CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 SUMMARY

3D spacer fabric can be either weft knitted or warp knitted but warp knitting is the most common method for spacer fabric manufacturing. Polyester multifilament was used to produce the face and back layer of WKSF and these two layers were connected by polyester monofilament as a middle layer. This fabric has unique and extraordinary characters and can be used for some special applications such as functional and protective clothing. Different possibilities of fabric structure and the middle layer thickness were tried to optimise the thermophysiological comfort, moisture management and mechanical properties. This lightweight, strong, flexible and shock absorbing WKSF was introduced as interlining material for body armour system. The impact of the projectile on the outer surface of the Kevlar body armour system transfers the kinetic impact energy to the inner layers and this energy is absorbed by means of WKSF to avoid or minimise the BABT effect.

8.2 CONCLUSIONS

The thesis shows clearly the influence of polyester filament denier on the different layers of WKSF. After optimising the polyester filament denier of the three layers of spacer fabrics, the fabric thickness and structure were optimised based on the fabric thermophysiological comfort properties and a suitable thickness and structure was selected for body armour interlining material. The impact of the projectile was analysed and the deformation depth and area were measured.
8.2.1 Effect of Polyester Filament Denier on Spacer Fabric Thermophysiological Comfort Properties

In chapter (4), the optimisation of polyester filament denier on WKSF layers with respect to fabric thermophysiological comfort properties was discussed. The relationship of porosity with air permeability, water vapour permeability, thermal conductivity and thermal resistance of polyester WKSF was analysed. Box and Behnken design of experiments were used to prepare the samples. Multiple regression analysis was conducted to develop a second degree polynomial equation and the response of models was analysed by $R^2$ values. Polyester filament deniers for spacer fabric layers were optimised and the effect was evaluated by means of RSM plots. The research findings are as follows:

- The open mesh and transparent structure create high porosity. This higher porosity exhibit superior air and water permeability and results in low thermal conductivity because of more void space between the spacer fabric layers and layer structures.

- The linear density of polyester multifilament on face layer has shown encouraging results on the thermophysiological comfort properties with the combination of middle layer. Polyester denier ranging from 93 to 104 results in better thermophysiological comfort properties and 100 denier is finalised as an optimum polyester denier for the face layer.

- The range between 21 and 23 denier of polyester monofilament in the middle layer exhibits better results and 20 denier was considered as optimum value for the middle layer.
• The bottom layer of the polyester WKSF has no significant influence on the fabric properties. Among 30, 50 and 70 deniers tried, the middle value of 50 denier was chosen for further process.

8.2.2 **Effect of WKSF Structure and Thickness on Low Stress Mechanical and Thermophysiological Comfort Properties**

The influence of WKSF thickness and structure on the low stress mechanical and the thermophysiological comfort properties were analysed in chapter (5). A suitable spacer fabric thickness and structure are finalised for the body armour manufacturing system. The research findings are as follows:

• The spacer fabric with locknit structure with 4mm thickness shows a negative impact on the low stress mechanical properties. The 2mm fabric thickness with open mesh hexagonal structure has proved to have better low stress mechanical properties. Moderate values were attained by the 3.1mm thickness with hexagonal net structure. In some cases like LT, RT, EMT % at wale direction and G, B and 2HB resulted in very similar values with 2mm thickness spacer fabric. However, 3.1mm thickness fabric produces better compression and resilience properties in comparison to other two thicknesses.

• The middle layer of spacer fabric decides the vertical gap between face and bottom surface layers and establishes the amount of porosity of the fabrics. The low vertical void space does not allow the air and moisture and hence the fabric has good thermal conductivity. At the same time, higher fabric
thickness increases the thermal resistance. Based on the fabric structure, the horizontal space between the polyester filament and stitching point decides the values of porosity. High porosity increases the permeability properties of fabric and reduces the thermal conductivity. One way ANOVA supported by Tukey's HSD examination confirms the influence and the significance of spacer fabric thickness and structure on low stress mechanical and thermophysiological comfort properties.

- Fabric with 3.1mm thickness and hexagonal net structure exhibits better thermophysiological comfort properties, compression properties and low stress mechanical properties compared to other fabrics.

8.2.3 Effect of WKSF Structure and Thickness on the Moisture management Properties

The effect of WKSF thickness and structure on moisture management properties was studied in chapter (6). The research findings are as follows:

- All the polyester WKSF samples show high rate of absorbancy of less than one second. The spacer fabric thickness and open structure are the reasons for rapid transfer of moisture.

- In vertical wicking, the rate of wicking was found to be superior in open structure compared to the closed structure. The porous surface allowed more water molecules to transfer to its surface and reach the highest wicking point. The fabric thickness has no influence on the vertical wicking properties of WKSF.
The thickness of the spacer fabric plays a comparatively vital role than the surface layers of fabric in in-plane wicking. A moderate in-plane wicking values were achieved in the 3.1mm thickness of WKSF and the hexagonal net structure shows superior vertical wicking.

8.2.4 Effect of WKSF Layers on Ballistic Body Armour System

The thermophysiological comfort properties and the impact resistance of Kevlar body armour system interlined with polyester WKSF were investigated in the chapter (7) and results are given below:

- Thickness of the spacer fabrics with different plies shows more impact on the thermophysiological comfort properties than the different polyester denier on face layer. By increasing spacer fabric plies, the fabric weight and void space increases. This leads to more entrapped air within the plies, which limits the permeability and conductivity.

- However, increasing the plies of interlining material in the body armour system decreases the deformation impact by the projectile. But more number of plies leads to increase in the weight of armour system and produces discomfort to the wearer. Based on the findings, the recommended number of plies of interlining material for the Kevlar body armour system is 3 and the fabric structure should be hexagonal net.

8.2.5 Findings from the Research

Spacer fabric is a 3D fabric, which has unique characteristics that meets a lot of functional requirements. The three layers in the spacer fabric
can be engineered according to the requirement and different combination of raw material, fabric structure and fabric parameters. By taking this as basic concept, the research was carried out and the important findings are as follows:

- Polyester filament was taken as a raw material and the denier of monofilament and multifilament were optimized with respect to thermophysiological comfort properties of WKSF. 100 and 50 denier of polyester multifilament on face and back layers were selected respectively and 20 denier monofilament at middle layer was chosen from the result findings for further process. Compared to front and middle layers, the impact of back layer was not significant on fabric comfort properties. However, any changes in front and middle layers, directly influencing the fabric functional properties.

- Spacer fabrics are available with different fabric thickness and structure. Thickness of the fabric is decided by the height of middle layer and the surface structure is by face and back layers. Among all the three layers, middle layer contributes more to achieve special properties like cushioning. By modifying the fabric thickness of spacer fabric, the middle layer not only influences the compression and resilience properties also influences the fabric thermophysiological comfort properties. The angle, height and amount of monofilament in middle layer influence the permeable properties of spacer fabric. It also influences the fabric tensile and bending properties. Considering all the above properties, 3.1mm thickness spacer fabric was selected and it produces optimum result compared to other fabric.
• On face layer structure, spacer fabrics are available with close to open structure. Obviously, open structure of spacer fabric having more pore size than close structure. This leads to high porosity and permit the fabric to permeable with air and moisture. The thermal conductivity on open structure was reduced and provides warm feel to the wearer. Highly porous and permeable open mesh hexagonal net structure was selected for next process.

• WKSF thickness of 3.1mm with hexagonal net structure on face layer was used as an inner lining material for Kevlar body armour system. The effect and the number of plies of inner lining material was analysed against the impact resistance test. The test result proves that, increasing the plies of inner lining material increases the weight of body armour system and shows good impact resistance by the projectile. While increasing the plies of inner lining material limits the fabric thermophysiological comfort properties and creates discomfort to the wearer. So the 3 plies inner lining WKSF was optimised for the Kevlar body armour system.

8.3 SCOPE FOR FUTURE WORK

• In this research, polyester is the only material used in the manufacture of spacer fabric even though many fibres and filaments are available. Different combination of raw materials on each surface layer of spacer fabric can be used to meet the special applications.
• Warp knitting is the most suitable technique for the manufacture of spacer fabric and other two techniques are also equally preferable. To get an idea and better results, the manufacturing techniques could be tried.

• Apart from the fabric moisture and thermophysiological comfort properties, the other mechanical properties may be evaluated in future. Because the middle layer contribution is found to be significant in spacer fabric, the peeling properties and the effect of monofilament diameter and angle are to be analysed.

• At the same time, it is essential to study the spacer fabric performance by applying certain finishes in particular, by microencapsulation or nanoencapsulation. As the middle layer and the high fabric porosity may retain the capsules and can hold them for a long period, these finished fabric may be used for durable applications.

8.3.1 Suggestions for Further Improvement

The most important advantage of using spacer fabric is to replace the polyurethane, neoprene and other types of foams. Lightweight, breathable and pressure reducing cushioned characteristics of spacer fabric are engineered for special applications. To meet the particular applications, the following points may be taken into account.

• The fibres used for spacer fabric is Polyester, Polypropylene, Nylon, Glass fibre, Metal and Aramid. These fibres may produce allergenic, odour and rough feel for regular uses. A
perfect surface treatment will provide great comfort and soft touch to the user.

- The spring characteristics and hardness monofilament creating cushion character on spacer fabric and it distribute the load / weight in all directions. A verity of spacer fabric thickness can be used for mattress, sleeping aprons, car seat covers and insole material for shoes. Still, the fabric thickness is decided by spacer yarn and that may attain permanent bent from its size by the regular usage and stable load. However, there will be a permanent deformation on the monofilament while there is a sudden and high impact load on spacer fabric. This can be reduced by using more number of fabric layers indeed of single fabric layer. The load can be distributed to successive layers of spacer fabric.

- Spacer fabric is used for protective inner lining, bra cups, shoulder pads and backpacks. In these applications the fabric need to be bend / curve movement according to the body posture. But this required bend / curve movement is restricted by middle layer because it connects both face and back layer of fabric in cross wise direction. By selecting appropriate thickness of material, the above problem may be rectified.

- A breathable and airflow characteristic of spacer fabric provides benefits to the skin and maintain the human body temperature. An open surface structure of spacer fabric facilitates the highly permeable and breathable fabric.