HIGH PERFORMANCE NONWOVEN AIR FILTERS FOR AUTOMOTIVE ENGINE INTAKE AIR FILTRATION

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by

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Dedicated to my Grandmother

CERTIFICATE

This is to certify that the thesis titled '**High Performance Nonwoven Air Filters for Automotive Engine Intake Air filtration**', being submitted by **Mr. Shivendra Yadav** 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 him. He has worked under my guidance and supervision and fulfilled the requirements for submission of 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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ABSTRACT

A sophisticated air intake system of automotive vehicles requires high quality air filters for greater engine life, improved vehicular performance, and decreased operational cost. In this research work, a variety of innovative nonwoven filter media were developed, characterized, and tested for commercial engine intake application. Hybrid nonwoven media with multimodal distributions of fiber size & fiber shape and composite nonwoven media with hierarchical arrangements of fiber geometries & fiber orientation were produced by employing a laboratory-based needle-punching nonwoven production line. Chemically-treated needle-punched nonwoven media were prepared by utilizing an in-house fabricated apparatus for spraying of a wide variety of viscous liquids. The particle filtration behavior of the said filter media was determined at the cleaned state as well as at the clogging state by employing a gravimetric test equipment and a fractional efficiency tester. Analytical modifications were suggested for prediction of overall filtration efficiency and pressure drop evolution in case multimodal nonwoven filter media. The composite nonwoven filter media comprising hierarchically arranged fibers of different sizes or shapes or with different levels of anisotropic orientation displayed excellent filtration performance. The liquid-treated filter media registered higher gravimetric as well as fractional filtration efficiency, slower rise of pressure drop, and higher dust holding capacity as compared to the untreated one. The liquid treatment registered a higher magnitude increase of fractional efficiency for smaller particles as compared to larger ones. An expression for determination of single fiber efficiency due to adhesion was proposed. A few selected nonwoven filter media developed in this work were first pleated and thereafter assembled in a commercial air intake system. The performance of the nonwoven air intake filters was assessed and compared with that of a commercial paper filter in accordance with the

globally accepted ISO 5011 standard. As compared to the commercial paper filter, the nonwoven air filters developed in this work exhibited much higher dust holding capacity, much lesser initial pressure drop, and much slower rise of pressure drop due to dust accumulation, besides much higher service life, more savings of energy, lower greenhouse gas emission, and less fuel consumption.

सार

मोटर वाहनों के इंजन के अधिक जीवन, बेहतर प्रदर्शन और कम परिचालन लागत के लिए इसमे लगे परिष्कृत वायु सेवन प्रणाली को उच्च गुणवत्ता वाले वायु फिल्टर की आवश्यकता होती है। इस शोध कार्य में वाणिज्यिक इंजन को स्वच्छ वायु के आपूर्ति के लिए विभिन्न प्रकार के नयें अन्वेषणो पर आधारित नानवोवेन फिल्टर मीडिया विकसित एवं उनके परीक्षण कियें गयें। भिन्न-भिन्न फाइबर के आकार और आकृति के बहुविध वितरण द्वारा निर्मित हाइब्रिड नानवोवेन फिल्टर मीडिया तथा अलग-अलग फाइबर आकार, आकृति और विभिन्न फाइबर अभिविन्यास की पदानुक्रमित व्यवस्था द्वारा प्रयोगशाला आधारित नीडलपंच नानवोवेन मशीन का प्रयोग करके कम्पोजिट नानवोवेन फिल्टर मीडिया का उत्पादन किया गया था। स्वनिर्मित स्प्रेइंग उपकरण द्वारा भिन्न-भिन्न तरल पदार्थों का छिड़काव करके रासायनिक रूप से उपचारित नानवोवेन फिल्टर मीडिया का उत्पादन भी किया गया।

विभिन्न आकार, आकृति एवं अभिविन्यास में पदानुक्रमित संरचना द्वारा निर्मित कम्पोजिट नानवोवेन फिल्टर मीडिया का निस्पंदन क्षमता का प्रदर्शन उत्कृष्ट पाया गया। तरल उपचारित फिल्टर मीडिया ने ग्रेविमीट्रिक के साथ-साथ आंशिक निस्पंदन क्षमता, दबाव मे धीमी वृद्धि के साथ-साथ अनुपचारित की तुलना में उच्च धूल धारण की क्षमता भी दर्ज की। तरल उपचारित मीडिया में बड़े कणों की तुलना में छोटे कणों के लिए आंशिक निस्पंदन क्षमता में उच्चपरिमाण वृद्धि दर्ज की।

आसंजन के कारण एकल फाइबर स्कंदन क्षमता के निर्धारण के लिए एक अभिव्यक्ति भी प्रस्तावित की गई है। इस शोध कार्य में विकसित कुछ चुनिंदा नानवोवेन फिल्टर मीडिया को पहले प्लीट किया गया और उसके बाद प्रदर्शन परीक्षण के लिए वाणिज्यिक वायु सेवन प्रणाली मे लगाया गया। विकसित फिल्टर मीडिया का परीक्षण विश्व स्तर पर स्वीकृत आई० एस० ओ० 5011 के मानक पर किया गया और इनके प्रदर्शन का मूल्यांकन और तुलना विश्व बाजार में उपलब्ध वाणिज्यिक पेपर फिल्टर के साथ की गयी। वाणिज्यिक पेपर फिल्टर मीडिया की तुलना में, इस शोध कार्य में विकसित नानवोवेन एअर फिल्टर ने बहुत अधिक धूल धारण क्षमता, बहुत कम प्रारंभिक दबाव और धूल जमा होने के कारण दबाव में धीमी वृद्धि के साथ-साथ इंजन की अधिक सेवा जीवन, अधिक ऊर्जा की बचत, कम ग्रीनहाउस गैस उत्सर्जन और कम इंधन की खपत भी पाया गया।

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T	absolute temperature
g	acceleration due to gravity
Q	air flow rate
A	area of the filter through which the air is flowing
$\bar{a}_i$	average cross-sectional area of fiber of *i*-th component
$\bar{d}$	average fibre diameter
$\bar{\rho}_i$	average fiber density of *i*-th component
$\bar{l}_i$	average fiber length of *i*-th component
$\bar{p}_i$	average fiber perimeter of *i*-th component
$\bar{t}_i$	average fineness of fiber of the *i*-th component
C	ambient average dust concentration
w_{F}	basis weight of filter media
K_{B}	Boltzmann constant
$F_{\mathrm{cap,\ p}}$	capillary force
$F_{\mathrm{cap,\ p,\ P}}$	capillary pressure
α	characteristic length of nozzle
b	coefficient that can be found from the best-fit curve
$C_{\mathrm{down}}\left(d_{\mathrm{p}}\right)$	concentration of particles of a specific size at downstream of filter media
$C_{\mathrm{down}}\left(d_x\right)$	concentration of particles of a same size at downstream of filter media

$C_{up}\left(d_p\right)$	concentration of particles of a specific size at upstream of filter media
$C_{up}\left(d_x\right)$	concentration of particles of same size at upstream of filter media
K_c	constant
ϑ	contact angle
$F_{con,\ p}$	contact force
C_c	Cunningham correction factor
ρ	density
C_D	drag coefficient
F_D	drag force
η	dynamic viscosity of air
ρ_a	density of air
ρ_f	density of fiber
$\overline{\rho}_i$	density of fiber of *i*-th component
ρ_i	density of *i*-th component of fibers in multimodal fibrous filter medium
ρ_l	density of liquid
ρ_p	density of particle
d_f	diameter of fiber
D_i	diffusion coefficient

β	dimensionless constant
d	distance between particle centre from filter surface and thickness of liquid layer
$C_{D,L}$	drag coefficient of the dust-loaded media
F_D	drag force acting on a unit length of a fiber
α	dynamic viscosity of air
η	dynamic viscosity of fluid
μ_l	dynamic viscosity of liquid
DHC	dust holding capacity
a	exponent
EF	emission factor
ΔH	energy saved due to reduced air resistance
U_0	face velocity
ζ	factor
v	filtration velocity
λ	free mean path length of gas molecules
$E\left(d_p\right)$	filtration efficiency for a test particle size
$E\left(d_x\right)$	filtration efficiency for a test particle size
E_Σ	filtration efficiency of a clean fiber

E_{Σ}^{*}	filtration efficiency of a dust-loaded fiber
$E_{F,l}$	filtration efficiency of liquid-treated filter media
E_{F}	filtration efficiency of untreated filter media
t_i	fineness of *i*-th component of fibers in multimodal fibrous filter medium
ρ_a	fluid density
E	filtration efficiency
FOT	filter operating time
LOF	filter service life
$F_{gra, p}$	gravitational force
ΔCO_2	greenhouse gases due to reduced air resistance
ψ	half-filling angle
$\Delta MABS$	increase in mass of absolute filter
ΔMU	increase in mass of test filter media
Kn	Knudsen number
h_K	Kozeny constant
Ku	Kuwabara hydrodynamic factor
l_f	length of fiber
l_i	length of *i*-th component of fibers in multimodal fibrous filter medium
w_l	liquid add-on

$d_{f,l}$	liquid-treated fiber diameter
$\bar{d}_i$	mean equivalent diameter of fiber of *i*-th component of fibers
$\bar{p}_i$	mean fiber perimeter of *i*-th component of fibers
$\bar{l}_i$	mean length of fibers of *i*-th component of fibers
w_i	mass fraction of *i*-th component of fibers
m_p	mass of accumulated dust particles
m_i	mass of *i*-th component of fibers
m_p	mass of the particle
$\bar{d}_L$	mean apparent diameter of the dust-loaded fiber
$\bar{\rho}_i$	mean density of *i*-th component of fibers
$\bar{d}_i$	mean diameter
$d_{p,k,t}$	mean diameter of the collected particles in *k*-th layer at time *t*
$(\bar{\varphi}_i)$	mean shape factor of *i*-th component of fibers
$\bar{s}_i$	mean surface area per unit mass of *i*-th component of fibers
η	measure of anisotropy of fiber orientation
$\bar{a}$	mean cross-sectional area of fibers in filter medium
$\bar{t}$	mean fineness of fibers in filter medium
m	mass of deposited particle
d_n	nozzle diameter
(κ_i)	number fraction

κ_i	number fraction. of *i*-th component of fibers
n_f	number of fibres present in this medium
n_p	number of particles approaching to infinitesimally thin layer
$n_{p,down}$	numbers of particles at downstream of filter medium
$n_{p,up}$	numbers of particles at upstream of filter medium
F_p	net force acting on particle
dn_p	number of particles collected by layer of a filter medium
E	overall filtration efficiency of filter medium.
α	packing density of filter media
α_p	packing density of cake
$\alpha_{p,k,t}$	packing density of dust deposited in *k*-th layer at time *t*
$\mu_{F,l}$	packing density of liquid-treated filter media
d_p	particle diameter
Pe	Peclet number
P_l	pressure acting on liquid of the volume-based median diameter (D_{50})
$\Delta P*$	pressure drop across a clogged filter medium,
ΔP	pressure drop across clean filter medium
$\Delta P'$	pressure drop due to accumulated
$P_{k,t}^*$	pressure drop of each layer due to fibres and collected particles

$f(\vartheta)$	probability density function of fibre inclination angle ϑ
μ_f	packing density of filter media
ΔP_t	pressure drop during filter operating time
r_{c}	radius of that part of the particle which is in contact with the liquid
r_{p}	radius of particle
Re_{p}	Reynolds number for particle
Re	Reynolds number for fiber
E_{Σ}	single fiber efficiency of multimodal fibrous filter media
$E_{\Sigma,i}$	single fiber efficiency of *i*-th component of fibers
E_{I}	single fibre filtration efficiency due to inertial impaction
$\eta_{\mathrm{f,l,a}}$	single fiber efficiency due to adhesion
E_{Σ}	single fiber filtration efficiency
E_{D}	single fibre filtration efficiency due to diffusion
E_{R}	single fibre filtration efficiency due to direct interception
E_{G}	single fibre filtration efficiency due to gravitational settling
a_{p}	specific area of particle
γ_i	surface area fraction of *i*-th component of fibers
σ_{l}	surface tension of liquid
$F_{\mathrm{cap,\,p,\,}\sigma}$	surface tension of liquid layer

ΔFC	saved fuel consumption
Z	thickness of filter media
t	time
$Z_{\mathrm{F,l}}$	thickness of liquid-treated filter medium
t_{p}	time taken by particle
E_{Σ}	total efficiency of a single fibre
m	total mass of filter media
S_i	total surface area of fibers of *i*-th component
L	total length of all fibers in filter medium
Li	total length of i-th component of fibers
ZF	thickness of filter media
v	velocity of fluid
$\mathbf{v}$	velocity vector
U_0	velocity of air at upstream approaching filter media
V_{l}	velocity of liquid
v_{p}	velocity of particle
v_{p}	velocity of the particle
μ_{l}	viscosity of liquid
$F_{\mathrm{vis,\,p}}$	viscous dissipative force
$\boldsymbol{\tau}$	viscous force acting on the fluid per unit volume of filter element

β_i	volume fraction of *i*-th component of fibers
V_k	volume of *k*-th layer of filter media
$V_{\mathrm{p},k}$	volume of particles collected in *k*-th layer of filter media
S	vehicle speed
g_f	weight fraction of fibers in filter media
g_l	weight fraction of liquid in filter media
w_l	weight of liquid per unit area of filter media