PARTICLE FILTRATION BEHAVIOUR OF OIL-TREATED FIBROUS AIR FILTERS FOR AUTOMOTIVE ENGINE INTAKE APPLICATION

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by

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Submitted

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

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To

My family

CERTIFICATE

This is to certify that the thesis entitled '**Particle Filtration Behaviour of Oil-treated Fibrous Air Filters for Automotive Engine Intake Application**', being submitted by **Mr. Ajay Kumar Maddineni** 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 our 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

The current research work dealt with development, characterisation and application of oil-treated cellulosic air filters for automotive engine intake air filtration. In this work, a numerical methodology was developed for estimation of pressure drop and flow field within an automotive engine intake air filter system suitable for space-constraint environments. The simulation results demonstrated that the flow field within the air filter housing was highly non-uniform. A set of new equations was proposed to parameterize the pleat geometry. A higher pleat pitch resulted in higher and uniform flow velocity. This effect was less pronounced at higher pleat height and higher inlet velocity. The pleat radius was found to decide the pressure drop and flow field significantly at higher velocities. The simulation results were found in good agreement with the findings of laboratory experiments carried out on a cellulosic air filter media typically used for automotive engine intake application.

Further, a numerical technique was developed to predict the capture of air-borne particles by fibrous filter media under collision effect. The Hamaker adhesion model in conjunction with particle rebound parameter was assessed for particle capture efficiency. The numerical results showed a good correspondence with the experimental data. The numerical technique was applied to examine the roles of particle size, media structure and flow velocity in deciding the particle bounce and particle penetration though the filter media. It was found that the particles of greater than 2 μm diameter predominantly rebounded and subsequently penetrated through the filter media. A higher reduction in filtration efficiency of large particles due to rebound and re-entrainment was observed for lower basis weight and thicker filter media. A highly packed filter media showed less particle penetration after collision due to availability of small re-entrainment space and vice-versa. It was found that, as fiber diameter increased, for a constant fiber packing

density, a significant reduction in filtration efficiency was observed beyond 4 µm fiber diameter. Finally, the filter media where the particles were most likely to bounce was identified and it was evaluated for increasing face velocity. A higher velocity was found to be a significant factor that caused particle bounce and penetration. This effect was in good agreement with empirical calculations. The numerical technique developed here could be a reliable predictor of particle bounce and re-entrainment behaviour of fibrous filter media.

It was demonstrated that the particle bounce could be suppressed by treating the cellulosic filter media with viscous oil. At less oil loading, the initial pressure drop across the oil-treated filter media was found to be almost the same as that of untreated media. But, when the oil loading was high, the initial pressure drop increased tremendously, depending upon the face velocity. This behavior was explained in the light of Davies equation by taking into account of the change in diameter of oil-coated fiber as well as in packing density due to oil treatment. The filtration efficiency of the oil-treated filter media increased at higher face velocities for large particles, unlike the untreated ones. At lower dust loading and lower face velocities, the oil-treated filter media exhibited lower pressure drop and lower filtration efficiency. However, at higher face velocities, the oil-treated filter media displayed higher filtration efficiency but with a similar pressure drop at lower dust loading. Nevertheless, the same media exhibited higher filtration efficiency at higher dust loading.

Further, the effect of pleat geometry on the filtration performance of pleated air filter element was examined. Pleat pitch and pleat height were found to play important roles in determining the filtration efficiency, pressure drop, and dust holding capacity. A pleated fibrous filter prepared with optimum levels of pleat pitch and pleat height showed the best filtration performance. The treatment to the pleated filter by viscous oil yielded remarkably higher dust

holding capacity and filtration efficiency, both at cleaned and clogged conditions. The role of oil treatment process in deciding the filtration performance of oil-treated pleated fibrous filters was examined by carrying out experiments in accordance with a two-level factorial design. The process factors of interest were oil weight, oil temperature and oil aging time, and the response variables were filtration efficiency, pressure drop, and dust holding capacity. The statistical analysis of experimental data revealed that the oil weight played a significant role in deciding the dust holding capacity and filtration efficiency of the pleated air filters. However, none of the aforementioned process factors was found to be statistically significant in determining the pressure drop.

Finally, an oil-treated pleated filter element was installed in a commercial air intake system and its filtration performance was assessed. The filter element displayed a significant delay in evolution of pressure drop during dust loading as compared to the untreated one. However, the difference in filtration efficiency between the oil-treated and untreated filter elements was not found to be too high. Nevertheless, both of them met the standard filtration performance as per the best practices followed by the automotive industry. Overall, the oil treatment to cellulosic air filters was found to be highly advantageous for motorcycle application. As compared to the untreated air filter, the oil-treated one was expected to offer increased service life by 2.3 times, decreased fuel consumption by 20 litre and reduced CO_2 emission by 50 kg per motorcycle for a ride of 12000 km before replacement of the filters.

सार

वर्तमान शोध कार्य ऑटोमोटिव इंजन वायु के निस्पंदन के लिए तेल-युक्त सेल्यूलोसिक एयर फिल्टर के विकास, विशेषता और अनुप्रयोग के सम्बध मे है। इस काम में, मोटर वाहन इंजन वायु फ़िल्टर प्रणाली के भीतर दबाव मे गिरावट और प्रवाह क्षेत्र के आकलन के लिए एक संख्यात्मक पद्धति विकसित की गई है। सिमुलेशन के नतीजे से पता चलता हैं कि वायु फ़िल्टर प्रणाली के भीतर प्रवाह क्षेत्र अत्यधिक असामान्य है। प्लीट ज्यामिति को पैरामीटराइज़ करने के लिए नए समीकरणों का एक सेट प्रस्तावित किया गया। उच्च प्लीट पिच के परिणामस्वरूप उच्च और समान प्रवाह वेग होता है। यद्दपि इसका प्रभाव उच्च प्लीट ऊंचाई और उच्च प्रवेश वेग पर कम पाया गया । उच्च वेगों पर, प्लीट त्रिज्या प्रेसर दबाव मे गिरावट और प्रवाह क्षेत्र नियंत्रित करने मे प्रभावकारी पाया गया । यह भी पाया गया की सिमुलेशन के परिणाम और सेल्यूलोसिक एयर फ़िल्टर मीडिया पर किए गए प्रयोगशाला प्रयोगों के निष्कर्षों के साथ सामन्जस्य बहुत अच्छे है।

इसके अलावा, कोलिज़न प्रभाव के तहत सेल्युलोसिक फ़िल्टर मीडिया द्वारा वायु मे उपस्थित कणों को कैप्चर करने हेतु भविष्यवाणी करने के लिए एक संख्यात्मक तकनीक विकसित की गई। कण रिबाउंड पैरामीटर के संयोजन के साथ हैमेकर मॉडल द्वारा कण कैप्चर दक्षता के लिए मूल्यांकन किया गया । संख्यात्मक परिणामों का प्रयोगात्मक डेटा के साथ एक अच्छा परिणाम दिखता है। फिल्टर मीडिया के माध्यम से कण उछाल और कण प्रवेश का निर्णय लेने में कण आकार, मीडिया संरचना और प्रवाह वेग की भूमिकाओं की जांच करने के लिए संख्यात्मक तकनीक लगाई गई । यह पाया गया कि दो माइक्रोन व्यास से अधिक के कण मुख्य रूप से टकराने के बाद फ़िल्टर मीडिया के माध्यम से अंदर प्रवेश कर जाते हैं। रिबाउंड और पुनः-प्रवेश के कारण बड़े कणों की निस्पंदन दक्षता में उच्च कमी आधार वजन और मोटे फ़िल्टर मीडिया के लिए देखी गई। एक बेहद पैक किए गए फ़िल्टर' मीडिया ने पुन: प्रवेश स्थान की उपलब्धता के कमी के कारण टकराव के बाद कम कण प्रवेश दिखाया और इसके विपरीत यह पाया गया कि, स्थिर फाइबर पैकिंग घनत्व के लिए, फाइबर व्यास में वृद्धि के कारण, निस्पंदन दक्षता में एक महत्वपूर्ण कमी 4 माइक्रोन फाइबर व्यास से अलग देखी गई । आखिरकार, फ़िल्टर मीडिया जहां कणों को उछालने की सबसे अधिक संभावना थी, पहचान की गई और इसका वेग बढ़ाने के लिए मूल्यांकन किया गया । उच्च वेग एक महत्वपूर्ण कारक पाया गया जो कण उछाल और प्रवेश के कारण हुआ। यह प्रभाव प्रयोगात्मक गणनाओं के साथ अच्छे सामंजस्य मे पाया गया। यहां विकसित संख्यात्मक तकनीक कण उछाल और सेल्युलोसिक फ़िल्टर मीडिया के पुन: प्रवेश व्यवहार का एक विश्वसनीय भविष्यवाणी करने का साधन हो सकती है।

यह पाया गया कि सेल्यूलोसिक फिल्टर मीडिया को तेल युक्त करके कण उछाल को कम किया जा सकता है। कम तेल लोडिंग पर, तेल से युक्त फ़िल्टर मीडिया में प्रारंभिक दबाव मे कमी बिना तेल युक्त मीडिया के समान ही पाया गया । लेकिन, जब तेल लोडिंग अधिक थी, तब वायु गति के आधार पर शुरुआती दबाव में गिरावट काफी बढ़ा हुआ पाया गया। तेल युक्त फिल्टर मे तेल-लेपित फाइबर के व्यास के साथ-साथ पैकिंग घनत्व में परिवर्तन के कारण डेविस समीकरण के प्रकाश में यह व्यवहार समझाया गया । तेल युक्त फ़िल्टर मीडिया की निस्पंदन दक्षता बिना तेल युक्त फिल्टर लोगों के विपरीत बड़े कणों के लिए उच्च वेग के लिए अधिक पाया गया। कम धूल लोडिंग और निचले वेग पर, तेल से युक्त फ़िल्टर मीडिया ने कम दबाव मे कमी और निचली निस्पंदन दक्षता प्रदर्शित की। हालांकि, उच्च वेगों पर, तेल से युक्त फ़िल्टर मीडिया ने उच्च निस्पंदन दक्षता प्रदर्शित की लेकिन कम धूल लोडिंग पर एक समान दबाव ड्रॉप के साथ पाया गया। फिर भी, उसी मीडिया ने उच्च धूल लोडिंग पर उच्च निस्पंदन दक्षता प्रदर्शित की।

इसके अलावा, प्लीटेड वायु फ़िल्टर तत्व के निस्पंदन प्रदर्शन पर प्लीट ज्यामिति का प्रभाव की जांच की गई . यह पाया गया की प्लीट पिच और प्लीट ऊंचाई निस्पंदन दक्षता, दबाव मे गिरावट और धूल को रखने की क्षमता निर्धारित करने मे महत्वपूर्ण भूमिका निभाते है। तेल युक्त फ़िल्टर मे साफ और क्लॉग्ड दोनो स्थितियों मे उल्लेखनीय रूप से उच्च धूल होल्डिंग क्षमता और निस्पंदन दक्षता प्राप्त हुई। तेल युक्त प्लीटेड फिल्टर के निस्पंदन प्रदर्शन का निर्णय लेने में तेल युक्त प्रक्रिया की भूमिका दो स्तर के फैक्ट्रोरियल डिजाइन के अनुसार प्रयोग करके जांच की गई । प्रक्रिया कारक तेल वजन, तेल का तापमान और तेल उम्र बढ़ने का समय और प्रतिक्रिया चर फिल्टरिंग क्षमता, दबाव ड्रॉप, और धूल होल्डिंग क्षमता थे। प्रयोगात्मक आंकड़ों के सांख्यिकीय विश्लेषण से पता चला कि तेल के वजन ने धूल होल्डिंग क्षमता और प्लीटेड हवा फिल्टर की निस्पंदन दक्षता का निर्णय लेने में एक महत्वपूर्ण भूमिका निभाई है। हालांकि, उपरोक्त प्रक्रिया कारकों में से कोई भी दबाव ड्रॉप निर्धारित करने में सांख्यिकीय रूप से महत्वपूर्ण नहीं पाया गया था।

अंत में, एक तेल-युक्त प्लीटेड फिल्टर तत्व एक वाणिज्यिक वायु सेवन प्रणाली में स्थापित किया गया और इसके निस्पंदन प्रदर्शन का आकलन किया गया . फिल्टर तत्व धूल लोडिंग के दौरान दबाव ड्रॉप के विकास में एक महत्वपूर्ण देरी प्रदर्शित करता है. हालांकि, तेल-उपचारित और अनुपचारित फिल्टर तत्वों के बीच निस्पंदन दक्षता में अंतर बहुत अधिक नहीं पाया गया। फिर भी, दोनों मोटर वाहन उद्योग द्वारा अपनाई जाने वाली सर्वोत्तम प्रथाओं के अनुसार मानक निस्पंदन प्रदर्शन को पूरा करते हैं। कुल मिलाकर, तेल युक्त सेल्युलोसिक एयर फिल्टर मोटरसाइकिल के प्रयोग हेतु अत्यधिक फायदेमंद पाया गया। अनुपचारित एयर फिल्टर की तुलना में, तेल उपचारित फिल्टर मे 2.3 गुना बढ़े हुए सेवा जीवन की संभावना है, ईंधन की खपत में 20 लीटर की कमी हुई और फ़िल्टर के प्रतिस्थापन से पहले 12000 किमी की सवारी के लिए प्रति मोटरसाइकिल 50 किलोग्राम कार्बनडाईआक्साइड उत्सर्जन कम हो गया ।

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LIST OF SYMBOLS

a_0	Adhesion distance
a_g	Specific area of the particle
A	Area of filter media
A_f	Area occupied by the fibres
C_c	Cunningham correction factor
$C_d\left(d_p\right)$	Concentration of particles of diameter d_p at downstream side of the filter media
$C_u\left(d_p\right)$	Concentration of particles diameter d_p at upstream side of the filter media
CF	Conversion factor
d_f	Fibre diameter
dn	Number of particles passing through the infinitely small layer of filter medium
dZ	Thickness of infinitely small layer of filter medium
D_i	Diffusion coefficient
d_p	Diameter of the particle
$d_{pk,t}$	Mean diameter of the collected particles in the k^{th} slice at time t
$d_{f,o}$	Diameter of the oil treated fiber
d_f	fiber Diameter of the fibrous filter
dn	Number of particles collected by the infinitely small layer
$dW(t)$	3-d Weiner probability measure
DHC	Dust holding capacity of the filter element

E_{Σ}	Total efficiency of the single fiber
E	Overall efficiency of the filter medium
E_D	Efficiency due to Brownian diffusion
E_I	Efficiency due to intertial impaction
E_R	Efficiency due to direct interception
E_G	Efficiency due to gravitation
Eq	Efficiency due to electrostatic charge
$E_{\Sigma,C}$	Collision efficiency of the single fiber
$E_{\Sigma,A}$	Adhesion efficiency of the single fiber
e_{pl}	Coefficient of restitution (plastic deformation only)
e_r	Coefficient of restitution (plastic and elastic deformation)
EF	Emission factor for $C0_2$
FOT	Filter operating time
g	Acceleration due to gravity
g_{f}	Mass proportion of fiber
g_{o}	Mass proportion of oil
$\hat{h}$	Parameter
h	Plank constant
h_P	Pleat Height
h_k	Kozeny constant
H	Hamakar constant
I	Parameter, which is a function of φ and Q

J	Parameter, which is a function of φ
Ku	Kuwabara hydrodynamic factor
Kn	Knudsen number
K_c	Constant
K_B	Boltzmann constant
KE_B	Kinetic energy required for bounce
K	permeability of the filter media
l_f	Fiber length
LOF	Life of the filter
m_p	Mass of the particle
M	Fiber material properties
N_{in}	Number of particles approached the fibrous domain
N_{out}	Number of particles left the fibrous domain
n	Number of particles approaching to the infinitesimally thin layer
n_f	Number of fibers present in the filter media
n_{up}	Number of particles upstream of the filter medium
n_{down}	Number of particles downstream of the filter medium
p_{pl}	Microscopic yield pressure
P_b	Probability of particle bounce
P_e	Peclet number
$\mathrm{p_p}$	Pleat pitch
PQF_1	Pleat quality factor 1

PQF_2	Pleat quality factor 2
Q	Interception parameter
$\dot{Q}$	Flow rate
q	Particle charge
Re_f	Reynolds number of the fiber
Re_p	Reynolds number of the Particle
r_p	Radius of the particle
r	Pleat radius
$\mathrm{r}_{\mathrm{max}}$	Maximum possible radius
S	Vehicle speed
St_c	Modified Stokes number
Stk	Stokes number
T	Ambient temperature in Kelvin
t	time
u	Velocity Vector
U_0	Face velocity
$V_{p,k}$	Volume of particles collected in filter media layer *j*
V_{k}	Volume of filter media layer *J*
$\vec{v}$	Particle velocity vector
$\overrightarrow{v_o}$	Fluid velocity vector within the fibrous structure
v	Fluid velocity of the within the fibrous structure
v_{cr}	Critical velocity

W_o	Weight of the oil per unit area of the filter
W_f	Weight per unit area of the untreated filter media
x	Separation distance of the centre of mass of particle and fiber surface
$\vec{x}$	Particle position vector
Z	Filter media thickness
Z_k	Thickness of the filter media layer k
α	Packing density of the filter media
α_p	Packing density of collected particles
α_{pc}	Packing density of dust cake
$\alpha_{pk,t}$	Packing density of particles collected in layer k for time t
β	Characteristic parameter of pore size
γ	Fluid friction coefficient
δ_{ij}	Dirac delta function
ΔP	Total pressure drop across the filter media
ΔP_f	Pressure drop across the filter media at clean condition
$\Delta P_{f,E}$	Pressure drop across the filter element at clean condition
$\Delta P_{f,o}$	Pressure drop across the oil-treated filter media at clean condition
ΔP_g	Pressure drop across the filter media at clogged condition
ΔP_t	Total Pressure drop across the filter media during dust loading
$\Delta P_{k,t}$	Total Pressure drop across the filter media slice k at time t
ΔH	Energy saving
ΔCO_2	Green house gas saving

ΔFC	Fuel consumption saving
ΔMU	Increase in mass of unit under test
$\Delta MABS$	Increase in mass of absolute filter
ε_f	Dielectric constant of fiber
ε_0	Permittivity of vacuum
$\eta_\mathrm{p}\left(d_\mathrm{p}\right)$	Filtration efficiency of the filter media for particles of diameter d_p
η_m	Gravimetric filtration efficiency of the filter media
η	Refractive index
θ	Pleat angle
λ	Free mean path length of gas molecules
μ	Dynamic viscosity of air
$\xi_{i,j}$	Viscous resistance tensor
ρ	Density of the air
ρ_p	Density of the particle
ρ_f	Density of the fiber
ρ_o	Density of oil
σ	Fluctuation dissipation
τ_{ij}	Shear stress tensor
φ	Packing density of filter media
$\varphi_{f,o}$	Packing density of oil-treated filter media
$\psi_{i,j}$	Inertial coefficient tensor
Ψ	Adhesion energy

ϑ_e	Electronic absorption frequency
∂D_w	Micro geometry