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Numerical and Experimental Investigation of the Particle Filtration Behaviour of a Single Fibre and Fibrous Air Filters

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Numerical and Experimental Investigation of the Particle Filtration Behaviour of a Single Fibre and Fibrous Air Filters

by

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&

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Dedicated to my family and friends

Supervisor Certification

This is to certify that the thesis entitled "**Numerical and Experimental Investigation of the Particle Filtration Behaviour of a Single Fibre and Fibrous Air Filters**" being submitted by **Mr. Utsav Bhardwaj** to the Indian Institute of Technology Delhi and The University of Queensland for the award of degree of **Doctor of Philosophy** is a record of *bonafide* research work carried out by him. **Mr. Utsav Bhardwaj** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

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Abstract

To mitigate the adverse effects of airborne particulate matter, nonwoven fibrous air filter media are increasingly used, particularly in regions with poor air quality where rapid clogging of filtration systems is common. Optimizing filter performance remains a complex challenge due to multifaceted interactions between air, particles, and filter media. This research investigates the behavior of airborne inertia-dominated particles in fibrous filter media, focusing on the influence of various filter-based parameters and operating conditions on particle deposition morphology, dust holding capacity, and filtration performance. The filtration performance parameters include particle capture efficiency, pressure drop, and quality factor. The filter-based governing parameters considered are the through-plane fibre orientation, segmental aspect ratio of fibres, fibre material, fibre diameter distribution, fibre volume fraction, and filter thickness. On the other hand, the operating conditions considered are the face velocity, particle size distribution, and dust feed rate. The study employs both computational and experimental methods, combining the two/three-dimensional numerical simulations of particle capture by a single fiber-segment with the full-scale filtration experiments on filter media in order to understand the filtration phenomena at an elementary as well as a realistic scale. The lattice Boltzmann method (LBM), coupled with Lagrangian approach for two-dimensional simulations and discrete element method (DEM) for three-dimensional simulations, has been employed for numerical modeling and simulations.

For inertia-dominated particles, it has been found that an optimum through-plane orientation, as well as an optimum segmental aspect ratio, exists for fibres at which the quality factor is highest. The optimum through-plane fibre orientation lies around 20°-25° for low segmental aspect ratios of a fibre whereas 35° for higher ones tested in the present study, and it is independent of the Stokes number. For the presented set of parameters, the optimum segmental aspect ratio of a fibre is found as “2”. The interplay between particle diameter and face velocity is such that despite the Stokes number and fibre-based Reynolds number remaining constant, different pairs of particle diameter and face velocity can exist, yielding substantially different particle deposition morphologies and filtration performance parameters during the initial stages of filtration. At a given Stokes number and fibre-based Reynolds number, large particles injected at a low face velocity can be captured with a better overall filtration performance compared to the small particles injected at a high face velocity, where these two combinations are equivalent in terms of inertia-dominated particle capture. A low dust feed rate is found to facilitate depth

filtration alone to a great extent of the dust loading of filter media, whereas a higher dust feed rate leads to an earlier transition (partial) to surface filtration. The surface coverage of dust cake increases with rise in dust feed rate and face velocity, but it decreases with rise in fibre diameter. The dust holding capacity (DHC) of filter media decreases until fibre diameter is increased to a certain extent, which is attributed to the associated reduction in the specific surface area of fibres. However, DHC increases with further increase in fibre diameter, which is attributed to the dominant influence of the associated increase in mean pore size.

An optimum face velocity for particle capture is found to exist, at which the cumulative particle capture efficiency is maximum. The optimum face velocity has been found to decrease with rise in particle diameter, but it increases with rise in fibre diameter and dust feed rate. The optimum face velocity is also conjectured to increase with enhancement in particle-fibre adhesion forces, filter thickness, and fibre volume fraction. When any operating condition varies during the filtration process, the cumulative filtration performance parameters are found to depend on the sequence in which the concerned operating condition varies. For example, if dust concentration in a given space changes due to nearby activities (such as smoke generation, windstorm, rainfall, or operation of another air filter), or if an air filter is relocated to a room of different size or to an environment with lower/higher pollution level, the filtration flow rate would need to be adjusted, which in turn alters the face velocity. In such a case, the cumulative particle capture efficiency, coverage of dust cake, and pressure drop are higher if a higher face velocity follows a lower one, compared to the respective quantities obtained when the same lower face velocity follows the higher one.

This research provides valuable insights for optimizing filter design and operation, contributing to improved filtration performance, energy efficiency, and extended service life in a wide range of applications.

Abstract in Hindi

वायु में मौजूद कण पदार्थों के हानिकारक प्रभावों को कम करने के लिए, विशेष रूप से उन क्षेत्रों में जहां वायु गुणवत्ता खराब है और फ़िल्टरेशन सिस्टम तेजी से अवरुद्ध हो जाते हैं, नॉनवोवन फाइबर युक्त एयर फ़िल्टर मीडिया का उपयोग बढ़ता जा रहा है। फ़िल्टर प्रदर्शन का अनुकूलन करना जटिल चुनौती बनी रहती है, क्योंकि वायु, कण और फ़िल्टर मीडिया के बीच बहुपरत क्रियाओं की उपस्थिति होती है। यह शोध फ़ाइबर फ़िल्टर मीडिया में हवा में तैरते जड़त्व-प्रधान कणों के व्यवहार का अध्ययन करता है, जिसमें कण जमाव संरचना, धूल धारित क्षमता और फ़िल्टरेशन प्रदर्शन पर विभिन्न फ़िल्टर-आधारित पैरामीटर और संचालन परिस्थितियों के प्रभाव पर ध्यान केंद्रित किया गया है।

फ़िल्टरेशन प्रदर्शन पैरामीटर में कण कैप्चर दक्षता, दबाव गिरावट, और गुणवत्ता कारक शामिल हैं। फ़िल्टर-आधारित नियंत्रक पैरामीटर में थ्रू-प्लेन फाइबर अभिविन्यास, फाइबर का खंडीय अनुपात, फाइबर सामग्री, फाइबर व्यास वितरण, फाइबर आयतन अंश और फ़िल्टर की मोटाई शामिल हैं। संचालन स्थितियों में फेस वेग, कण आकार वितरण, और धूल फीड दर को ध्यान में रखा गया है। अध्ययन में दोनों, गणनात्मक और प्रायोगिक विधियों का उपयोग किया गया है, जिसमें एकल फाइबर-सेगमेंट द्वारा कण कैप्चर के दो/तीन-आयामी संख्यात्मक सिमुलेशन को फ़िल्टर मीडिया पर पूर्ण पैमाने के फ़िल्टरेशन प्रयोगों के साथ संयोजित किया गया है, ताकि फ़िल्टरेशन घटनाओं को बुनियादी और यथार्थवादी दोनों स्तरों पर समझा जा सके। संख्यात्मक मॉडलिंग और सिमुलेशन के लिए लैटिस बोल्ट्ज़मैन मेथड (LBM) का उपयोग किया गया, जिसमें दो-आयामी सिमुलेशन के लिए लैग्रेंजियन दृष्टिकोण और तीन-आयामी सिमुलेशन के लिए डिस्क्रीट एलिमेंट मेथड (DEM) जोड़ा गया।

जड़त्व-प्रधान कणों के लिए पाया गया कि फाइबर के लिए एक अनुकूल थ्रू-प्लेन अभिविन्यास और एक अनुकूल खंडीय अनुपात मौजूद है, जिस पर गुणवत्ता कारक अधिकतम होता है। कम खंडीय अनुपात वाले फाइबर के लिए अनुकूल थ्रू-प्लेन फाइबर अभिविन्यास लगभग 20°-25° है, जबकि उच्च अनुपात वाले फाइबर के लिए यह 35° है और यह स्टोक्स संख्या से स्वतंत्र है। प्रस्तुत पैरामीटर सेट के लिए, फाइबर का अनुकूल खंडीय अनुपात "2" पाया गया। कण व्यास और फेस वेग के बीच अंतःक्रिया ऐसी है कि भले ही स्टोक्स संख्या और फाइबर-आधारित रेनॉल्ड्स संख्या स्थिर रहें, अलग-अलग कण व्यास और फेस वेग के संयोजन मौजूद हो सकते हैं, जिससे फ़िल्टरेशन के प्रारंभिक चरणों में कण जमाव संरचनाएं और फ़िल्टरेशन प्रदर्शन पैरामीटर महत्वपूर्ण रूप से भिन्न हो जाते हैं।

दिए गए स्टोक्स संख्या और फाइबर-आधारित रेनॉल्ड्स संख्या पर, कम फेस वेग पर इंजेक्ट किए गए बड़े कण समग्र फ़िल्टरेशन प्रदर्शन में बेहतर पकड़े जा सकते हैं, तुलना में उच्च फेस वेग पर इंजेक्ट किए गए छोटे कणों के, जहाँ ये दोनों संयोजन जड़त्व-प्रधान कण कैप्चर के संदर्भ में समान होते हैं। कम धूल फीड दर केवल गहराई फ़िल्टरेशन को अधिकतम करने में सहायक पाई गई, जबकि उच्च धूल फीड दर सतही फ़िल्टरेशन की ओर पहले संक्रमण (आंशिक) करती है। धूल केक का सतही आवरण धूल फीड दर और फेस वेग बढ़ने पर बढ़ता है, लेकिन फाइबर व्यास बढ़ने पर घटता है। फ़िल्टर मीडिया की धूल धारण क्षमता (DHC) फाइबर व्यास को एक निश्चित सीमा तक बढ़ाने पर घटती है, जो फाइबर की विशिष्ट सतह क्षेत्र में कमी के कारण है। हालांकि, फाइबर व्यास और बढ़ने पर DHC फिर से बढ़ती है, जो औसत छिद्र आकार में वृद्धि के प्रभुत्व प्रभाव के कारण है।

कण कैप्चर के लिए एक अनुकूल फेस वेग मौजूद है, जिस पर संचयी कण कैप्चर दक्षता अधिकतम होती है। अनुकूल फेस वेग कण व्यास बढ़ने पर कम होता है, लेकिन फाइबर व्यास और धूल फीड दर बढ़ने पर बढ़ता है। अनुकूल फेस वेग कण–फाइबर आसंजन बल, फ़िल्टर मोटाई और फाइबर आयतन अंश बढ़ने पर भी बढ़ने का अनुमान है। फ़िल्टरेशन प्रक्रिया के दौरान यदि कोई संचालन स्थिति बदलती है, तो संचयी फ़िल्टरेशन प्रदर्शन पैरामीटर उस क्रम पर निर्भर करते हैं जिसमें संबंधित संचालन स्थिति बदलती है। उदाहरण के लिए, यदि किसी स्थान में धूल सांद्रता आसपास की गतिविधियों (जैसे धुआँ, तूफ़ान, वर्षा, या किसी अन्य एयर फ़िल्टर का संचालन) के कारण बदलती है, या यदि एयर फ़िल्टर को किसी अलग आकार के कमरे या कम/अधिक प्रदूषण वाले वातावरण में स्थानांतरित किया जाता है, तो फ़िल्टरेशन प्रवाह दर समायोजित करनी होगी, जिससे फेस वेग बदल जाता है। ऐसे मामलों में, यदि उच्च फेस वेग निम्न फेस वेग के बाद आता है, तो संचयी कण कैप्चर दक्षता, धूल केक का आवरण और दबाव गिरावट अधिक होती है, तुलना में जब वही निम्न फेस वेग उच्च फेस वेग के बाद आता है।

यह शोध फ़िल्टर डिज़ाइन और संचालन के अनुकूलन के लिए मूल्यवान अंतर्दृष्टि प्रदान करता है, जो बेहतर फ़िल्टरेशन प्रदर्शन, ऊर्जा दक्षता, और व्यापक अनुप्रयोगों में दीर्घ सेवा जीवन में योगदान देता है।

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis and have sought permission from co-authors for any jointly authored works included in the thesis.

Publications included in this thesis

1. **Utsav Bhardwaj**, Bahni Ray, Dipayan Das, Travis Mitchell, Apurba Das, and Christopher Leonardi, "Contextual Existence of an Optimum Through-plane Orientation and Aspect Ratio of a Fibre-segment in Fibrous Air Filters", *Physics of Fluids*, Volume 36, Issue 3, 033348, 2024; DOI: 10.1063/5.0192443.
2. **Utsav Bhardwaj**, Nathan J. Di Vaira, Bahni Ray, Travis Mitchell, Dipayan Das, Apurba Das, and Christopher Leonardi, "Numerical Investigation of the Filtration Performance of a Clean Fibre-segment using a Coupled LBM-DEM Approach", *Surfaces and Interfaces*, Volume 76, 107838, 2025; DOI: 10.1016/j.surfin.2025.107838.

Submitted manuscripts included in this thesis

1. **Utsav Bhardwaj**, Dipayan Das, Bahni Ray, Apurba Das, and K. Arul Prakash, "Interdependent Influences of Filter Microstructure and Operating Conditions on Filtration Regimes and Transient Performance of Fibrous Filter Media", under review in *Chemical Engineering Research and Design*.
2. **Utsav Bhardwaj**, Sangamesh Prabhu Suligavi, Dipayan Das, Bahni Ray, Apurba Das, and K. Arul Prakash, "Existence of an Optimum Face Velocity for Non-woven Fibrous Air Filter Media", under review in *Chemical Engineering Science*.

Other publications during candidature

- **Utsav Bhardwaj**, Rabindra Kumar, and Shyama Prasad Das, "Experimental Investigation of the Oscillation Threshold to Limit State Operation of a Single Branch Pulsating Heat Pipe", *International Journal of Thermal Sciences*, Volume 201, 2024, 109031; DOI: 10.1016/j.ijthermalsci.2024.109031.

- **Utsav Bhardwaj**, Rabindra Kumar, and Shyama Prasad Das, "Experimental Investigation of the Flooding Phenomenon in a Pulsating Heat Pipe Unit Cell", *Experimental Thermal and Fluid Science*, Vol. 150, 2024, 111058; DOI: 10.1016/j.expthermflusci.2023.111058.

- **Utsav Bhardwaj**, and Shyama Prasad Das, "Operational Regimes in a Confined Pulsatory Two-phase Thermosyphon", *Thermal Science and Engineering Progress*, Volume 30, 2022, 101233; DOI: 10.1016/j.tsep.2022.101233.

- Rabindra Kumar, **Utsav Bhardwaj**, and Shyama Prasad Das, "Thermo-hydrodynamic Characterization and Mapping of the Two-phase Flow in a Capillary Tube", *Thermal Science and Engineering Progress*, Volume 55, 2024, 102890; DOI: 10.1016/j.tsep.2024.102890.

- **Utsav Bhardwaj**, Rabindra Kumar, and Shyama Prasad Das, "Geyser Boiling in a Pulsating Heat Pipe Unit Cell", *Proceedings of the 26th National and 4th International ISHMT-ASTFE Heat and Mass Transfer Conference*, IIT Madras, Chennai, Tamil Nadu, India, 2021, pp. 1651-1657; ISSN Online: 2688-7231, ISBN Online: 978-1-56700-524-0; DOI: 10.1615/IHMTC-2021.2490.

- **Utsav Bhardwaj**, Vikram Singh, and Bahni Ray, "Parametric Investigation of the Below-cloud Scavenging of Atmospheric Aerosols by Raindrops", *Proceedings of the 26th National and 4th International ISHMT-ASTFE Heat and Mass Transfer Conference*, IIT Madras, Chennai, Tamil Nadu, India, 2021, pp. 1485-1491; ISSN Online:2688-7231, ISBN Online: 978-1-56700-524-0, DOI: 10.1615/IHMTC-2021.2240.

Contributions by others to the thesis

All chapters

Editorial suggestions were provided by the candidate's supervisors, Assoc. Prof. Bahni Ray, Prof. Dipayan Das, Assoc. Prof. Christopher Leonardi, Dr. Travis Mitchell, and Prof. Apurba Das, and PhD committee, Prof. Amit Gupta, Dr. Vikram Singh, and Emeritus Prof. Suresh Bhatia.

Chapter 6

1. Contribution of Dr. Nathan J. Di Vaira, former Doctoral Research Scholar, School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, Australia.

- Extended initial help with different steps of three-dimensional modeling and simulations, such as customizing and coupling the opensource codebases (TCLB and LIGGGHTS), preparing the input script files, and analyzing the data.

Chapter 7 and Chapter 8

2. Contribution of Prof. K. Arul Prakash, Department of Applied Mechanics, Indian Institute of Technology (IIT) Madras, Chennai, India.
    - Provided access to the research laboratory and required resources (like experimental setup, one of the test dusts, etc.).
    - Extended initial guidance for performing the air filtration experiments. Additionally, facilitated the utilization of Scanning Electron Microscope and Mechanical Workshop located at IIT Madras for experimental purposes.
3. Contribution of Mr. Sangamesh Prabhu Suligavi, Doctoral Research Scholar, Department of Applied Mechanics, Indian Institute of Technology (IIT) Madras, Chennai, India.
    - Extended help with operating the experimental setup initially, and administrative as well as personal support regarding a few other steps, like, filter media sample preparation, sputter coating of samples, scanning electron microscopy (SEM), etc.

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research involving human or animal subjects

No animal or human subjects were involved in this research.

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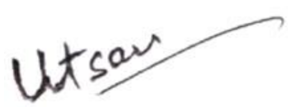

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Research classifications

Keywords

air pollution, particles, nonwoven fibrous air filters, air filtration, particle deposition morphology, particle capture efficiency, pressure drop, quality factor, depth filtration, and dust cake

Australian and New Zealand standard research classifications (ANZSRC)

ANZSRC code: 091399, Mechanical Engineering not elsewhere classified, 40%

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Fields of research classification

FoR code: 0913 Mechanical Engineering, 60%

FoR code: 0907 Environmental Engineering, 15%

FoR code: 0915 Interdisciplinary Engineering, 25%

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Nomenclature

a_d or a_0	adhesion distance (m)
A	area (m^2), or *nominal* surface area (m^2), or Avagadro's number, or a designated experiment (*expt-A*)
AE	adhesive energy (J)
AR	aspect ratio
b	a dimension of fibre-segment (m)
B	weighting function (in PSM), or *absolute* surface area (m^2), or a designated experiment (*expt-B*)
c	volumetric concentration (m^{-3}), or damping coefficient (Ns/m)
c_{fr}	macroscopic friction coefficient
c_{fr}^{m}	microscopic coefficient of Coulomb friction
c_{res} or e	coefficient of restitution
c_s	sound velocity (lattice units)
C	Courant number, or coverage *of dust cake*
$\vec{C}_\alpha$	microscopic velocity (lattice units)
C_c	Cunningham slip correction factor
C_{Df}	drag coefficient
d	diameter (m)
d_a	collisional cross-section (m)
dW	3D Wiener measurement
D_{FM}	diameter of a filter medium (m)
D_m	intermolecular cut-off distance (m)
D_p	diffusion coefficient for particles (m^2/s)
DFR	dust feed rate (kg/m^2s)
DoF	depth of filtration (m)
m	mass (kg)
m_{BW}	basis weight of filter media (kg/m^2)
m_{DC}	cumulative mass of dust captured by filter media per unit area (kg/m^2)
n	number, or number of fibres a particle interacts with
$\vec{n}$	radius (normal) vector's direction for a particle
N	number, or number *of particles*
p	pressure (Pa)/particle
P	pressure (Pa), or atmospheric pressure *in particular* (Pa)
Pe	Peclet number
q	number *of dust cake patches*
QF	quality factor (Pa^{-1})
$\vec{r}$	position vector
R	gas constant (J/K/mol), or dimensionless separation between the centres of two particles
R_{CAP}	capture coefficient
R_{INT} or J	interception coefficient
Re	Reynolds number
s	degree of slippage
S	specific surface area
St	Stokes number
SVF	solid volume fraction
t	time (s or lattice units)
T	operating temperature (K)
$\vec{T}$	torque (N m)

f_α	probability distribution function (LBM)
F	force (N or lattice units)
FVF	fibre volume fraction (%)
G	refractive index
h	Planck's constant (J s)
h_D	height of dust column in dust container (m)
H	Hamaker constant (J)
I	moment of inertia (kg m^2)
k	spring coefficient (N/m)
k_B	Boltzmann constant ($m^2 kg\ s^{-2} K^{-1}$)
Kn	Knudsen number
KE	kinetic energy (J)
Ku	Kuwabara factor
l or L	length or thickness (m or lattice units)
Tr	tortuosity
u	velocity (m/s or lattice units)
u_{ap0}	face velocity (m/s)
$\vec{U}_S^*$	velocity of solid after collision operation as per PSM (lattice units)
V	potential (V), or volume (m^3)
w	a dimension of fibre-segment (m)
w_α	weight (LBM)
W	windward side (of fibre-segment)
x	coordinate/direction, or any particle diameter (m), or any distance (m)
y	coordinate/direction
z	coordinate/direction, or a ratio (density/efficiency/pressure drop/gaps), or distance (m)
Z_{FM} (or Z)	thickness of filter media (m)
Z_{min}	minimum required thickness of filter media (m)

Greek symbols

α	direction parameter (LBM), or area fraction of fibre in computational domain
β_p	solid (particle) volume fraction (in PSM)
β^M	momentum coupling parameter
γ	separation between a particle and fibre, or between two particles (m)
δ	extent of overlap (m)
Δ	difference/drop/step-size
ε	specific surface energy (J/m^2), or porosity
η	particle capture efficiency
ν	kinematic viscosity (lattice units or m^2/s)
ξ	static dielectric constant, or Gaussian random variable
ρ	density (kg/m^3 or lattice units)
σ	thickness of Stern layer (m)
τ	relaxation time (lattice units)
ϑ_e	main electronic absorption frequency (s^{-1})
φ	volume fraction, or the angle at which Brownian force acts (rad)
χ	pressure drop factor

θ	inclination angle of fibre-segment (rad) with respect to flow direction	ω	angular velocity (rad/s)
κ	degree of hardness in repulsion between the particles	Ω_α	BGK operator (LBM)
λ	mean free path of air (m)/ diameter ratio for two particles	Ω_α^S	solid (particle) collision operator (in PSM)
μ	dynamic viscosity (Pa s)		

Subscripts/Superscripts

a	air/airflow	lim	limit
act	actual	L	axial or longitudinal
ap0	air with particles at inlet	LBM	lattice Boltzmann method
avg	average	LE	lattice element(s)
A	adhesion	LvdW	London-van der Waals
b	body	max/Max	maximum
B	Born	min	minimum
BD	Brownian diffusion	mD	*based on* mass of dust
c	collision/contact/ computational domain/*during or before* collision	n	node(s)/normal
cake	*dust* cake	nf	nodes across fibre diameter
cp	captured particles	np	nodes across particle diameter
cr	critical	Norm	normalized
C	computational domain, or collision	og	orthogonal
Cap	captured	opt	optimum
CZ	clogged/clogging zone *of filter media*	p	particle(s), or, *based on* particle size, or *based on* pressure
d	deposition, or diametral	pe	particles at efflux (outlet)
dn	*at* downstream	pi	particles at inlet
dp	deposited particles	pl	parallel
D	(aerodynamic) drag, or dust, or dimensions	pore	*of* pore
DEM	discrete element method	QF or $\overline{QF}$	quality factor, or *based on* cumulative quality factor
DFS	dusty fibrous surface	req	required
e	electrostatic/efflux/outlet	sa	surrounding air
ec	electrostatic cut-off	t	tangential
en	entrance	T	total/transpose/transient
eq	equilibrium (LBM)	up	*at* upstream
ex	exit	x	coordinate/direction

EDL	electric double layer	y	coordinate/direction
f	fibre/fibre-segment/filter media, or final, or at outlet, or in the outlet section of flow channel	0	initial, or at inlet, or in inlet section of flow channel
F or (F)	final, or *at* final *stage*	*	in lattice units (LBM)
Fed	fed *to the filter media*	η	*based on* particle capture efficiency
Flange	*fallen at* flange	$\bar{\eta}_{mD}$	*based on* cumulative dust-mass-based particle capture efficiency
fm/FM	filter medium/media, or *based on* filter medium/media		
FO	*at* final *stage but* original *condition (face velocity)*	$\bar{\eta}_{mD\ (FM)}$	*based on* cumulative dust-mass-based particle capture efficiency associated with filter media alone
i	initial/inlet	η_p	*based on* particle-size-based particle capture efficiency
inj	injection/injected		
Imp/IMP	*inertial* impaction	ρ	*based on* density
Int/INT	interception		

Abbreviations

AR	aspect ratio	LBM	lattice Boltzmann method
BD	Brownian diffusion	LE	lattice element(s)
CADR	clean air delivery rate	LIGG GHTS	LAMMPS Improved for General Granular and Granular Heat Transfer Simulations
CFD	computational fluid dynamics	max	maximum
CPU	central processing unit	min	minimum
CUDA	Compute Unified Device Architecture (NVIDIA's parallel computing platform)	MPI	message passing interface
DEHS	Di-Ethyl-Hexyl-Sebacat	OCDS	overall control and display station
DEM	discrete element method	PET	polyethylene terephthalate
DFR	dust feed rate	PM	particulate matter
DHC	dust holding capacity	PP	polypropylene
DLVO	Derjaguin-Landau-Verwey-Overbeek	PSM	partially saturated method
expt	experiment	QF	quality factor
FM	filter medium/media	RPM	revolutions per minute
FVF	fibre volume fraction	SEM	scanning electron microscope/ microscopy

GPU	graphics processing unit	SVF	solid volume fraction
HEPA	high efficiency particulate air	TCLB	Templated MPI+CUDA/CPU Lattice Boltzmann *code*
ISO	International Organization for Standardization	UNICEF	United Nations International Children's Emergency Fund (now, United Nations Children's Fund)
LAMMPS	Large-scale Atomic/Molecular Massively Parallel Simulator		

Additionally, "i, j, q, and m" as subscripts are the indices used for designating the set of particles under consideration; and the asterisk (*) as superscript indicates the concerned parameter in lattice units (LBM). Also, any symbol with an overhead bar (for example, $\bar{\eta}_{mD}$, $\overline{\Delta p}$, $\overline{QF}$, $\bar{C}_{cake}$, etc.) indicates either the cumulative/total/overall value of the concerned parameter, or its average value in the concerned context, and the relevant meaning in this regard has been explicitly mentioned wherever applicable. Furthermore, a few additional symbols, used sparingly, have been defined in the text at their first appearance.