Investigation of Fouling Layer Growth in Compact Heat Exchangers for Electrified Aviation

Claudia Calle González[1,a,*] Markus Kober[1,b] Stefan Kazula[1,c]

[1]German Aerospace Center (DLR), Institute of Electrified Aero Engines,
Lieberoser Straße 13A, 03046 Cottbus, Germany

[a]claudiacallegonzalez@gmail.com [b]markus.kober@dlr.de [c]stefan.kazula@dlr.de

November 7, 2025

Abstract

Hydrogen-electric propulsion systems, essential for reducing emissions in aviation, demand innovative thermal management solutions that can efficiently handle the high thermal loads of fuel-cell electric power generation. In addition, reducing waste from maintenance operations is key to minimize environmental impact. One of the primary failure mechanisms that can lead to damage and degradation of heat exchangers, crucial components for thermal management, is the accumulation of undesired materials on their surfaces, known as *fouling*. This work explores the impact of fouling on compact heat exchangers, a critical factor affecting their lifespan and performance characteristics. A fouling-prediction framework starting from a preliminary analytical study to guide future CFD investigations is outlined. By examining the key parameters influencing particle deposition, guidelines for designing more efficient and fouling-resistant heat exchangers are established, building a foundation for future research.

Keywords Electrified aviation; thermal management system; compact heat exchanger; fouling; damage; degradation; CFD.

1 Introduction

To meet international emission reduction targets, aviation is turning to alternative propulsion technologies, with hydrogen fuel-cells and battery systems among the most promising candidates [1]. The transition toward More Electric Aircraft (MEA) generates significant thermal loads, while the low operating temperatures of fuel cells lead to large and heavy heat exchangers, making thermal management a central challenge [2, 3]. Hence, compact and lightweight heat exchangers (HEX) are essential for enabling fuel cell-powered electrified propulsion systems. Plate-fin and offset-strip-fin designs provide the best balance between efficiency, compactness, and weight. More advanced concepts such as micro-channel, Triply Periodic Minimal Structures (TPMS), and printed circuit HEX offer further potential but at the expense of higher pressure losses and greater manufacturing complexity [4]. Thermal management roadmaps set progressive milestones, with heat removal capacities increasing from 5 kW/kg in 2026 to 20 kW/kg in 2050, while also extending overhaul intervals from 30,000 to 45,000 hours within the same period [5]. Meeting these goals requires not only improved HEX design but also a deeper understanding of degradation mechanisms such as fouling, which will become increasingly important as HEX evolve toward more compact and complex geometries. This paper reviews the fundamentals of fouling, the analytical, numerical, and experimental methods used to study it, and the key parameters that govern deposition. Building on this, the current work presents a preliminary analytical model as a first step toward predictive tools that can ultimately be integrated into automated design processes for compact HEX in electrified aviation.

2 State of the Art

Heat exchangers experience degradation from mechanisms such as fouling, corrosion, erosion, and fatigue, triggered by chemical, thermal, or mechanical stresses, along with contaminants, poor design, and insufficient maintenance. These can lead to failure modes like cracking, leakage, or blockage [6, 7]. Among them, fouling is especially critical, as it reduces efficiency by increasing thermal resistance and pressure drop, raising pumping power requirements [8]. Contributing factors include dissolved solids, chemical reactions, low flow velocities, high pH (alkaline conditions), or stagnant zones [6]. In air-cooled HEXs, fouling results from particulate deposition mechanisms such as inertial impaction, gravitational settling, or thermophoresis [9], as shown in Fig. 1. In liquid-cooled systems, it is often linked to scaling or the solidification of salts and fluids [8]. Its effects are most severe on the air side, where deposits concentrate on the front face, blocking flow more than insulating surfaces, which leads to an increase in pressure drop of up to 45% and heat transfer losses of 10–15% [6, 10].

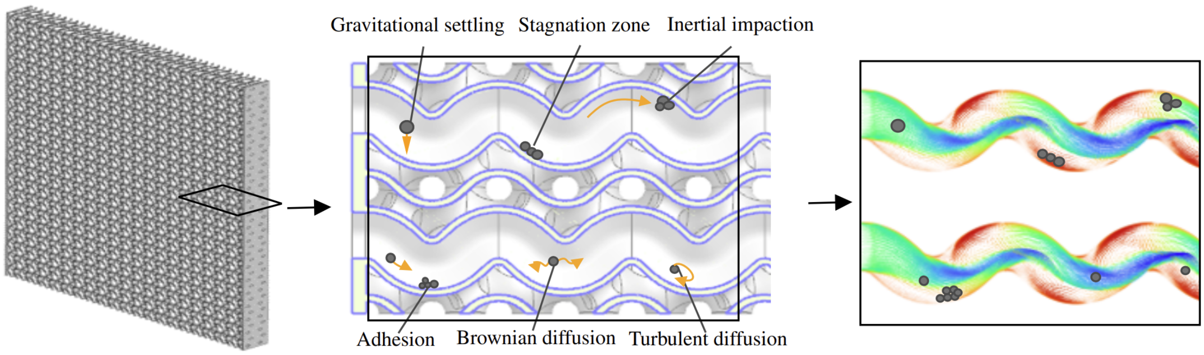


Figure 1: Illustration of fouling mechanisms in a compact TPMS HEX: (left) gyroid TPMS geometry, (middle) schematic representation of deposition mechanisms, (right) flow velocity colormap with deposition sites.

Fouling has particularly severe consequences in compact HEX, where narrow channels and tight fin spacing increase the risk of particle accumulation. These designs, while thermally efficient, are highly sensitive to pressure drop increases under fouling conditions [10]. As deposits build up, especially at the HEX's front face, they cause flow constriction, elevate drag, and lower cooling capacity. The resulting performance losses accelerate component degradation through increased wall temperatures, localized corrosion, and reduced hydraulic diameter [6, 7]. Operationally, fouling raises system-level energy demands and may force overdimensioning, more frequent maintenance, or premature shutdowns. In aviation, where weight and reliability are crucial, this combination of degraded performance and added lifecycle costs makes fouling one of the limiting factors in the deployment of compact, high-efficiency HEXs.

Understanding the mechanisms that govern fouling is essential for predicting its initiation and mitigating its effects. Fouling arises from a balance between deposition and removal processes, and is influenced by flow conditions, particle properties, and surface characteristics [8]. On the air side, relevant mechanisms include inertial impaction, gravitational settling and Brownian motion [11, 12, 9]. Turbulent eddies enhance transport, while thermophoresis and diffusiophoresi drive particles along temperature and concentration gradients, respectively [13]. Surface roughness, recirculation zones, and electrostatic forces further promote particle retention [11, 14]. The probability of adhesion depends on impact velocity and local shear stress, as high enough stress can re-entrain particles, while low stress enables stable deposition [12]. These interconnected mechanisms are illustrated in Fig. 1, which summarizes how particle dynamics and surface interactions lead to fouling in compact TPMS HEX, based on the design published by DLR [15], and are listed in Table 1.

Table 1: Fouling mechanisms

Fouling mechanism	**Explanation**	**Flow condition**	**Particle size**
Inertial impaction	Particles with sufficient inertia cannot follow curved streamlines and impact the wall [11, 12].	Laminar; high velocity [11]	Large [12]
Gravitational settling	Particles move under gravity and settle on surfaces [11, 12].	Horizontal; inclined [11]; Laminar [11]	Large; heavy [12]
Brownian diffusion	Random thermal motion of particles leads to collisions with walls [9, 14, 12].	Low velocity [9]	Small; submicron [12]
Turbulent diffusion	Turbulent eddies enhance mixing and transport particles to the wall [11, 12, 14].	Turbulent [11]	Small [12]
Turbophoresis	Migration from high to low turbulence regions [11].	Turbulent [11]	Small to medium [11]
Thermophoresis	Temperature gradients drive particles to colder surfaces [13, 14, 12].	Strong temperature gradients [13]	Small; submicron [13]
Diffusiophoresis	Particles migrate along species concentration gradients [13].	Multicomponent gas mixtures with concentration gradients [13]	Small [13]
Electrostatic interaction	Charged particles are attracted to surfaces or other charges [14].	Flows with charging effects or electric fields [14]	Small; light [14]
Surface roughness	Rough walls or previously deposited particles disrupt flow or reduce wall distance [11].	Laminar and turbulent [11]	Small [11]
Flow stagnation / recirculation	Particles accumulate in wakes, low-vorticity and high-strain regions [12].	Corrugated tubes [12]	All [12]
Adhesion / sticking probability	Particles may stick or rebound depending on impact and adhesion energies [12, 14].	Low velocity; low shear stress [12]	All [12]

3 Methodology

Fouling is usually modeled as a dynamic balance between deposition and removal mechanisms [8]. The evolution of the deposited mass on the surface is described by the ordinary differential equation 1:

$$\frac{dm_f}{dt} \;=\; \dot{m}_d - \dot{m}_r \;=\; S_p\,J \;-\; \frac{k_r\,\tau_w}{\Psi\,\rho_{\text{dep}}} m_f, \tag{1}$$

Solving Eq. 1 yields the deposited mass as a function of time:
Solving (1) for $m_f(t)$ with $m_f(0) = 0$ gives

$$m_f(t) \;=\; \frac{S_p\,J\,\Psi\,\rho_{\text{dep}}}{k_r\,\tau_w} \Big(1 - e^{-\frac{k_r\,\tau_w}{\Psi\,\rho_{\text{dep}}}\,t}\Big). \tag{2}$$

The deposited mass can be related to the additional due to fouling thermal resistance through:

$$R_f \;=\; \frac{m_f}{\rho_{\text{dep}}\,\lambda_f}, \tag{3}$$

Substituting Eq. 2 into Eq. 3 yields the asymptotic model for fouling resistance:

$$R_f(t) \;=\; \frac{S_p\,J\,\Psi}{k_r\,\tau_w\,\lambda_f} \Big(1 - e^{-\frac{k_r\,\tau_w}{\Psi\,\rho_{\text{dep}}}\,t}\Big). \tag{4}$$

Here, the particle flux towards the wall, J, is obtained from the particle continuity equation:

$$J \;= (D_B + \varepsilon_p)\,\frac{\partial C}{\partial y} \;+\; C_c\,\frac{(\rho_p - \rho_l)\,g\,d_p^2}{18\,\mu}\,C \;+\; D_T\,\frac{\mu}{\rho_l\,T}\,\frac{\partial T}{\partial y}\,C \;+\; \tau_p\,\frac{\partial \overline{v_{py}'^2}}{\partial y}\,C, \tag{5}$$

where m_f is the deposited mass, $\dot{m}_d$ and $\dot{m}_r$ are deposition and removal rates, S_p the sticking probability (likelihood that a colliding particle adheres instead of rebounding), J the particle flux, k_r the removal coefficient, τ_w the wall shear stress, Ψ the strength bond factor, ρ_{dep} the deposit density, λ_f the deposit thermal conductivity, C the particle concentration, D_B the Brownian diffusivity, ϵ_p the turbulent diffusivity, C_c the Cunningham slip correction factor, ρ_p and ρ_l the particle and fluid densities, g the gravitational acceleration, d_p the particle diameter, μ the dynamic viscosity, D_T the thermophoretic coefficient, T the temperature, τ_p the particle relaxation time, and $\partial\overline{(v'_{py})^2}/\partial y$ the variance of the particle velocity fluctuations in the wall-normal direction.

To establish the reliability of the proposed model, its predictions are first benchmarked against a well-documented reference case from the literature under identical boundary conditions and parameters [16]. This comparison ensures that the implementation correctly captures the dominant mechanisms governing particle deposition and provides confidence in the robustness of the numerical framework. Once validated, the model is employed to conduct a sensitivity analysis aimed at quantifying the effect of selected parameters on fouling resistance. In particular, the influence of flow velocity and particle size is investigated, as these parameters are known to play a critical role in deposition. The outcome of this analysis not only highlights the importance of each factor but also provides physical insight into the governing trends, thereby supporting the subsequent discussion of fouling layer growth in compact heat exchangers.

4 Results

The analytical model was validated against the experimental and numerical results of Zhang et al. [16], who investigated particulate fouling growth in a horizontal tube with a length of 1 m and an inner diameter of 25 mm. In their work, water carrying suspended dust particles was circulated through the tube, and the temporal evolution of the fouling thermal resistance was recorded under controlled operating conditions. In the present study, the same physical configuration and boundary conditions were adopted, while a sticking probability of unity was assumed. The comparison between the predicted fouling resistance and the reference data, presented in Fig. 2, shows very good agreement, thereby supporting the validity of the proposed model.

Parameter	Symbol	Value
Inlet velocity	v	0.3 m/s
Inlet temperature	T	298.15 K
Wall temperature	T_{wall}	288.15 K
Particle size	d_p	10 μm
Particle concentration	C_{bulk}	0.4 kg/m^3
Pipe diameter	D	0.025 m
Fluid viscosity	μ	8.9×10^{-4} Pa·s
Fluid density	ρ_l	997.05 kg/m^3
Particle density	ρ_p	1900 kg/m^3
Porosity	ε	0.25

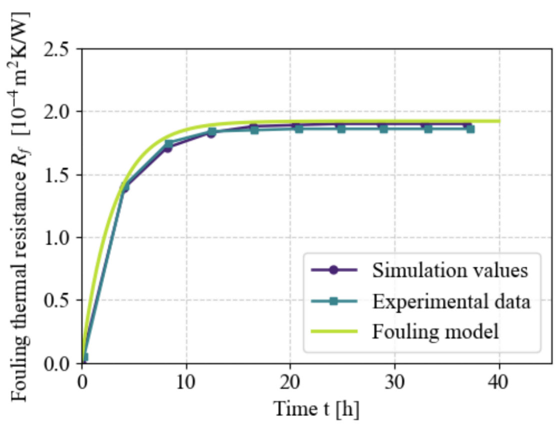
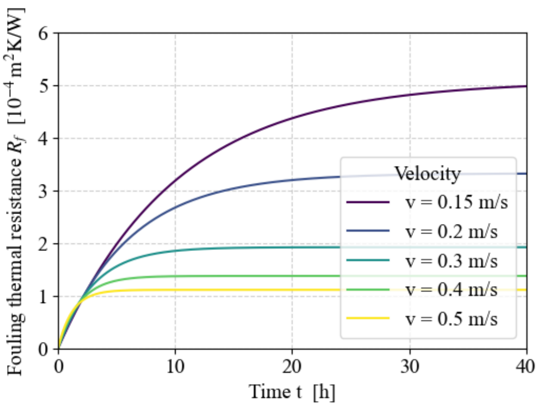
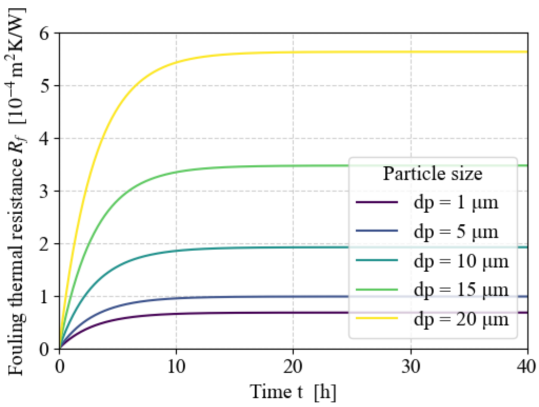


Figure 2: Validation: (left) schematic and boundary conditions; (right) comparison between reference data [16] and the proposed model. (Placeholder figure.)

The sensitivity analysis highlights a very strong dependence of fouling on flow velocity and particle size, among the most influential parameters investigated, as illustrated in Fig. 3. When the flow velocity increases, the predicted fouling thermal resistance decreases, as there is less deposited matter. This trend can be attributed to the higher shear stress at the wall, which promotes the removal of deposited particles and reduces their likelihood of forming a stable layer. Conversely, when the particle size increases, fouling becomes more pronounced. Larger particles possess a greater inertial response, which enhances their tendency to settle and adhere to the wall rather than being dispersed by the fluid motion. These results are particularly relevant because they confirm that the analytical model is able to capture the competing mechanisms of deposition and removal, providing physical insight into the conditions under which fouling occurs.



(a)



(b)

Figure 3: Sensitivity of fouling resistance to (a) flow velocity and (b) particle size.

5 Conclusion

An analytical model for predicting the average evolution of particulate fouling inside the tube of HEXs, which can be later applied locally within CFD simulations has been introduced. The model was compared against experimental and numerical data from the literature and subsequently used in a sensitivity study to quantify the influence of parameters such as flow velocity and particle size on deposition. The results demonstrated that the framework is capable of capturing the interaction between deposition and removal mechanisms, providing insight into the conditions that mitigate or accelerate fouling. This framework lays the foundation for the integration of the model into a CFD environment through a dynamic mesh approach, in which the fouling thickness can be evaluated locally at each wall-adjacent cell. This extension is particularly important for compact heat exchangers with complex geometries, such as TPMS structures, in which fouling is not uniformly distributed but depends strongly on the local flow conditions. By coupling CFD-assessed flow properties with the present model, it becomes possible to resolve the spatial distribution of fouling and identify the regions most prone to deposition. Such information can guide geometry modifications at the design stage, helping to extend component lifetime, reduce maintenance frequency, and ultimately contribute to more sustainable propulsion systems.

References

[1] T. Yusaf, A. S. F. Mahamude, K. Kadirgama, D. Ramasamy, K. Farhana, H. A. Dhahad, and A. R. A. Talib, “Sustainable hydrogen energy in aviation – a narrative review,” *International Journal of Hydrogen Energy*, vol. 52, pp. 1026–1045, 2024.

[2] S. Jafari and T. Nikolaidis, “Thermal management systems for civil aircraft engines: Review, challenges and future,” *Applied Sciences*, vol. 8, no. 11, p. 2044, 2018.

[3] M. Asli, P. König, D. Sharma, E. Pontika, J. Huete, K. R. Konda, *et al.*, "Thermal management challenges in hybrid-electric propulsion aircraft," *Progress in Aerospace Sciences*, vol. 144, p. 100967, 2024.

[4] C. K. Sain, J. Hänsel, and S. Kazula, "Conceptual design of air and thermal management in a nacelle-integrated fuel cell system for an electric regional aircraft," in *AIAA AVIATION Forum*, 2023. AIAA Paper 2023-3875.

[5] Aerospace Technology Institute (ATI), "Thermal management roadmap report," tech. rep., FlyZero, 2022.

[6] S. Addepalli, D. Eiroa, S. Lieotrakool, A.-L. François, J. Guisset, D. Sanjaime, *et al.*, "Degradation study of heat exchangers," *Procedia CIRP*, vol. 38, pp. 137–142, 2015.

[7] R. K. Shah and D. P. Sekulić, *Fundamentals of Heat Exchanger Design*. Wiley, 2003.

[8] T. R. Bott, *Fouling of Heat Exchangers*. Elsevier, 1995.

[9] H. V. Inamdar, E. A. Groll, J. A. Weibel, and S. V. Garimella, "Prediction of air-side particulate fouling of hvacr heat exchangers," *Applied Thermal Engineering*, vol. 104, pp. 720–733, 2016.

[10] I. H. Bell and E. A. Groll, "Air-side particulate fouling of microchannel heat exchangers: Pressure drop and heat transfer vs. plate-fin," *Applied Thermal Engineering*, vol. 31, no. 5, pp. 742–749, 2011.

[11] M. Massah, E. Khamehchi, S. A. Mousavi-Dehghani, B. Dabir, and H. N. Tahan, "A new theory for modeling transport and deposition of solid particles," *International Journal of Heat and Mass Transfer*, vol. 152, p. 119568, 2020.

[12] S.-Z. Tang, F.-L. Wang, Q. Ren, and Y.-L. He, "Fouling characteristics analysis and morphology prediction of heat exchangers with a particulate fouling model considering deposition and removal mechanisms," *Fuel*, vol. 203, pp. 725–738, 2017.

[13] K. H. Leong, "Thermophoresis and diffusiophoresis of large aerosol particles," *Journal of Aerosol Science*, vol. 15, no. 6, pp. 623–632, 1984.

[14] C. Paz, E. Suárez, J. Vence, and A. Cabarcos, "Numerical modelling of fouling process in egr systems: A review," in *Environmental Issues and Sustainable Development*, IntechOpen, 2021.

[15] DLR, "Hex-4-electra project information." `https://www.dlr.de/de/el/forschung-transfer/themen/hex-4-electra`. Accessed: 2025-09-24.

[16] N. Zhang, X. Wei, Q. Yang, N. Li, and E. Yao, "Growth characteristics of particulate fouling on pipe heat-transfer surface: Simulation and experiment," *Heat and Mass Transfer*, vol. 55, no. 3, pp. 687–698, 2019.