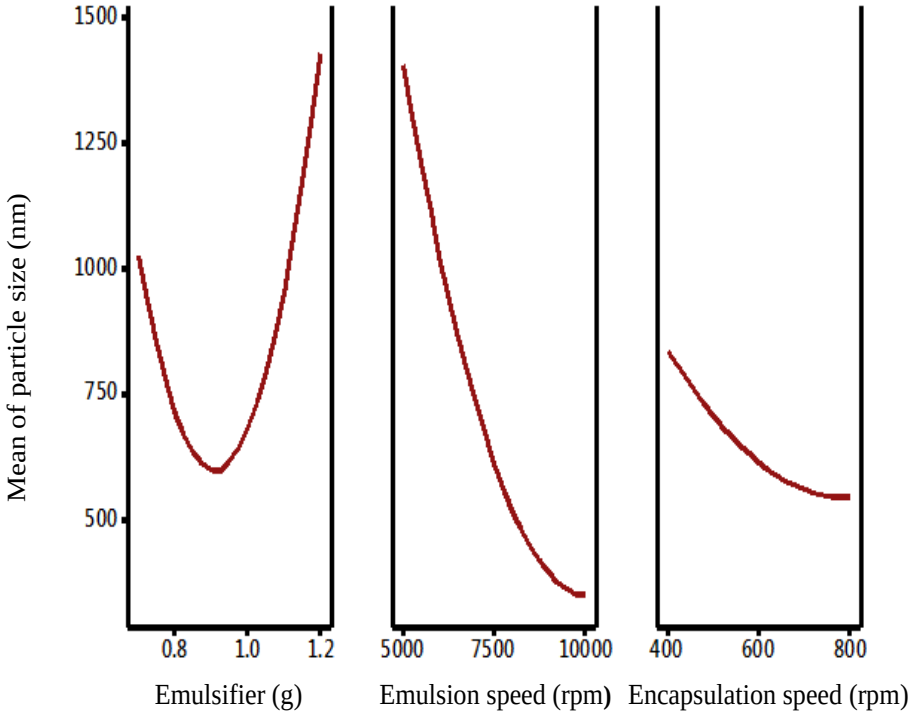
Fig. 11 FTIR for NPCM paraffin

Effect of factors on response of particle size

Main effect plots for particle size

Three parameters called the amount of emulsifier, emulsion stirring speed and encapsulation stirring speed were studied to investigate the effect of nanocapsules particle size. The main effect plot for particle size is shown against each parameter individually in Figure 12. The graph shows that particle size decreases as the amount of emulsifier increases up to a certain level, then increases when further increasing the amount of emulsifier. This is caused by emulsifier which has functionality of enhancing the emulsification process by linking its hydrophobic tail to the oily paraffin. As the amount of emulsifier increases, the emulsification increases hence the droplet size decreases. After the saturation takes place, any addition amount of emulsifier starts agglomeration among the individual mono-molecular droplets which affect the efficiency of emulsification process by increasing the droplet size in the form of agglomerate. Hence the amount of emulsifier is important to ensure the formation of nano-emulsion.

The second factor in the graph is emulsion stirring speed which plays the main role in the particle size. The graph clearly indicates that increase in rpm decreases the droplet size which helps in getting nano size capsules. The reason can be described as the stirring creates physical agitation which keeps the emulsion in mono molecular form and even become more severe when the stirring rate is increased.



248

249 **Fig. 12** Main effect plots for particle size

250 The third parameter was stirring speed during encapsulation process. Figure 14 shows that the
251 stirring speed during nanoencapsulation also affects the particle size of NPCM. The effect of
252 encapsulation stirring speed on particle size is less drastic than emulsion stirring speed. The
253 optimum stirring speed is found to be 600 rpm for the encapsulation. As the encapsulation speed
254 increased up to 800 rpm, the nanocapsules were found ruptured because of severe agitation and
255 shear force of the stirring blades acting on capsules as shown in Figure 13.

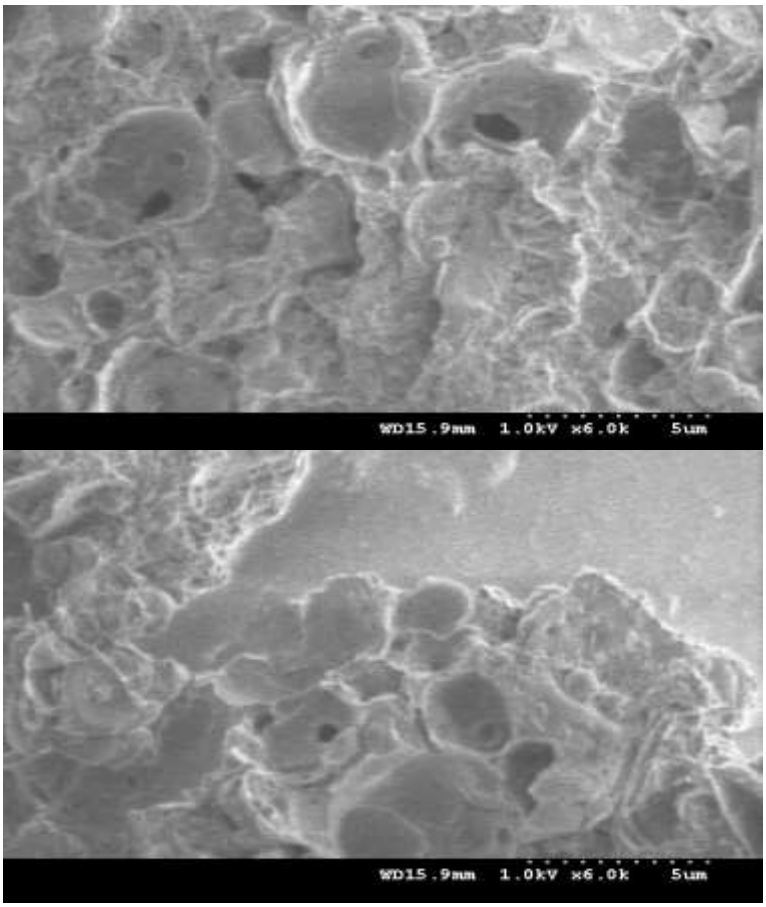
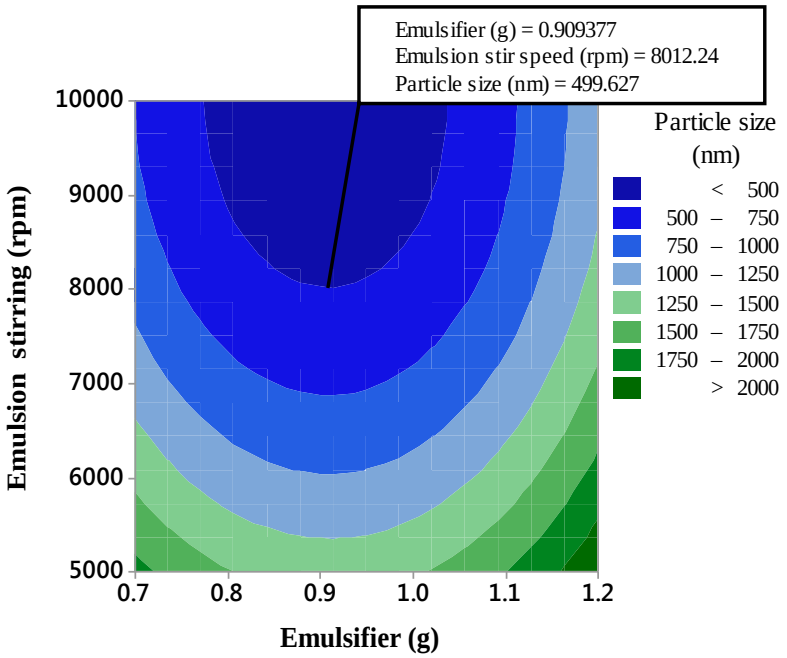


Fig. 13 Ruptured capsules with higher encapsulation speed

Contour plots for particle size

The contour plot shows how a response factor relates to the two continuous variables during experimentation. With the help of contour plots, the relationship between outcome and variables (parameters) can be determined. The contour plot in Figure 13 shows how emulsion stirring speed and the amount of emulsifier influence on the size of the nanocapsules. The contour plot also helps in determining desirable response values against the value of each factor. The particle size of 500 nm of NPCM paraffin can be achieved by using 0.9g emulsifier and around 8000 rpm emulsion speed as shown in Figure 14. The above parameter values were taken by setting the value of third factor (encapsulation speed) at 600 rpm.



267

268 **Fig. 14** contour plot of particle size with emulsifier vs emulsion stir speed

269 Figure 15 shows the effect of emulsion speed and encapsulation speed on the particle size of
270 NPCM paraffin. The flag in Figure 15 shows the desired outcome of nanocapsules by setting the
271 emulsifier value at optimum level. If the size of particle is required for instance 500nm, then the
272 emulsion and encapsulation speed would be required around 8000rpm and 600 rpm respectively.

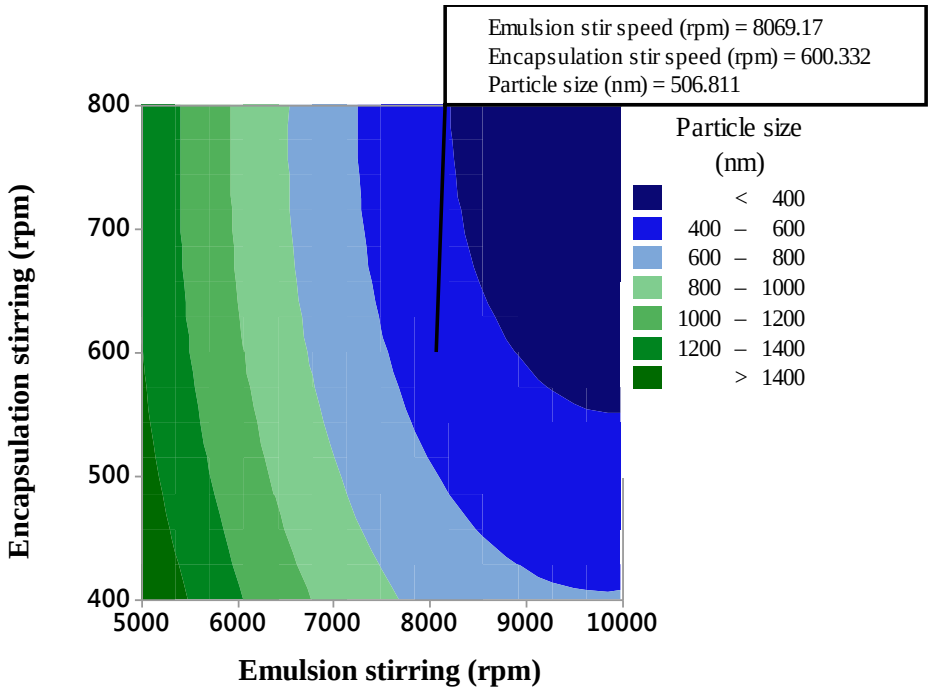


Fig. 15 Contour plot of particle size with emulsion vs encapsulation stir speed

Incorporation of NPCM paraffin in filament

The monofilament polypropylene yarn containing 4% NPCM paraffin was developed to study the sustainability of nanocapsules in the filament. The developed filament was analyzed using SEM and DSC and was compared to the previously developed polypropylene monofilament incorporated with 4% MPCM 28.

SEM of NPCM paraffin incorporated filament

The SEM images are shown in Figure 16 which ensures the incorporation of NPCM within the filament. The filament was cut diagonally cross-section wise in order to have better chance of capturing nano capsules and images of nanocapsules were captured at different magnifications. It is very clear from the images that the filament surface at its cross section is quite rough because

of the presence of nanocapsules within the filament. The image taken at higher magnification shows the presence of nanocapsules scattered randomly.

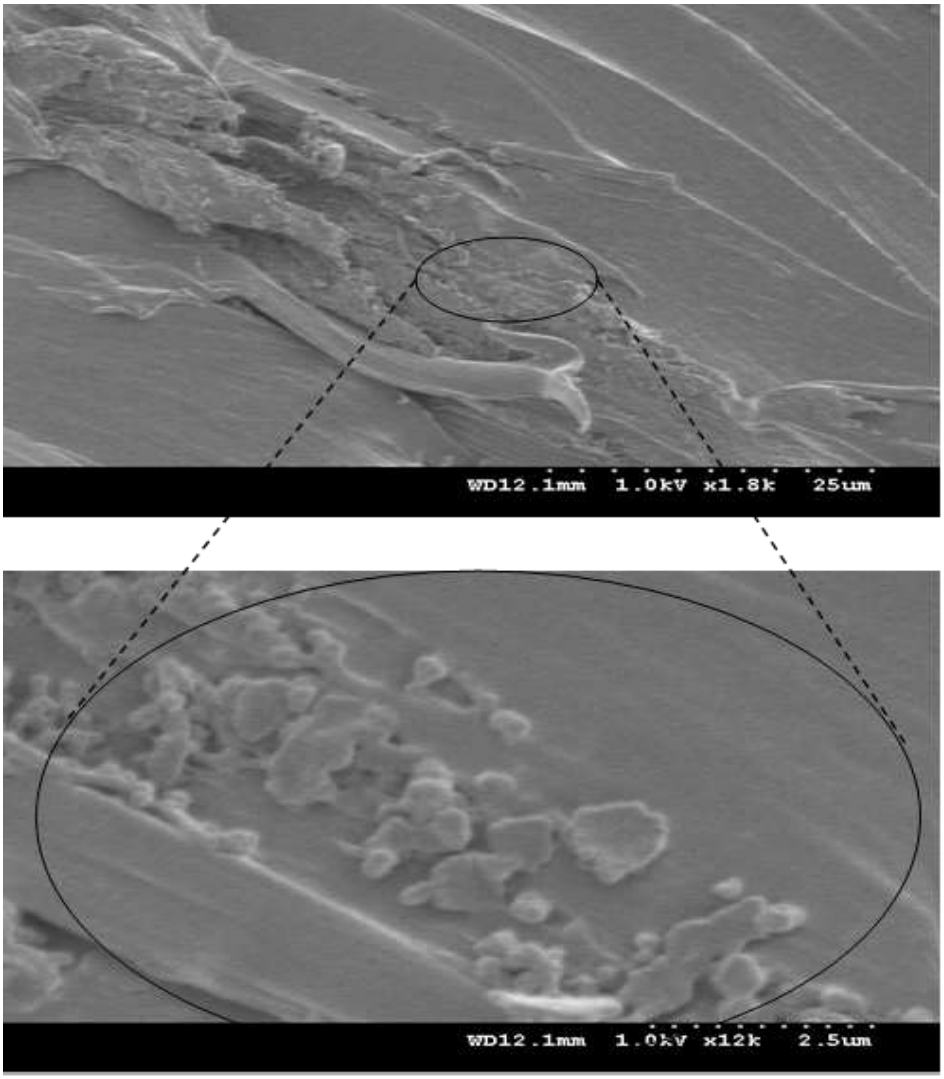


Fig. 16 Nanocapsules within the yarn at higher magnification

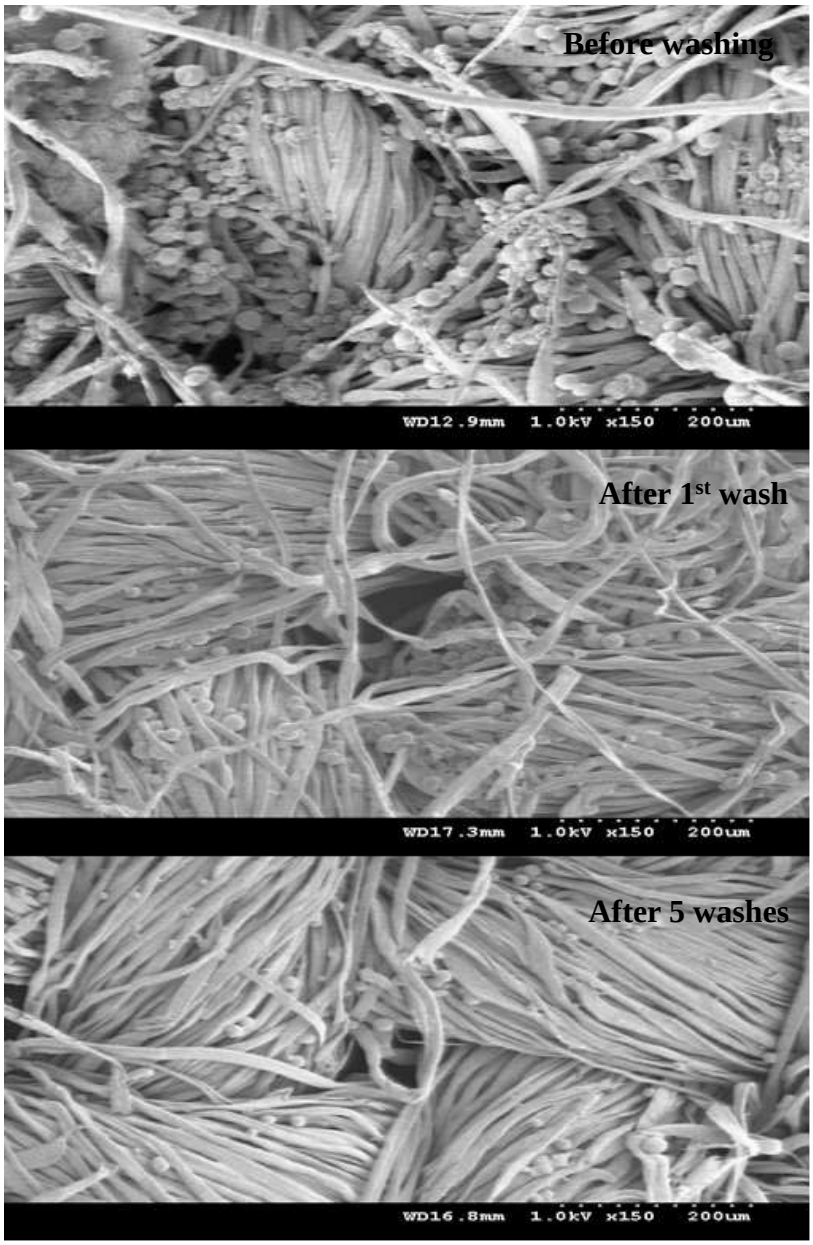
DSC study of NPCM paraffin incorporated filament

Latent heat for the filaments incorporated with 4% MPCM 28 and NPCM paraffin were tested using DSC and were found to be 2.31 Jg^{-1} and 3.24 Jg^{-1} for filaments with MPCM 28 and NPCM paraffin respectively. The reason for more latent heat in yarn incorporated with NPCM paraffin

can be described as the NPCM paraffin capsules are smaller as compared to that of the MPCM 28 which increases the incorporation of nanocapsules resulting in enhanced thermal characteristics. The larger the size of capsules, the more difficult would be for capsules to be incorporated into the filaments during extrusion process. Secondly during extrusion process surface deposition of microcapsules occurred resulting in the capsules adhered to the surface of the filaments to be removed easily in the subsequence drawing process. On the other hand, the nanocapsules are prone to incorporate inside the yarn and even because of the smaller size they make integral part of the surface which is not removed significantly during the subsequent process of drawing.

SEM for NPCM paraffin treated cotton fabric

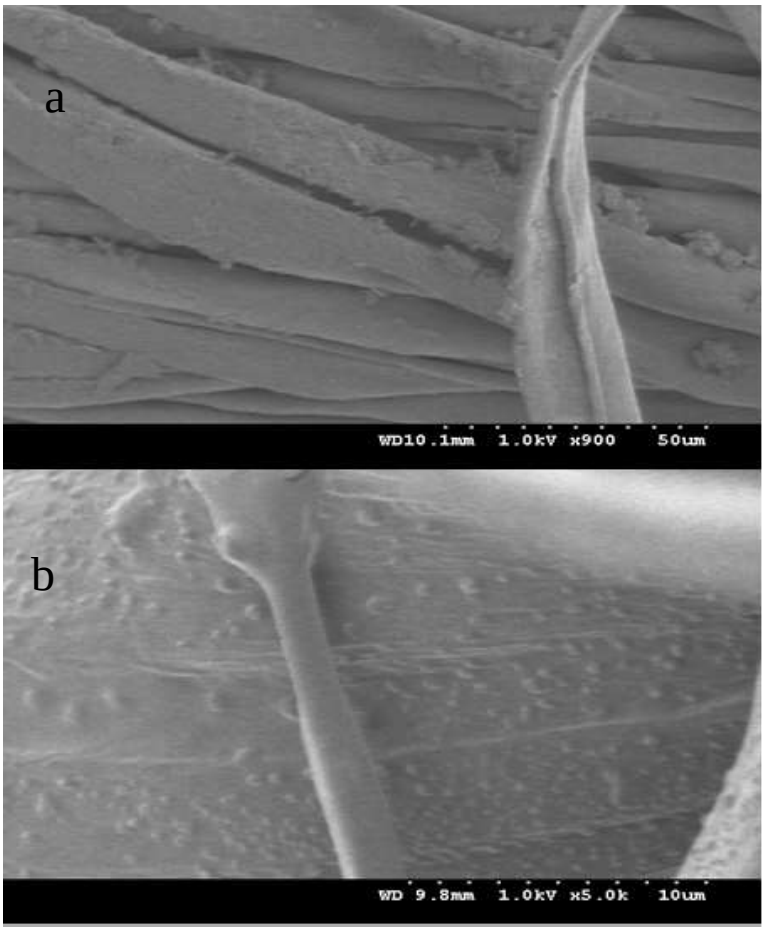
Figure 17 shows the images of fabric finished with MPCM 28 before and after washing. The microcapsules are spread all over the fabric after pad application and attached to the surface with the help of binder. The images of the same fabric after 1st and 5 washes show that microcapsules are still present but not in large amount especially for the fabric after 5 wash. When the capsules are in large size, most of the capsules are attached on the surface of yarn and fabric but would not sustain after severe washing. Only those capsules bound firmly to the yarns and fabric with the aid of binder would not be washed off.



309

310 **Fig. 17** Fabric treated with MPCM 28 before and after washing

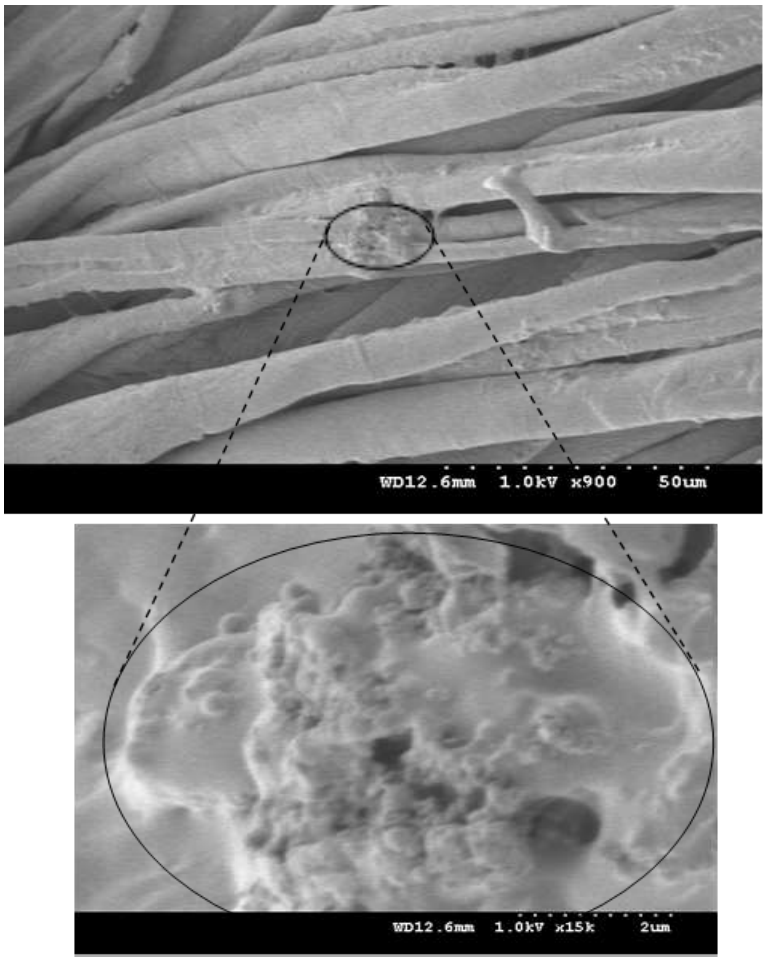
311 Figure 18 shows the images of fabric treated with NPCM paraffin before washing. It is clear from
312 Figure 18a that large amount of nanocapsules are bound on the yarns of fabric. Figure 18b is a
313 magnified image which even more clarifies that nanocapsules are firmly bound to the yarn surface
314 and not just adhered to the fabric as was seen for the case of MPCM 28 treated fabric.



315

316 **Fig. 18** Fabric treated with NPCM paraffin before washing

317 Figure 19 shows the SEM images of treated fabric after one wash. The nanocapsules are attached
318 to fibre level in comparison to microcapsules which are attached to yarns of the fabric; they are
319 more firmly attached and perform better resistance to washing. The image in Figure 19 is
320 magnified to show how nanocapsules are mixed within the resinous material of binder.



321

322 **Fig. 19** SEM for fabric treated with NPCM paraffin after 1st wash

323 Figure 20 shows the images of fabric treated with NPCM paraffin after 5 washes. The nanocapsules
324 are still present in large amount on the surface of yarns up to the fibre level along with binder
325 because of the nano scale size.

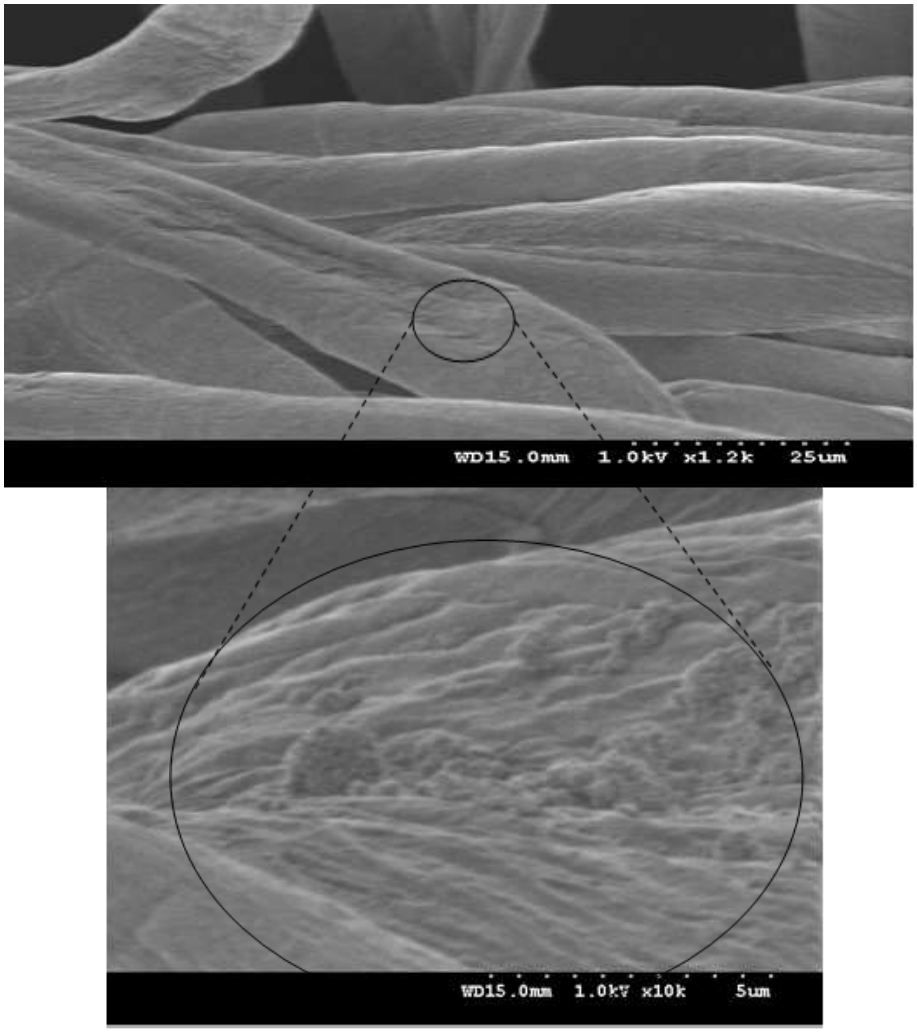


Fig. 20 Fabric treated with NPCM paraffin after5 washes

Figure 21 shows the comparison of images of fabric treated with both MPCM 28 and NPCM paraffin in one bath. This is clear from the images that microcapsules with MPCM 28 are attached to the surface of the filaments while the newly developed nanocapsules are bound to the fibre as its integral part with the help of binder. As long as binder is present, the nanocapsules are difficult to be removed. In Figure 21 larger capsule is magnified showing that a significant amount of nanocapsules is spread even on the surface of microcapsule; this means if nanocapsules are used instead of microcapsules, they can enhance the thermal characteristic of the treated fabric.

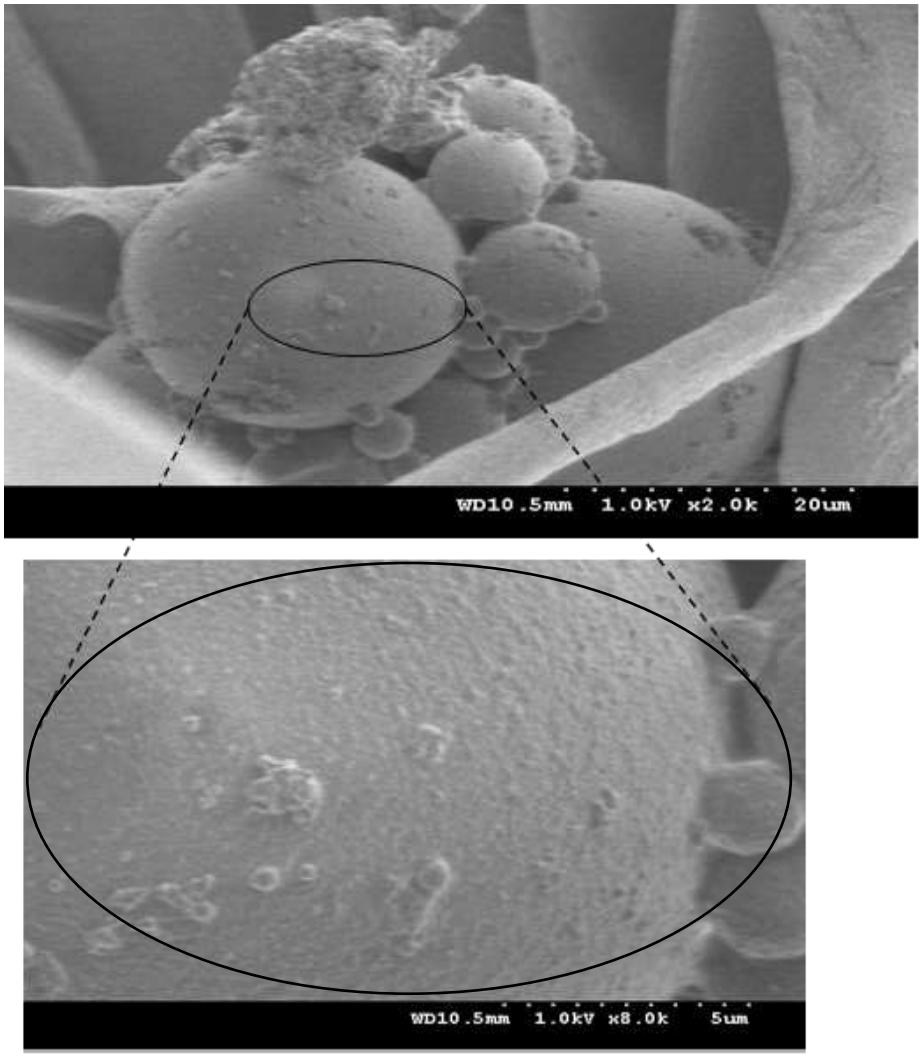


Fig. 21 Comparison of MPCM 28 and NPCM paraffin in one bath

DSC study of NPCM paraffin treated fabric

DSC was performed for all fabrics treated with MPCM 28 and NPCM paraffin before and after being washed. Table 3 shows the values of MPCM latent heat in comparison to NPCM paraffin latent heat after certain washes. Figure 22 shows the graph of DSC curves of treated cotton fabrics with MPCM 28 and NPCM paraffin after one wash and after five washes in comparison to the original. This is clear from Figure 22 that after washing the latent heat of the fabric decreases 60% and 83.4% for the fabrics after one wash and five washes respectively in case of MPCM 28

344 (microcapsules) while the latent heat of cotton fabrics decreases 32.2% and 62.8% after one wash
345 and 5 washes respectively in case of NPCM paraffin (nanocapsules). The reason is that
346 nanocapsules are difficult to be removed as they bind well with filaments in the fabric due to the
347 nano scale of the particles. The smaller the size of capsules, the more firmly it bound to the
348 filaments in fabric. The developed nanocapsules are more durable to washing as compared to
349 commercially supplied microcapsules.

350 Table 3 Comparison of latent heat from DSC

Durability	MPCM 28 latent heat (J/g)	NPCM Paraffin latent heat (J/g)
Without washing	14.6	12.3
After 1st wash	5.83	9.31
After 5 washes	2.42	4.64

351

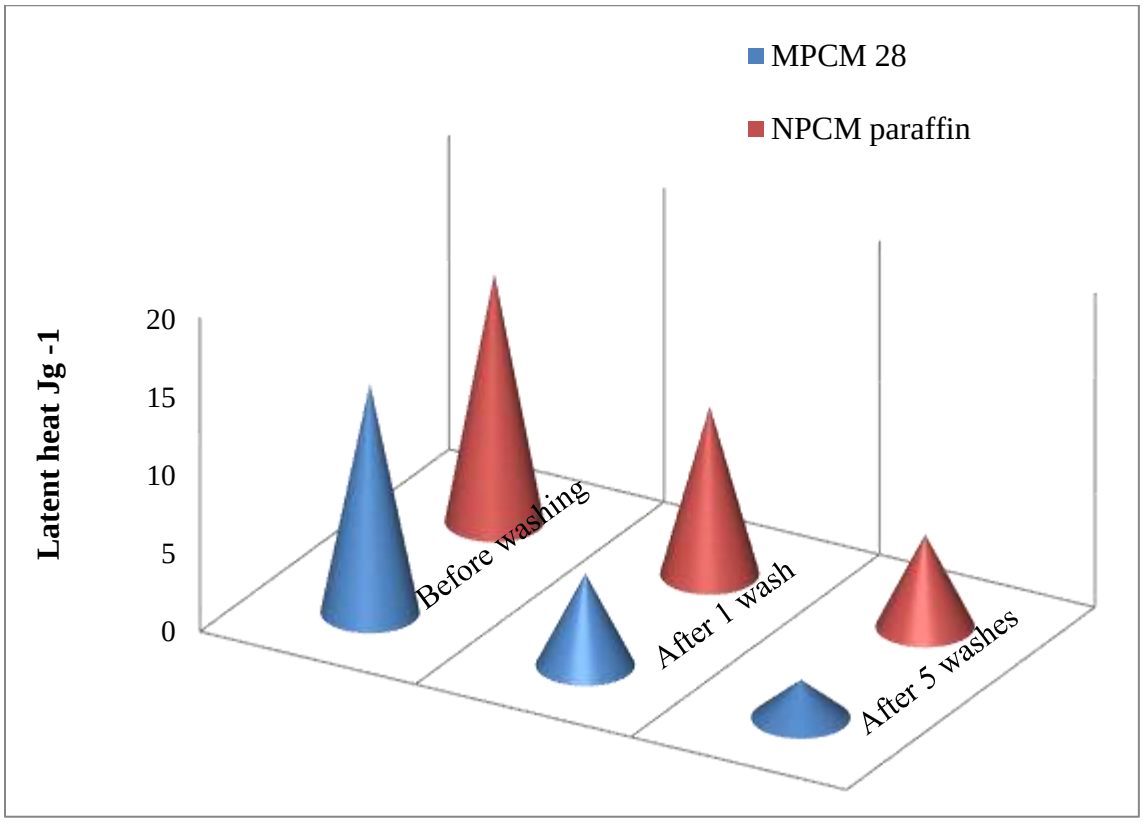


Fig. 22 Comparison of latent heat of cotton fabrics treated with MPCM 28 and NPCM paraffin

Conclusion

The objective of this research was to synthesize and optimize the process of nanoencapsulated PCM and compare their durability with microencapsulated PCM after the application on cotton fabric. Also to synthesize capsules in the nano range using paraffin in combination and to bring the phase change temperature closer to the human skin. The NPCM paraffin were incorporated in to polypropylene fibre and was compared to the MPCM developed yarn. The NPCM paraffin was also applied on cotton fabric via pad-dry-cure method and following conclusions are drawn based on the analysis:

- The melting temperature of NPCM paraffin was found in the range of 32-33°C which is closer to skin comfort temperature. The capsules formed were also in nano scale range and the size obtained was in the range of 320 nm.
- The NPCM paraffin incorporated polypropylene showed 28% more latent heat than commercial MPCM 28 incorporated polypropylene yarn.
- The application of nanocapsules on fabric showed better results than the microcapsules. The fabric treated with NPCM paraffin showed 32.2% decrease in latent heat after one washing while fabric treated with commercial MPCM showed 60% decrease in latent heat.
- The cotton fabric treated with nanocapsules shows better durability than microencapsulated PCM due to its better adhesion with fibrous material of cotton. Hence the thermoregualting cotton fabric with more durability has been developed using synthesized nanoencapsulated paraffin.

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Conflict of interest

The authors of this research declare that they have no conflict of interest.

References

Agbossou A, Zhang Q, Sebald G, Guyomar D (2010) Solar micro-energy harvesting based on thermoelectric and latent heat effects. Part I: Theoretical analysis Sensors and Actuators A: Physical 163:277-283

Alay S, Göde F, Alkan C (2010) Preparation and characterization of poly (methylmethacrylate-coglycidyl methacrylate)/n-hexadecane nanocapsules as a fiber additive for thermal energy storage Fibers and Polymers 11:1089-1093

Alkan C (2006) Enthalpy of melting and solidification of sulfonated paraffins as phase change materials for thermal energy storage Thermochimica acta 451:126-130

Black JK, Tracy LE, Roche CP, Henry PJ, Pesavento JB, Adalsteinsson T (2010) Phase transitions of hexadecane in poly (alkyl methacrylate) core− shell microcapsules The Journal of Physical Chemistry B 114:4130-4137

Borreguero A, Valverde J, Rodríguez J, Barber A, Cubillo J, Carmona M (2011) Synthesis and characterization of microcapsules containing Rubitherm® RT27 obtained by spray drying Chemical engineering journal 166:384-390

Buddhi D, Sawhney R, Sehgal P, Bansal N (1987) A simplification of the differential thermal analysis method to determine the latent heat of fusion of phase change materials Journal of Physics D: Applied Physics 20:1601

Chen W, Liu X, Lee DW (2012) Fabrication and characterization of microcapsules with polyamide–polyurea as hybrid shell Journal of Materials Science 47:2040-2044

Choi J-K, Lee JG, Kim JH, Yang H-s (2001) Preparation of microcapsules containing phase change materials as heat transfer media by in-situ polymerization Journal of Industrial and Engineering Chemistry 7:358-362

Fang G, Chen Z, Li H (2010) Synthesis and properties of microencapsulated paraffin composites with SiO 2 shell as thermal energy storage materials Chemical engineering journal 163:154-159

Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S (2004) A review on phase change energy storage: materials and applications Energy conversion and management 45:1597-1615

Feldman D, Shapiro M, Banu D (1986) Organic phase change materials for thermal energy storage Solar energy materials 13:1-10

Jin Z, Wang Y, Liu J, Yang Z (2008) Synthesis and properties of paraffin capsules as phase change materials Polymer 49:2903-2910

Karthikeyan M, Ramachandran T, Shanmugasundaram O (2014) Synthesis, characterization, and development of thermally enhanced cotton fabric using nanoencapsulated phase change materials containing paraffin wax The Journal of The Textile Institute 105:1279-1286

Kwon HJ, Cheong IW, Kim JH (2010) Preparation of n-octadecane nanocapsules by using interfacial redox initiation in miniemulsion polymerization Macromolecular research 18:923-926

Lacroix M (1993) Study of the heat transfer behavior of a latent heat thermal energy storage unit with a finned tube International Journal of Heat and Mass Transfer 36:2083-2092

Li MG, Zhang Y, Xu YH, Zhang D (2011) Effect of different amounts of surfactant on characteristics of nanoencapsulated phase-change materials Polymer bulletin 67:541-552

Mondal S (2008) Phase change materials for smart textiles–An overview Applied Thermal Engineering 28:1536-1550

Onofrei E, Rocha A, Catarino A (2010) Textiles integrating PCMs–A review Buletinul Institutului Politehnic din Iaşi 2:99-110

Pauken M, Emis N, Watkins B Thermal energy storage technology developments. In: SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM-STAIF 2007: 11th Conf Thermophys. Applic. in Micrograv.; 24th Symp Space Nucl. Pwr. Propulsion; 5th Conf Hum/Robotic Techn & Vision Space Explor.; 5th Symp Space Coloniz.; 4th Symp New Frontrs & Future Con, 2007. AIP Publishing, pp 412-420

Salaün F, Devaux E, Bourbigot S, Rumeau P (2009) Development of Phase Change Materials in Clothing Part I: Formulation of Microencapsulated Phase Change Textile Research Journal

Sánchez P, Sánchez-Fernandez MV, Romero A, Rodríguez JF, Sánchez-Silva L (2010) Development of thermo-regulating textiles using paraffin wax microcapsules Thermochimica acta 498:16-21

Sarı A, Alkan C, Karaipekli A, Uzun O (2009) Microencapsulated n-octacosane as phase change material for thermal energy storage Solar Energy 83:1757-1763

Sarier N, Onder E (2007) The manufacture of microencapsulated phase change materials suitable for the design of thermally enhanced fabrics Thermochimica acta 452:149-160

Sarier N, Onder E (2012) Organic phase change materials and their textile applications: an overview Thermochimica acta 540:7-60

Shin Y, Yoo DI, Son K (2005) Development of thermoregulating textile materials with microencapsulated phase change materials (PCM). II. Preparation and application of PCM microcapsules Journal of Applied Polymer Science 96

Tyagi VV, Buddhi D (2007) PCM thermal storage in buildings: a state of art Renewable and Sustainable Energy Reviews 11:1146-1166

Uddin M, Zhu H, Hawlader M (2002) Effects of cyclic operation on the characteristics of a microencapsulated PCM storage material International journal of solar energy 22:105-114

Yang X et al. (2007) Using lymphocyte and plasma Hsp70 as biomarkers for assessing coke oven exposure among steel workers Environmental health perspectives:1573-1577

Zalba B, Marín JM, Cabeza LF, Mehling H (2003) Review on thermal energy storage with phase change: materials, heat transfer analysis and applications Applied Thermal Engineering 23:251-283

Zhao C-Y, Zhang GH (2011) Review on microencapsulated phase change materials (MEPCMs): fabrication, characterization and applications Renewable and Sustainable Energy Reviews 15:3813-3832