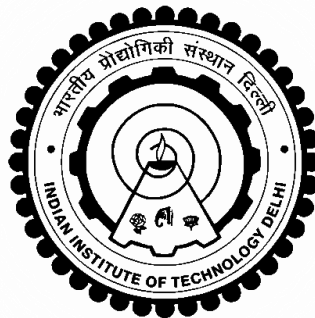


**STUDY OF COMPOSITE NONWOVEN STRUCTURE ON
THE PROPERTIES OF NEEDLE PUNCHED FABRIC**

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**DEPARTMENT OF TEXTILE & FIBRE ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

FEBRUARY 2023

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by

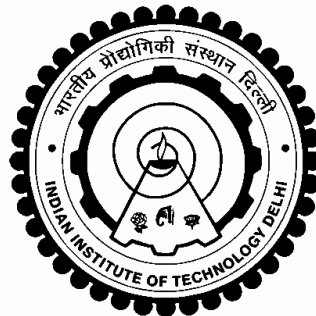
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Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

February 2023

Dedicated to my parents

CERTIFICATE

This is to certify that the thesis titled '**Study of Composite Nonwoven Structure on the Properties of Needle Punched Fabric**', being submitted by Ms. Priyal Dixit to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy, is a record of bonafide research work carried out by her. She has worked under my guidance and supervision and fulfilled the requirements for submitting the thesis, which has attained the standard required for a Ph.D. degree of this Institute.

The results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.

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PRIYAL DIXIT

ABSTRACT

Air pollution is regarded the one of the most grave environmental concerns of the world. Effective air filters are a key component in capturing a wide spectrum of air contaminants. Therefore, requirement for highly complex and efficient air filtration systems has increased. Nonwoven fabrics find wide applications in the field of air filtration. The main objective of the filter medium is to maximise the chance of trapping of the suspended particles in the air stream while minimising the energy loss to the air stream. The arrangement of fibres in a nonwoven filter media plays a significant part in deciding the structure of the media which ultimately governs the filtration properties.

This work begins with an investigatory study on the structure and properties of nonwoven fabrics produced from fibres of different fineness. The image analysis and Lindsley's techniques were employed to analyse the structure of the nonwoven fabric. The porous paths created in the fibrous assembly were quantified by calculating the pore channel tortuosity. A relationship was developed between the structure of nonwoven fabrics and its properties which ultimately helped in designing a suitable nonwoven filter media. An air filtration instrument was also designed and fabricated for the evaluation of filtration performance of nonwoven filter fabrics. An attempt was made to regulate the structure of composite nonwoven fabrics having constituent layers of varying structure influenced by different approaches to improve the filtration performance. The structure of composite nonwoven fabrics was investigated by X-ray computed tomography (XCT) and its relationship with the filtration performance was probed. Interestingly, it was established that an inverse gradient of carded batts having increasing order of fibre fineness in the composite nonwoven fabric provided the lowest pressure drop along with next to highest filtration efficiency.

Subsequently, an attempt was made to highlight the significance of the carding parameters (feeder speed, cylinder speed and doffer speed) required for fibre of different fineness for regulating the orientation of fibres in carded web and ultimately the properties of the nonwoven fabric. Three factor three level Box-Behnken factorial design was employed to analyse and optimise the carding parameters required for fibre of different fineness to improve the fibre orientation in carded web. Orientation of fibres was measured with the help of Lindsley's and image analysis techniques in terms of proportion of curved fibre

ends, coefficient of relative fibre parallelisation and anisotropy of inclination angle of fibre and tortuosity factor. A non-linear regression technique was used to establish a relationship between tortuosity factor and measured values of fibre diameter, proportion of curved fibre ends, coefficient of relative fibre parallelisation, anisotropy of inclination angle of fibres and mean flow pore size. Subsequently, the regression models were developed to establish relationship between specific property of nonwoven fabric and structural indices. The findings of this study demonstrated the significance of fibre fineness specific carding parameters for modulating the orientation of fibres in carded web to improve the physical, functional as well as mechanical properties of needle punched nonwoven fabric. The work further explored the possibility of tuning the structure of composite layered nonwoven fabrics by distinctly placing the layers of batts of differently oriented fibres influenced by carding parameters. X-ray computed tomography technique was used for comprehensive evaluation of the packing densities at incremental thickness of composite nonwoven fabrics. The obtained trends of packing density were found to be in good agreement with the measured properties of nonwoven fabrics. Creation of an inverse gradient having an increasing order of orientation of fibre in composite nonwoven fabric displayed improved filtration efficiency and reduced pressure drop.

After realising the role of fibre fineness and fibre orientation in carded web influenced by carding parameters, emphasis was laid on the punching process for further enhancement of functional properties of needle punched nonwoven fabrics. A unique approach of sequential punching was proposed in which composite nonwoven fabrics having layers of semi punched fabrics of either different punch densities or different needle penetration depths were prepared. Initially, the Box-Behnken factorial design was used to optimise the basis weight, punch density and needle penetration depth. The optimised punching parameters for 100 g/m² basis weight were used to prepare composite nonwoven fabrics having layers of semi punched fabrics of either different punch densities or different needle penetration depths. X-ray computed tomography technique was used for evaluation of the packing densities of composite nonwoven fabrics. The obtained trends of packing density were found to be in good agreement with the measured properties of nonwoven fabrics. It was established again that formation of an inverse gradient structure in both the cases possessed high filtration efficiency by simultaneously achieving a low pressure drop. However, composite nonwoven fabrics having different punch densities in layered structure performed better than the composite fabrics having different needle penetration depths.

Lastly, influence of external factors like quantity of dust, operating time, and air velocity on the performance of sequentially punched composite nonwoven fabrics was investigated. The study reconfirmed that inverse gradient structure having layers of increasing order of packing density in composite nonwoven fabric resulted in lower pressure drop and improved filtration efficiency as compared to gradient structure having layers of decreasing order of packing density.

सारांश

वायु प्रदूषण को दुनिया की सबसे गंभीर पर्यावरणीय चिंताओं में से एक माना जाता है। वायु प्रदूषकों के व्यापक विस्तार को पकड़ने में प्रभावी वायु फ़िल्टर एक महत्वपूर्ण घटक है। इसलिए, अत्यधिक जटिल और कुशल वायु फिल्ट्रेशन प्रणालियों की आवश्यकता बढ़ गई है। नॉनवॉवन कपड़े वायु फिल्ट्रेशन के क्षेत्र में व्यापक अनुप्रयोग पाते हैं। फ़िल्टर माध्यम का मुख्य उद्देश्य हवा की धारा में ऊर्जा हानि को कम करते हुए हवा की धारा में निलंबित कणों के फंसने की संभावना को अधिकतम करना है। नॉनवॉवन फिल्टर मीडिया में फाइबर की व्यवस्था मीडिया की संरचना तय करने में महत्वपूर्ण भूमिका निभाती है जो अंततः फिल्ट्रेशन गुणों को नियंत्रित करती है।

यह काम विभिन्न सूक्ष्मता के फाइबर से निर्मित नॉनवॉवन कपड़ों की संरचना और गुणों पर एक खोजी अध्ययन से शुरू होता है। नॉनवॉवन कपड़े की संरचना का विश्लेषण करने के लिए छवि विश्लेषण और लिंडस्ले की तकनीकों को नियोजित किया गया था। रेशेदार समूह में बनाए गए झरझरा रास्तों को पोर चैनल टोर्टुओसिटी की गणना करके निर्धारित किया गया था। नॉनवॉवन कपड़ों की संरचना और इसके गुणों के बीच एक संबंध विकसित किया गया, जिसने अंततः एक उपयुक्त नॉनवॉवन फिल्टर मीडिया की रचना करने में मदद की। नॉनवॉवन फिल्टर कपड़ों के फिल्ट्रेशन एफिशिएंसी के मूल्यांकन के लिए एक वायु फिल्ट्रेशन उपकरण भी रचित और निर्मित किया गया था। फिल्ट्रेशन एफिशिएंसी को बेहतर बनाने के लिए विभिन्न तरीकों से प्रभावित अलग-अलग संरचना की घटक परतों वाले समग्र नॉनवॉवन कपड़ों की संरचना को विनियमित करने का प्रयास किया गया था। एक्स-रे कंप्यूटेड टोमोग्राफी (XCT) द्वारा समग्र नॉनवॉवन कपड़ों की संरचना की जांच की गई और फिल्ट्रेशन एफिशिएंसी के साथ इसके संबंध की भी जांच की गई। दिलचस्प बात यह है कि यह स्थापित किया गया था कि समग्र नॉनवॉवन कपड़े में फाइबर महीनता के बढ़ते

क्रम वाले कार्डेड बैट्स के एक उलटे ढाल ने उच्चतम के करीब फिल्ट्रेशन एफिशिएंसी के साथ-साथ सबसे कम प्रेशर ड्रॉप प्रदान किया।

इसके बाद, कार्डिंग वेब में फाइबर ओरिएंटेशन और अंततः नॉनवॉवन कपड़े के गुणों को विनियमित करने के लिए विभिन्न सूक्ष्मता के फाइबर के लिए आवश्यक कार्डिंग मापदंडों (फीडर गति, सिलेंडर गति और डॉफर गति) के महत्व को उजागर करने का प्रयास किया गया था। कार्डेड वेब में फाइबर ओरिएंटेशन में सुधार के लिए विभिन्न सूक्ष्मता के फाइबर के लिए आवश्यक कार्डिंग मापदंडों का विश्लेषण और अनुकूलन करने के लिए तीन कारक तीन स्तरीय बॉक्स-बेहकेन फैक्टोरियल डिज़ाइन को नियोजित किया गया। प्रोपोरशन ऑफ़ कर्वेड फाइबर एंड्स, कोएफिशिएंट ऑफ़ रिलेटिव फाइबर पार्लेलायीसेशन, एनईसोट्रोपी ऑफ़ इंकलिनाशन एंगल ऑफ़ फाइबर, टोटैओसिटी फैक्टर के संदर्भ में लिंडस्ले और छवि विश्लेषण तकनीकों की मदद से फाइबर ओरिएंटेशन को मापा गया था। एक नॉन लीनियर रिग्रेशन तकनीक का उपयोग टोटैओसिटी फैक्टर और फाइबर व्यास के मापा मूल्यों, प्रोपोरशन ऑफ़ कर्वेड फाइबर एंड्स, कोएफिशिएंट ऑफ़ रिलेटिव फाइबर पार्लेलायीसेशन, एनईसोट्रोपी ऑफ़ इंकलिनाशन एंगल ऑफ़ फाइबर और औसत फ्लो पोर साइज के बीच संबंध स्थापित करने के लिए किया गया था। इसके बाद, नॉनवॉवन कपड़े की विशिष्ट संपत्ति और संरचनात्मक सूचकांकों के बीच संबंध स्थापित करने के लिए रिग्रेशन प्रतिमान विकसित किए गए थे। इस अध्ययन के निष्कर्षों ने सुई छिद्रित नॉनवॉवन कपड़े के भौतिक, कार्यात्मक और साथ ही यांत्रिक गुणों में सुधार के लिए कार्डेड वेब में फाइबर ओरिएंटेशन को संशोधित करने के लिए फाइबर सूक्ष्मता के अनुरूप विशिष्ट कार्डिंग मापदंडों के महत्व को प्रदर्शित किया। कार्य ने कार्डिंग मापदंडों से प्रभावित अलग-अलग फाइबर ओरिएंटेशन के बैट्स की परतों को अलग-अलग रखकर समग्र स्तरित नॉनवॉवन कपड़ों की संरचना को समस्वरण करने की संभावना का पता लगाया। समग्र नॉनवॉवन कपड़ों की वृद्धिशील मोटाई पर पैकिंग घनत्व के व्यापक मूल्यांकन के लिए एकस-रे कंप्यूटेड टोमोग्राफी तकनीक का उपयोग किया गया

था। पैकिंग घनत्व की प्राप्त प्रवृत्ति के नॉनवॉवन कपड़ों के मापा गुणों के साथ अच्छे समझौते पाए गए। समग्र नॉनवॉवन कपड़े में फाइबर ओरिएंटेशन के बढ़ते क्रम वाले एक उलटे ढाल का निर्माण बेहतर फिल्ट्रेशन एफिशिएंसी और कम प्रेशर ड्रॉप प्रदर्शित करता है। कार्डिंग मापदंडों से प्रभावित कार्डेड वेब में फाइबर की सूक्ष्मता और फाइबर ओरिएंटेशन की भूमिका को महसूस करने के बाद, सुई छिद्रण किए गए गैर-बुने हुए कपड़ों के कार्यात्मक गुणों को और बढ़ाने के लिए छिद्रण प्रक्रिया पर जोर दिया गया। सीकुएनशीएल पंचिंग का एक अनूठा तरीका प्रस्तावित किया गया था जिसमें अलग-अलग पंच डेंसिटी या अलग-अलग नीडल पेनेट्रेशन डेप्थ के अर्ध छिद्रित कपड़ों की परतों वाले समग्र नॉनवॉवन कपड़े तैयार किए गए थे। प्रारंभ में, बॉक्स-बेहेनकेन फैक्टोरियल डिज़ाइन का उपयोग आधार वजन, पंच डेंसिटी और नीडल पेनेट्रेशन डेप्थ को अनुकूलित करने के लिए किया गया था। 100 ग्राम/वर्ग मीटर आधार वजन के लिए अनुकूलित छिद्रण मापदंडों का उपयोग अलग-अलग पंच डेंसिटी या अलग-अलग नीडल पेनेट्रेशन डेप्थ के अर्ध छिद्रित कपड़ों की परतों वाले समग्र नॉनवॉवन कपड़े तैयार करने के लिए किया गया था। समग्र नॉनवॉवन कपड़ों की पैकिंग घनत्व के मूल्यांकन के लिए एक्स-रे कंप्यूटेड टोमोग्राफी तकनीक का उपयोग किया गया था। पैकिंग घनत्व के प्राप्त रुझान नॉनवॉवन कपड़ों के मापा गुणों के साथ अच्छे समझौते में पाए गए। यह फिर से स्थापित किया गया था कि दोनों मामलों में एक उलटी ढाल संरचना का निर्माण एक साथ कम प्रेशर ड्रॉप प्राप्त करके उच्च फिल्ट्रेशन एफिशिएंसी रखता था। हालांकि, स्तरित संरचना में अलग-अलग पंच डेंसिटी वाले समग्र नॉनवॉवन कपड़े अलग-अलग नीडल पेनेट्रेशन डेप्थ वाले समग्र कपड़ों की तुलना में बेहतर प्रदर्शन करते हैं।

अंत में, बाहरी कारकों जैसे धूल की मात्रा, परिचालन समय, और हवा के वेग का सीकुएनशीएली पंच समग्र नॉनवॉवन कपड़ों के प्रदर्शन पर प्रभाव की जांच की गई। अध्ययन ने पुष्टि की कि समग्र नॉनवॉवन कपड़े में पैकिंग डेंसिटी के घटते क्रम की परतों वाली ढाल

संरचना की तुलना में पैकिंग डेंसिटी के बढ़ते क्रम की परतों वाली उलटी ढाल संरचना के परिणामस्वरूप कम प्रेशर ड्रॉप और बेहतर फिल्ट्रेशन एफिशिएंसी प्राप्त हुई।

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LIST OF SYMBOLS

N_p	Punch density
f	Needle punch frequency
d	Density of needle board
v	Throughput speed
a	Advance per stroke
p	Number of needling passages used
C	Weight of combed out portion under the side plate
E	Weight of projected portion from the edge of the front plate after combing
N	Weight of material after combing and cutting under the front plate
ψ	Measured angles of inclination
$P(\psi)$	Probability density function of all measured angles of inclination ψ
η	Anisotropy
$P(0)$	Maximum probability density of fibre orientation
$P(\pi/2)$	Minimum probability density of fibre orientation
U_p	Number of upstream particles
D_p	Number of downstream particles
F_e	Filtration efficiency
ρ	Proportion of curved fibre ends
K_p	Coefficient of relative fibre parallelisation
Y	Response values (physical, mechanical, functional properties)
β_{00}	Constant
X_n	Process parameters
$\beta_{11}, \beta_{22}, \beta_{33}$	Pure quadratic coefficients
$\beta_{12}, \beta_{13}, \beta_{23}$	Mixed quadratic coefficients
ε	Error
σ^2_{total}	Total variance
$\sigma^2_{product}$	Product variance

σ^2_{gauge}	Gauge variance
i	Number of operators
k	Number of measurements
j	Number of parts
μ	Constant
τ	Part effect
β	Operator effect
$\tau\beta$	Operator part interaction
σ^2_{τ}	Variance of part effect
σ^2_{β}	Variance of operator effect
$\sigma^2_{\tau\beta}$	Variance of interactive effect of operator and part
σ^2_{ε}	Variance of error
SS	Sum of squares
MS	Mean sum of squares
n	Number of replicates
a	Number of parts
b	Number of replicates
C	Ratio of gauge variability to product variability
d	Fibre diameter
l_y	Number of layers in fibre web geometry
ν	Porosity
Df	Degree of freedom
n_f	Number of fibres captured by single barb of needle
R	Fibre diameter
ρ_f	Fibre density
W_n	Areal density of fabric
S	Barb opening area
n_b	Number of barbs in action
Z_{av}	Average length of fibre in unit area
θ	Orientation angle
Q	Fibre orientation index