

MATHEMATICAL MODELLING OF AN IONISER-ASSISTED FILTER SYSTEM

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ABSTRACT

Electret filters use electrostatically charged nonwoven layers to enhance particle separation efficiency. However, this positive electret effect decreases as the particle loading increases. The aim of ionizer-assisted filtration is to significantly enhance the separation efficiency of a conventional filter with low pressure loss, or to achieve the same degree of separation with reduced electrical power consumption.

The approach is based on the ionization of the air and the subsequent electrical charging of the particles in the electric field of an ionizer. A downstream electric field induces the polarization of the filter and the separation of the particles. This effect is switchable and persists (remains active) as long as the ionizer and the electric polarization field are in operation.

For the optimal design of the ionization and polarization unit, a comprehensive CFD model was developed as an extension of the open-source software OpenFOAM. The model takes into account the physical processes in detail, including ionization, particle charging, and separation in the gas, as well as, bipolar charge transport within the solid filter medium. These processes are coupled via the spatially resolved calculation of the electric field.

The model is validated through a combination of numerical simulation and experimental investigations. For the experiments, a laboratory test rig is available that allows the investigation of particle charging by ionization and particle separation due to electrostatic effects on dielectric components. For this purpose, both fibre filter media and plastic grid structures are used.

The use of a plastic grid structure keeps the numerical effort manageable and makes it possible to calculate the physical relationships at the microscale and verify them experimentally without having to perform the simulation on a real filter structure.

KEYWORDS:

Ioniser-assisted filtration, Electret filter, Polarisation, Electrohydrodynamic Flow, CFD-simulation

1. Introduction

Ongoing urbanization has profoundly altered human exposure patterns. In densely populated metropolitan areas comprising residential, commercial, and industrial zones, residents spend approximately 85 to 90% of their time indoors [1]. At the same time, the efforts aimed at energy saving and environmental protection are driving the design and construction of low-energy buildings with increasingly airtight building envelopes. Under these conditions, ensuring adequate indoor air quality has become a matter of central importance for both the operation of buildings and the health of their occupants. In larger buildings, the purification of outdoor air and recirculated indoor air is typically treated by heating, ventilation, and air-conditioning systems (HVAC systems), or in individual rooms by mobile air purifiers. Factors that determine the quality of indoor air are, for example, air exchange rate, relative humidity, temperature, CO₂ content and particulate impurities.

Alongside ensuring an optimal indoor air quality (high separation efficiency), maximising the energy efficiency of HVAC filtration is also a key design objective. Because replaceable textile filter elements used in HVAC systems strongly influence both air purity and system operating costs. In practice, a reduction in the filter pressure drop directly lowers the required fan power and thus the overall energy demand of the ventilation system. The design and development of filter media therefore involve a fundamental trade-off between high separation efficiency and low pressure drop. A high separation efficiency is required to achieve the target particle concentration downstream of the filter, whereas a low-pressure drop across the filter is needed to minimise energy consumption and thus operating costs. However, for fine-particle separation, especially in the ePM_{2.5} range, this trade-off remains particularly challenging – because an improved collection efficiency in this range is still commonly associated with a high pressure drop.

Filters that offer additional functionalities beyond purely mechanical particle capture are generally referred to as multi-effect filters (MEFs). A well-established type of this class is the electret filter, which employs electrostatically charged nonwoven layers (electret media). Owing to electrostatic interactions between particles and charged fibre surfaces, electret filter can achieve higher fractional separation efficiencies than purely mechanical filters at a comparable pressure drop, particularly at the beginning of filter operation. However, this positive electret effect decreases over time as particle loading increases.

Recent developments have shown that the "electret effect" can be preserved permanently by ionising the gas phase and polarising the filter fibres in an externally applied electric field, i.e., by using an ***ioniser-assisted filter concept***. Under these conditions, the separation efficiency of a conventional filter can be increased significantly, with low

pressure drop, analogous to an electret filter, thereby reducing electrical energy consumption and associated CO₂ emissions. In contrast to electret filters, however, this effect persists as long as the ionisation of the gas phase and the electric field are maintained [2, 3]. Preliminary investigations of this concept were carried out at IUTA within the research project "Development of switchable functionalities of nonwoven surface structures for applications in filtration and the automotive sector - NGF 2.0" [4]. The experiment results have clearly demonstrated that electrically conditioning the air stream (ionising the gas phase) enabled a non-electret medium to achieve a separation efficiency comparable to that of an electret medium, thereby confirming the proof-of-principle. The effect is based on the ionisation of the air in conjunction with an electrical charging of the particles. Simultaneously, the filter fibres are polarised by the applied electric field, giving rise to attractive electrostatic forces between the particles and the fibres that are comparable to those in an electret medium. However, unlike the electret effect, the polarisation is sustained as long as the ioniser and the electric field are in operation.

To optimise the design of an ioniser-assisted filter system, a detailed understanding of the coupled physical processes involved – e.g., particle charging, charged particle transport, and the interaction of charged particles with polarised filter fibre, etc. – is required. This paper, therefore, presents a comprehensive CFD model implemented in the open-source framework OpenFOAM. The model resolves the relevant charge-dynamic processes in both the gas phase and the filter fibre medium. Charge dynamics in the gas phase, including ionisation, particle charging, and the transport of ions and charged particles, are described by an Electro-Hydrodynamics Model (EHDM). Charge transport within the filter medium, including polarisation of the fibre, is represented by a Bipolar Charge Transport (BCT) model. These sub-models are coupled through Poisson's equation to determine the electric field in both the air and the fibre material. The resulting formulation comprises a large, strongly coupled system of partial differential equations and therefore entails a high computational cost, particularly when individual filter fibres are resolved. To keep the numerical effort manageable, the present study is carried out by using plastic grid structures as model geometries instead of fibrous filter media. The numerical results are validated against laboratory-scale experiments.

2. Mathematical Model for Ioniser-assisted filter system

Filter fibres (glass, PE, or PET, etc.) [5,6] are typically high-resistance or electret materials in which a strong external electric field induces polarisation, depending on their permittivity. When these materials are charged or exposed to the strong electric field, the current transport or charge dynamics lead to complex behaviour of the electric field within the material. The behaviour becomes even more complex when these materials consist of porous structures (as in our case). This complex behaviour can be attributed

to the injection of charges into the fibre material and to the subsequent charge dynamics within the fibres [7-9]. Therefore, it is clear that a model intended to optimise an “Ioniser-assisted filter system” must capture charge transport and its interaction with the local electric field in both the gas and fibre phases. To illustrate the relevant charge dynamics in both phases, Figure 1 shows a single fibre exposed to a negative ioniser under an external electric field. In this schematic, the fibre is shown in contact with the ground electrode to illustrate the bipolar charge injections and their dynamics. In reality, depending on the boundary conditions at the fibre surface, the model can account for either unipolar or bipolar charge injection.

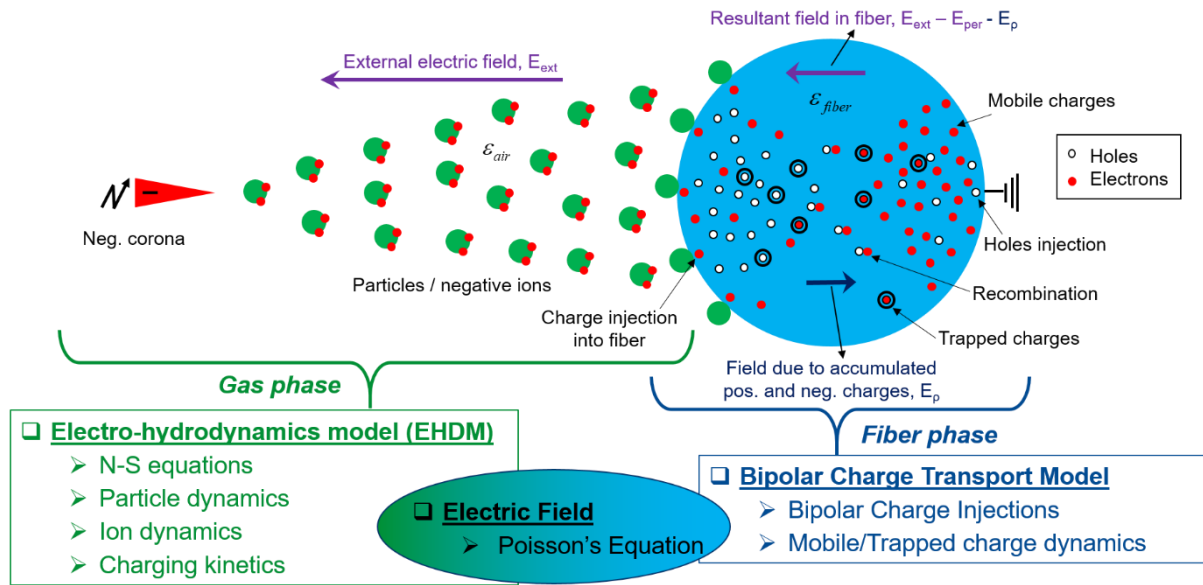


Figure 1: Schematics of Coupling of Electro-Hydrodynamics and Charge Dynamics in Electret Medium in OpenFOAM

The coupled charge dynamics in both phases can be summarised as follows: Above corona onset, the high electric field at the ioniser initiates the ionisation of the air by corona mechanisms and generates a continuous current in the form of the negative ions, which are distributed non-uniformly between the ioniser and the fibre region under an external electric field. As particles pass through this region, they acquire a charge through ion attachment. Subsequently, both the negative ions and charged particles drift towards the fibre due to the electrostatic force. Upon reaching the fibre surface, these negative charges may first occupy the surface traps and may then penetrate into the fibre in the form of electron charge carriers. At the same time, positive charge carriers (holes) are injected into the fibre from the grounded electrode (anode). Within the solid phase, both charge carrier types undergo drift, diffusion, recombination, and trapping/de-trapping (detailed discussion in section 2.2). Over time (depending on carrier concentration), these dynamics of charge carriers can alter the local electric field inside the fibre and, consequently, the surrounding gas-phase field. The altered electric field

in the gas phase then influences the ion transport, particle transport, and the particle charging kinetics.

The complete charge dynamics inside the gas phase can be described by the Electrohydrodynamics model (EHDM), whereas the complete charge dynamics inside the fibre media can be described by the Bipolar charge transport model (BCTM). The detailed mathematical descriptions of both models are summarised below.

2.1. Charge transport in the gas phase: Electro-Hydrodynamics Model (EHDM)

The EHDM was originally developed at IUTA for ANSYS Fluent [10,11] as a User Defined Function, but has since been extended and implemented in the open-source simulation software OpenFOAM [12] to model all aspects of an “Ioniser-assisted filter system”. The EHDM essentially couples the five fields: base fluid flow, electric potential, ion space charge, particle motion and particle charge. The base fluid flow fields can be solved by any suitable standard solver. In the present work, the OpenFOAM solver “buoyantPimpleFoam” is chosen as the base solver, which provides the distribution of base fluid flow fields of velocity, pressure and temperature by solving the Navier-Stokes equations for buoyant, turbulent flow of compressible or incompressible fluids. Whereas, the models for electrostatic fields, particle charging kinetics, ion dynamics and particulate phase transport are implemented as a library in OpenFOAM. This library is then integrated with the base solver to obtain the complete solution of EHD flow. The detailed mathematical formulation of the implemented models in the library is outlined below.

Electrostatics

The distribution of the electric potential (V) is determined by the Poisson equation, which accounts for the influence of both ions and charged particles in the domain:

$$\nabla \cdot (\nabla V) = - \frac{\rho_{ion} + \rho_p}{\epsilon_0 \cdot \epsilon_r} \quad (1)$$

Where ϵ is the permittivity of the fluid, ρ_{ion} is the ion space charge density [C/m^3], and ρ_p is the space charge density contributed by the particulate phase [C/m^3]. The electric field is subsequently derived from the potential gradient: $\mathbf{E} = -\nabla V$.

Particle dynamics

In this model, the particulate phase is treated as a continuous phase (Eulerian approach) rather than discrete entities, which is particularly efficient for high-concentration flows. The transport of particle concentration C_p (number density) [$1/m^3$] is described by a scalar transport equation:

$$\frac{\partial C_p}{\partial t} + \nabla \cdot [C_p (\mathbf{U} + \mu_p \mathbf{E})] = \nabla \cdot (D_p \nabla C_p) \quad (2)$$

The particle velocity is calculated by considering the fluid velocity and the drift velocity induced by the electric field. μ_p is the particle mobility [$m^2/(V \cdot s)$] and is defined via the Stokes-Cunningham drag law [13]: $\mu_p = (q_p \cdot e \cdot C_c) / (3\pi \cdot \eta \cdot d_p)$. D_p is the diffusion coefficient [m^2/s] of the particle and is defined by the Stokes-Einstein equation [13]: $D_p = (k_B \cdot T \cdot C_c) / (3\pi \cdot \eta \cdot d_p)$. q_p is the particle charge, C_c is the Cunningham slip correction factor, η is the dynamic viscosity [$Pa \cdot s$], d_p is the diameter of the particle [m], k_B is the Boltzmann constant [J/K] and T is the temperature [K].

Ion dynamics

The gas ions (typically generated by corona discharge) phase is also treated as a continuous single species within the Eulerian framework. Neglecting the magnetic effects and assuming a single species of ions, the ion conservation is then expressed as:

$$\frac{\partial n_{ion}}{\partial t} + \nabla \cdot [n_{ion} (\mathbf{U} + \mu_i \mathbf{E}) - D_i \nabla n_{ion}] = S_I - S_R \quad (3)$$

Where μ_i is the ion mobility - defined by the Einstein equation [14] $\mu_i = e \cdot D_i / (k_B \cdot T)$. D_i is the ion diffusion coefficient and is calculated [15] as $D_i = (\lambda/3) / \sqrt{8 \cdot R \cdot T / (M \cdot \pi)}$. λ is the free mean path of gas [m], R is the gas constant [$J/(kmol \cdot K)$], M is the molar mass of gas [g/mol]. The migration by field is usually much larger than the fluid velocity, hence ions move primarily along field lines. Here, S_I is ion production resulting from thermal and photoemission as well as corona discharge. S_R represents the loss of ions (recombination) as they attach to particles (based on the Lawless model [16]).

Particle charging equation

To track the evolution of the particle charge within the Eulerian framework, a transport equation for the number of mean particle charges $q_p = \rho_p / (n_p \cdot e)$ is implemented. This avoids the need for Lagrangian tracking and allows for direct coupling with the Poisson equation. The scalar transport equation for the number of mean particle charges is expressed as:

$$\frac{\partial q_p}{\partial t} + \nabla \cdot [q_p (\mathbf{U} + \mu_p \mathbf{E})] = S_R \quad (4)$$

In this formulation, particle charge is treated as a field variable convected with the particle velocity. A major advantage of Equation 4 is that it couples naturally with the ion conservation equation and Poisson equation.

Charging kinetics: The Lawless model

Particles acquire charge through two mechanisms: Field Charging (ions pushed by the E-field on the particle) and Diffusion Charging (driven by random thermal collisions).

The Lawless model [16] employs a non-dimensional approach to bridge the gap between field and diffusion charging and provides a unified charging rate that smoothly transitions between these regimes. In dimensionless form, the charging rate is divided into 3 parts:

$$\frac{dv}{d\tau} = \begin{cases} f(w) \frac{v-3w}{e^{(v-3w)} - 1}, & v > 3w, \\ \frac{3w}{4} \left(1 - \frac{v}{3w}\right)^2 + f(w), & |v| \leq 3w, \\ (-v + f(w)) \frac{-v-3w}{e^{(v-3w)} - 1}, & v < -3w, \end{cases} \quad \text{With } f(w) = \begin{cases} (w+0.475)^{-0.575}, & w \geq 0.525, \\ 1, & w < 0.525 \end{cases} \quad (5)$$

Where the v is the dimensionless particle charge, w is the dimensionless field parameter and τ is the dimensionless time. These dimensionless variables are defined as:

$$v = \frac{q_p \cdot e^2}{2\pi \cdot \epsilon_0 \cdot d_p \cdot k_B \cdot T}; \quad w = \left(\frac{\epsilon_p}{\epsilon_p + 2} \right) \left(\frac{|\mathbf{E}| \cdot d_p \cdot e}{2 \cdot k_B \cdot T} \right); \quad \tau = \frac{\rho_{ion} \cdot \mu_i \cdot t}{\epsilon_0} \quad (6)$$

Where, ϵ_p is the particle dielectric factor.

Equation 5 shows that Lawless combines the effects of electric-field charging and diffusion charging through the empirical blending function $f(w)$. The model remains active even when the particle approaches the classical field-charging saturation level, thereby overcoming a key limitation of pure field-charging laws. This feature is particularly important for submicron particles, for which diffusion charging remains significant. Finally, the dimensional charging source is obtained by transforming Equation 5 back to physical units:

$$S_R = \frac{2\pi \cdot d_p \cdot k_B \cdot T \cdot n_{ion} \cdot \mu_i}{e} \left(\frac{dv}{d\tau} \right) \quad (7)$$

The local charging rate therefore depends on the local ion density, electric field magnitude, temperature, and particle diameter. Equation 7 is inserted as the source term in both the ion and particle charge transport equations.

Corona discharge modelling

The corona discharge at needle, wire or brush ionisers is usually the primary source of the ion generation in the EHD flow. The simulation of ion generation at the ioniser can either be modelled based on the underlying physical processes, which requires explicit resolution of the active corona zone and is computationally expensive, or described empirically. In the present EHDM, the active zone is not resolved explicitly; instead, ion generation is modelled based on Kaptzov's hypothesis, which states that once corona is initiated, the electric field at the surface of the ioniser stays constant at the onset value (E_{onset}) and any further increase in applied potential is accommodated

primarily through generating more ions rather than increasing the surface field strength. Based on this hypothesis, for an applied potential, the implemented model calculates the ion space charge density at the ioniser surface iteratively till the ratio of the actual electric field strength (E_{Actual}) to the onset field strength (E_{onset}) reaches to 1:

$$S_{IQ} = \frac{E_{Actual}}{E_{Onset}}; \quad \rho_{ion}^{new} = \rho_{ion}^{old} \cdot S_{IQ} \quad (8)$$

During the iterative solution procedure, the source term for the ion space charge density at the ioniser is increased or decreased until the value of S_{IQ} reaches 1 in every finite element along the ioniser. This means that, for any given ioniser geometry, the model requires only the onset electric field for that ioniser to calculate the ion space charge density at the ioniser surface. For a wire ioniser, the corona onset electric field is calculated empirically using the Peek equation [17]. Since the Peek equation was originally developed for wire-cylinder configurations, it is necessary to calibrate the current-voltage characteristic curve for other ionisers, e.g., needles or brushes, using experimentally measured values.

2.2. Charge transport in the Fibre (Electret) Phase: Bipolar Charge Transport Model (BCTM)

The charge transport within the fibre (highly resistive or dielectric) phase can be described using electret theory [6]. Since electret materials generally contain no (or only negligible amounts of) mobile (conduction band) charge carriers, current transport through these materials occurs primarily via excess charges, which can exist in the form of electrons (negative) and holes (positive). These excess bipolar charge carriers can be generated in electret materials through various effects, such as doping or impurities in the materials and/or injection via surfaces, either through corona discharges or through contact with metallic electrodes at high electric field strengths. In our case, the main source of excess charges in the fibre is injection via corona discharge. Therefore, the injection density is calculated based on the total amount of current reaching the fibre surface in the form of charged particles and ions.

The transport of injected charges (excess charges) and intrinsically available free charges in the electret material is associated with the generation and loss of charge carriers. Initially, the excess charges injected into a material are mobile. However, these charges can be immobilised by trapping in so-called “Deep Traps”. These deep traps are typically structural disorders at the molecular level, which behave as additionally localised energy states in the band gap energy region where electrons or holes can reside at a lower energy level, with ϕ_{tr} the depth of a trap specified in eV. In a simplified model, these trap states are assumed to be uniformly distributed in the electret material with densities n_{et0} and n_{ht0} for electrons and holes in m^{-3} .

Deeply trapped charges are immobile and therefore cannot contribute to the current transport, but they do contribute to the space charge density within the electret, whose field distorts the external field when the charge density reaches a sufficient magnitude. At the same time, the trapped charges play a role through recombination with mobile charges of opposite polarity. Due to the high concentration of trapped charges, this mechanism of mobile charge loss is considerably more effective than the direct recombination of mobile electrons and holes. Trapped charges can be remobilised, as they may escape from their trap with a certain probability due to thermal energy $k_B T$ (de-trapping). In extremely strong electric fields, de-trapping can be enhanced by the Poole–Frenkel effect [18,19].

The mathematical description of this model in terms of electron and hole concentrations is based on the current continuity condition. For the mobile electron concentration n_e in m^{-3} , the governing equation is obtained as follows:

$$\begin{aligned} \underbrace{\frac{\partial n_e}{\partial t}}_{\text{Temporal}} - \underbrace{\nabla \cdot (n_e \mu_e \mathbf{E} + D_e \nabla n_e)}_{\text{Drift and Diffusion}} \\ = \underbrace{-R_{eht} n_e n_{ht} - R_{eh} n_e n_h}_{\text{Recombinations with trapped and mobile holes}} - \underbrace{T_e n_e \left(1 - \frac{n_{et}}{n_{et}^0}\right)}_{\text{Trapping in deep traps}} + \underbrace{\nu n_{et} \exp\left(-\frac{e}{k_B T} \left(\Phi_{etr} - \sqrt{\frac{eE}{\pi\epsilon}}\right)\right) \frac{n_{et}}{n_{et}^0}}_{\text{Detrapping from deep traps (including P-F effect)}} \end{aligned} \quad (9)$$

Similarly, for the concentration of trapped electrons n_{et} :

$$\begin{aligned} \underbrace{\frac{\partial n_{et}}{\partial t}}_{\text{Temporal}} = \underbrace{-R_{eth} n_{et} n_h - R_{etht} n_{et} n_{ht}}_{\text{Recombinations with mobile and trapped holes}} - \underbrace{\nu n_{et} \exp\left(-\frac{e}{k_B T} \left(\Phi_{etr} - \sqrt{\frac{eE}{\pi\epsilon}}\right)\right) \frac{n_{et}}{n_{et}^0}}_{\text{Detrapping from deep traps (including P-F effect)}} + \underbrace{T_e n_e \left(1 - \frac{n_{et}}{n_{et}^0}\right)}_{\text{Trapping in deep traps}} \end{aligned} \quad (10)$$

The term on the left-hand side describes the temporal variation in electron density and its transport due to drift and diffusion (diffusion coefficient for electrons D_e in m^2/s). The terms on the right-hand side represent the sources for losses and the generation of mobile electrons. Here, n_{th} is the density of trapped holes in m^{-3} . R denotes the recombination coefficients between mobile electrons and mobile holes (R_{eh}), mobile electrons and trapped holes (R_{eht}), and between trapped electrons and trapped holes (R_{etht}) in m^{-3}/s . T_e is the capture coefficient for electrons in s^{-1} , ν is the “attempt-to-escape frequency” in s^{-1} and Φ_{etr} the barrier height for electron escape in eV. The reduction in the barrier height due to the electric field (Poole-Frenkel effect) is given by the term $\sqrt{eE/\pi\epsilon}$ [18,20].

Equivalent equations for mobile holes and trapped holes are obtained by simply interchanging the indices e and h .

The total space charge density in the electret is then defined by Equation 11:

$$\rho = e \cdot (n_h + n_{ht} - n_e - n_{et}) \quad (11)$$

Finally, the electric potential and fields generated by the space charge density are determined by the Poisson equation:

$$\nabla \cdot (\nabla V) = -\frac{\rho}{\epsilon} \quad \& \quad \mathbf{E} = -\nabla V \quad (12)$$

Poisson's equations 12 and 1 are essentially identical, although the source terms for the space charge density differ depending on the phase (gas or fibre).

2.3. Coupling of EHDM and BCTM in OpenFOAM

Since the electric field and therefore the charge dynamics in both phases are strongly interdependent, the EHDM solver ("buoyantPimpleFoam" coupled with Equations 1-8) and the BCTM solver (Equations 9-12) are combined into a new OpenFOAM solver termed "*Conjugate Charge Transport Multi-region Foam*" (**CCTM-Model**). The coupling of both phases utilises a partitioned multi-region framework, conceptually analogous to the architecture of the *chtMultiRegionFoam* solver in OpenFOAM: The CCTM solver treats each gas (or fluid) and Fibre (solid) part as a distinct computational domain with its own mesh, fields and physical properties; and solves the fluid equations (EHDM) and solid equations (BCTM) separately. But, at the same time, the regions are coupled at their shared interfaces by ensuring both the electrical potential continuity ($V_1 = V_2$ or $E_{t1} = E_{t2}$) and current flux conservation at each time step or iteration.

3. Experimental Setup

To validate the mathematical model, a test rig was set up, which enables the experimental investigation of all relevant aspects of the model, ranging from ionisation and particle charging to particle deposition and the polarisation of the filter material.

The test rig consists of a rectangular flow channel with an edge length of 20 cm and a length of 3 m ($U = 0.2\text{--}2$ m/s), in which particle charging by various ionisers and particle deposition on plastic grid structures and flat filter media can be investigated. The channel is made of stainless steel, with the channel walls in the vicinity of the ioniser capable of being either grounded or electrically insulated (free-floating potential). The test setup allows the generation of two high-voltage fields: first, the operation of the ioniser at voltages up to +15 kV, and second, the polarisation of a dielectric structure (grid or filter medium) by means of a downstream metal grid at voltages of +/- 20 kV. To electrically decouple these two electrostatic potential fields from one another and to sepa-

rate the excess ions not consumed by particle charging, a grounded metal grid is positioned immediately upstream of the plastic grid structure. Figure 2 shows the experimental setup.

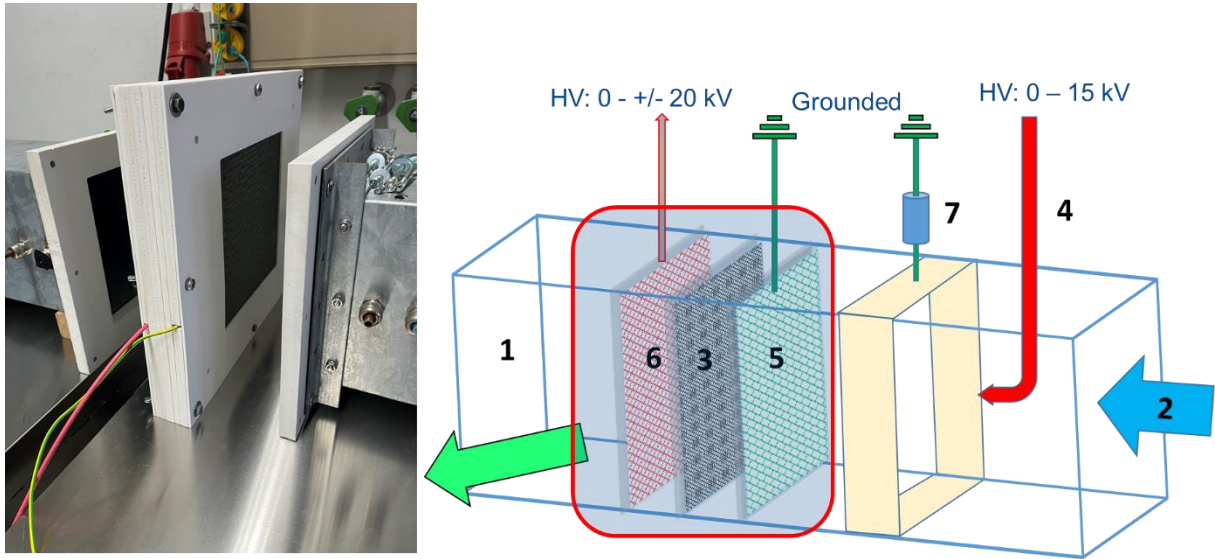


Figure 2: Experimental setup (left: photo of the filter and polarisation unit; right: schematic diagram: 1 – channel, 2 – flow, 3 – separation grid, 4 – ioniser, 5 – grounded grid, 6 – polarisation grid, 7 – copper foil)

4. Results

The results presented here comprise the validation of the corona model and the design of an optimised ioniser array with respect to maximising particle charging, and reflect the current state of the ongoing research project INNO-KOM 49VF230012. Validation results for particle deposition on plastic grid structures will be reported in future work.

4.1. Ionisation

Various ionisers and configurations were investigated experimentally using the laboratory test rig and numerically using the EHDM Model. In addition to the brush ionisers presented here, needle and wire ionisers were also examined, and their current-voltage characteristics were determined both experimentally and numerically. In all simulations, the ion mobility was assumed to be $0.0002 [m^2/Vs]$. Figure 3 shows a comparison of the measured and simulated current-voltage characteristics for various configurations using a brush ioniser.

The investigated configurations can be characterised as follows: a) one ioniser with grounded channel walls, b) one ioniser with free-floating channel walls and a grounded grid positioned 10 cm downstream of the ioniser, c) one ioniser with free-floating channel walls, but grounded with copper foil ($L = 7$ cm) in the vicinity of the ioniser, and a grounded grid located 30 cm downstream from the ioniser. The objective of this optimisation was to achieve the highest possible ioniser current at the lowest possible

operating potential whilst simultaneously minimising particle losses on the channel walls in front of the grounding grid.

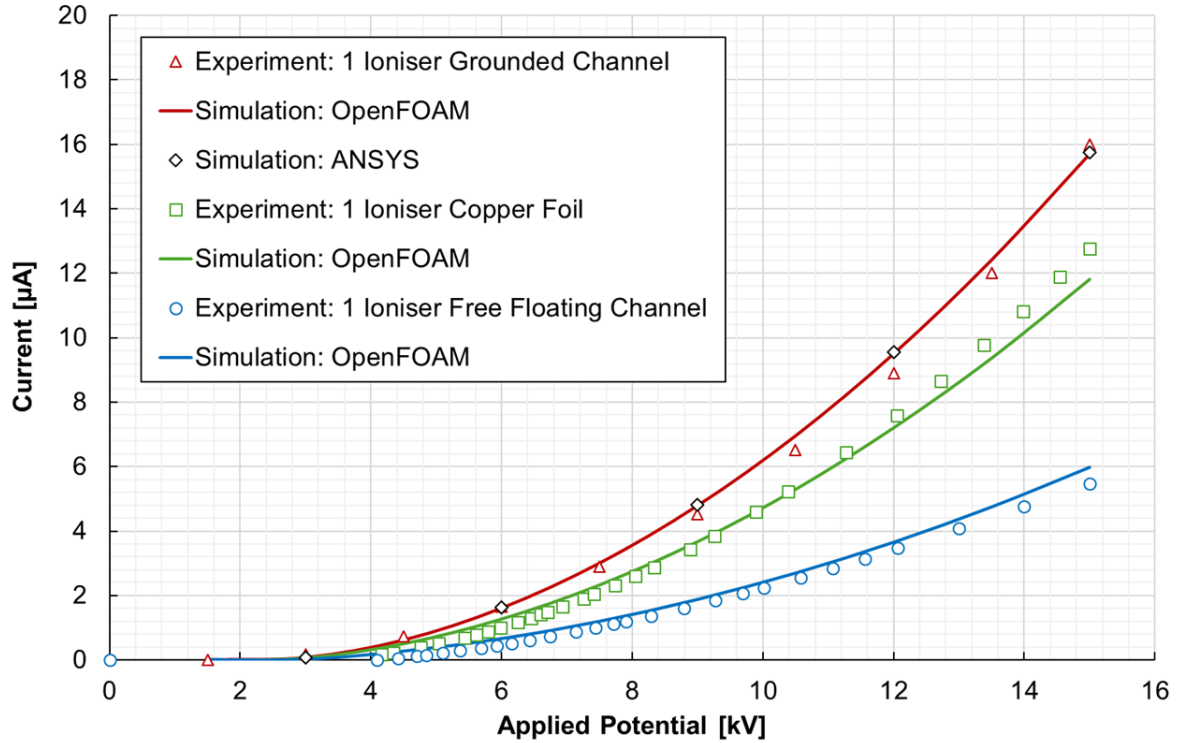


Figure 3: Current-voltage characteristics for 1 brush ioniser, various configurations

It is clear that the configuration with grounded channel walls produces the highest ioniser current, followed by the configuration with targeted grounding via the copper foil. The free-floating configuration exhibits the lowest current, but this also results in no significant particle losses within the ioniser system. Overall, the agreement between the measured and simulated current-voltage characteristics is very good. The particle losses in the ioniser section of the test rig are discussed below.

Based on these findings, an ioniser array consisting of four brush ionisers and appropriate electrostatic shielding was developed (Figure 4). Compared with a single ioniser, this array enables substantially higher ioniser currents and is ideally scalable to different channel cross-sections. The distance between ionisers and walls is 5 cm. At a distance of 5 cm in the direction of flow, a grounding grid is placed. The grounding grid acts as an ion trap, too.

During experimental operation, the four ionisers exhibited very similar current-voltage characteristics. For comparison with simulations, an average current-voltage characteristic was derived from the four individual characteristics, which served as the basis for the numerical comparison. Figure 5 shows the derived current-voltage characteristics. Here, again, a good agreement was achieved between experimental and simulation results, and the ioniser array shows substantially higher current levels compared to the single ioniser setups (Figure 3).

With regards to real-world channel cross-sections (edge length approx. 60 cm) and flow velocities (approx. 2 m/s), the array is ideally adaptable and scalable to different flow channel diameters, both due to its higher electrical power and its design.



Figure 4: 2 x 2 Ioniser-array (4 brush ionisers)

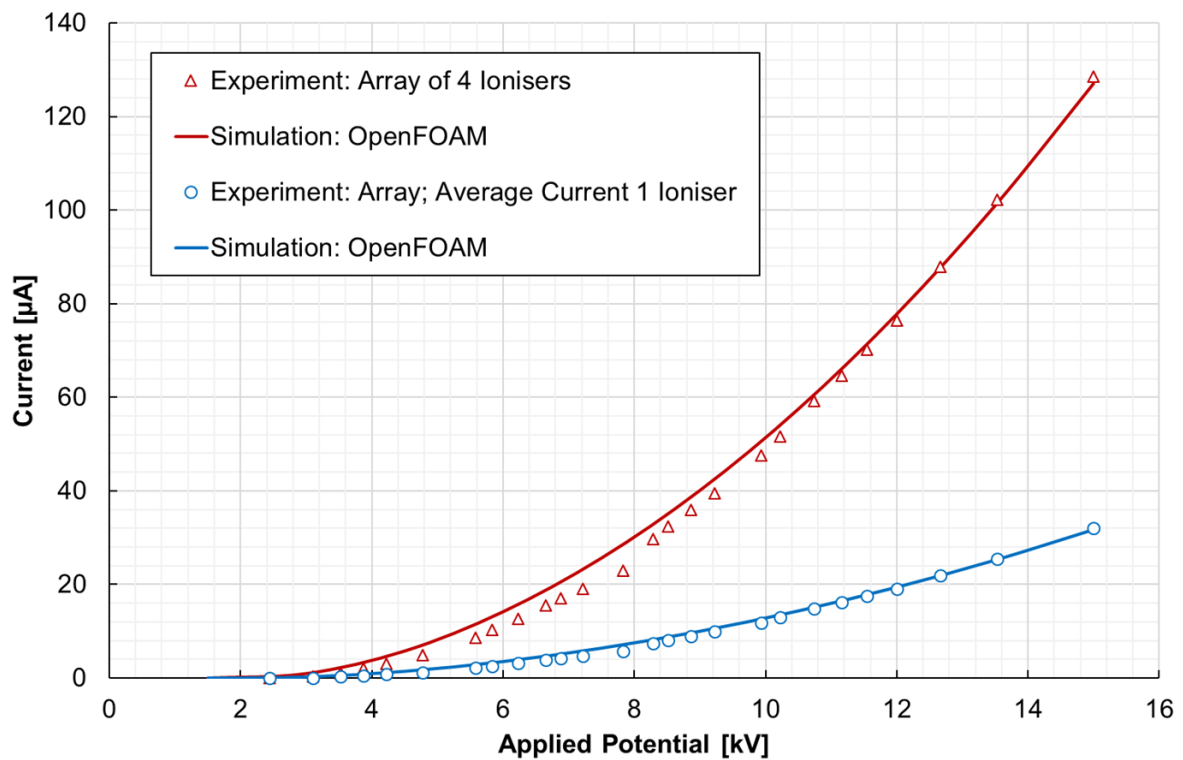


Figure 5: Current-voltage characteristics of ioniser array

4.2. Particle charging and particle losses (simulation results)

As experiments can only determine the filter performance but not the actual particle charges attained, the simulation model was used to calculate average particle charges for different ioniser configurations and to quantify the influence of the flow velocity on particle charging. The maximum achievable particle charge is crucial for achieving high separation efficiency. Furthermore, particle losses in the ioniser system were calculated numerically. Monodisperse NaCl aerosol ($d_p = 400 \text{ nm}$; $N_p = 2 \times 10^9 \text{ 1/m}^3$) was used as the test aerosol.

The flow velocity at the laboratory test rig is only 0.2 m/s to enable the usage of one-layer grid structures and flat filter media with reasonable particle separation efficiency, whilst the flow velocity in typical HVAC systems, which use pleated filter elements, is approximately 10 times higher.

4.2.1. Simulation of test setup ($U = 0.2 \text{ m/s}$; single ioniser current = $5 \mu\text{A}$)

Figure 6 shows the measured average particle charges and the electric potential required at each ioniser to generate a current of $5 \mu\text{A}$, together with the calculated particle losses in the ioniser system for the configurations shown above.

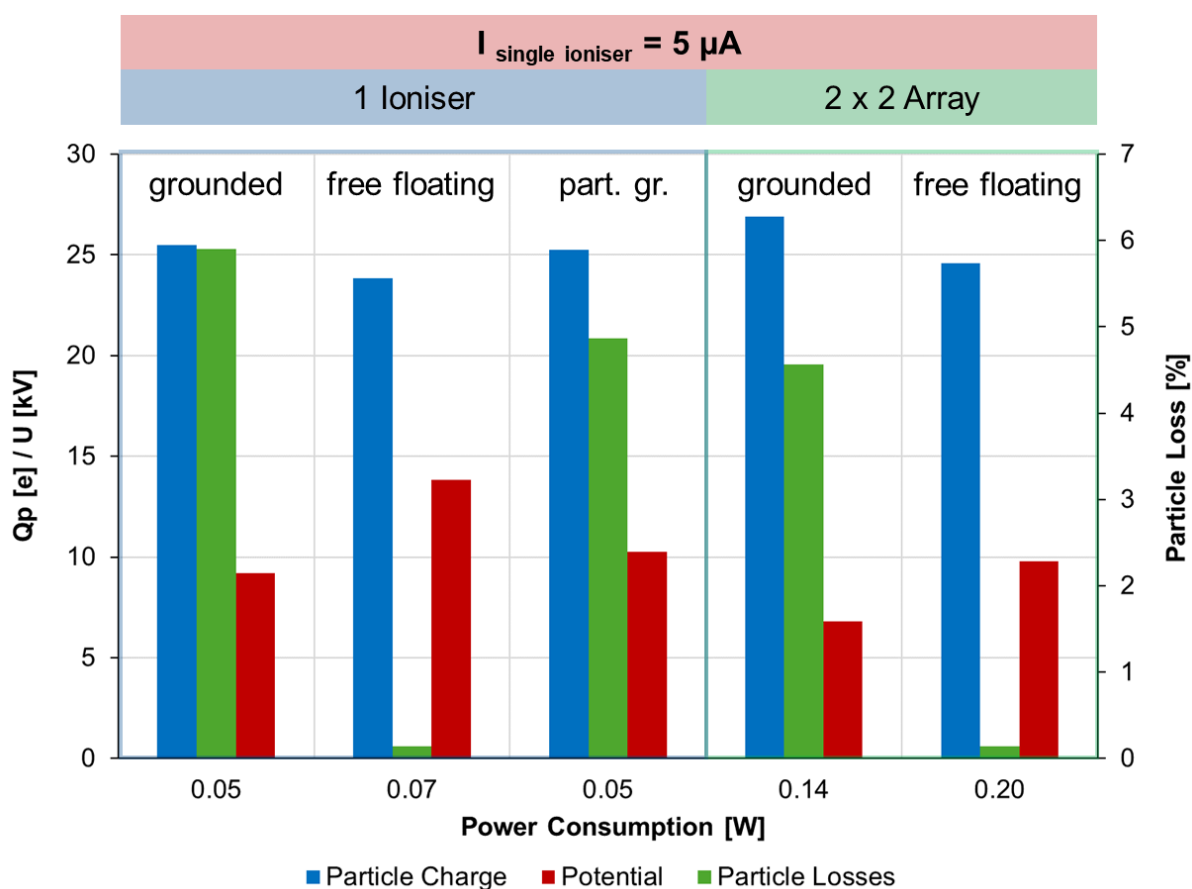


Figure 6: Comparison of ioniser setups (1 brush ioniser vs. 2 x 2 array; channel walls completely grounded, free floating and partially grounded)

For a given ioniser current (5 μA), the achievable particle charges vary only slightly, whereas the potential differences required to generate the current vary considerably (7–14 kV). This is particularly relevant from a practical perspective, because the higher operating voltages increase both component costs and ozone production at the ioniser. The largest differences, however, arise in the measured particle losses. Here, it is clear that the fully grounded walls lead to the highest losses, whilst partial grounding using copper foil in the vicinity of the ionisers causes a slight reduction in particle losses. Only the specification of free-floating boundary conditions reduces particle losses to almost zero.

It can therefore be concluded that a design of the ioniser array without partitions between the ionisers and with free-floating wall conditions should be chosen in order to minimise particle deposition in the ioniser system and to keep the required operating electrical potentials relatively low.

4.2.2. Simulation of typical HVAC-Setup ($U = 2 \text{ m/s}$)

Based on this conclusion, a parametric study was carried out for the design of a scalable ioniser array for a flow velocity of 2 m/s. A rectangular duct with an edge length of 0.6 m is considered. The simulations were carried out using a single ioniser with symmetrical boundary conditions instead of walls. This corresponds to floating conditions, so that the ioniser behaves as if it were part of an equidistant ioniser array. For each investigated array, the distance of the grounding grid was set to half the ioniser spacing to ensure a symmetrical electric field. This results in the following grid spacings for the investigated array layouts: 3 x 3 (10 cm), 4 x 4 (7.5 cm), 5 x 5 (6 cm), 6 x 6 (5 cm).

Two scenarios were considered. In the first, the ioniser current (single ioniser) was set to 5 μA for all arrays. In the second, the maximum operating voltage of 15 kV was applied. Figure 7 shows the results of the parameter study.

Because of the high flow velocity, the achievable particle charge level at a single ioniser current of 5 μA is only about half of that achieved at a flow velocity of 0.2 m/s (Figure 7, left). At the same time, the charge level cannot be increased linearly with the number of ionisers. Instead, the particle charge curve shows an upward trend and reaches a maximum for a 5 x 5 array, whereas the required ioniser voltage decreases continuously. As the distance to the grounding grid decreases as the number of ionisers increases, this suggests that, at a flow velocity of 2 m/s, the minimum required distance to the grounding grid is approximately 6 cm. Although the ion concentration continues to increase when using a 6 x 6 array, the average achieved particle charge decreases. Thus, the 5 x 5 ioniser arrangement represents the optimum at this flow velocity.

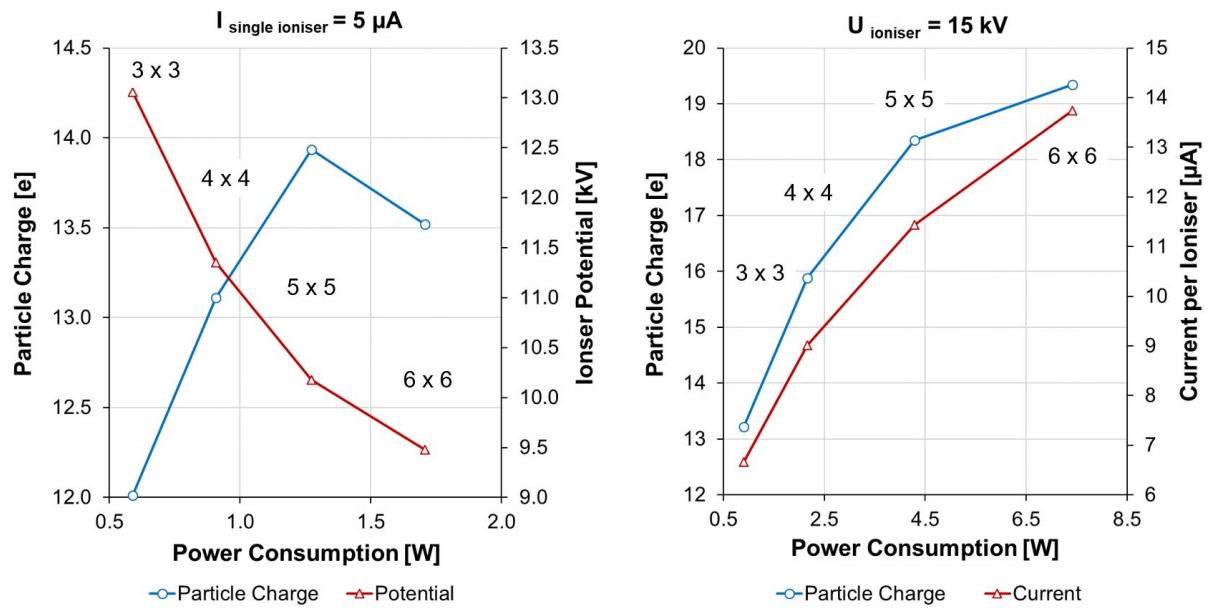


Figure 7: Comparison of array setups in a typical HVAC system (60 x 60 cm channel)

If, on the other hand, the voltage is increased without limiting the current, higher particle charges can be achieved and the particle charge increases steadily with the number of ionisers (Figure 7, right); however, the electrical power then also rises sharply without the particle charge level being reached at a flow velocity of 0.2 m/s.

5. Conclusion and Outlook

A mathematical model for simulating an ioniser-assisted filter system has been developed. The model includes the simulation of corona discharge for various ioniser designs, the particles charging by diffusion and field charging, the particle transport in the gas phase due to diffusion and electrophoresis, as well as charge exchange and charge transport within the filter medium. The processes in the gas and solid phases are coupled through the electric field.

The model has since been applied to brush ionisers and validated against measured current-voltage characteristics. Based on a parameter study, an optimal ioniser array has been developed for use in typical HVAC applications.

The next step will be to validate the capture of electrically charged particles on plastic grid structures within an electrostatic polarisation field.

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