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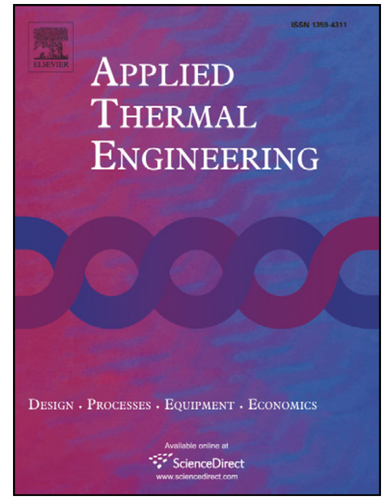

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A review of heat exchanger fouling in the context of aircraft air-conditioning systems, and the potential for electrostatic filtering.

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Abstract

This paper presents a focused literature review to understand the common problem of fouling of air-conditioning heat exchangers aboard aircraft, with the academic consideration to employ Electrostatic Precipitation to remove airborne particulate matter.
Particulate matter suspended in air, is carried through the matrices of aircraft environmental cooling systems. The deposition and build up of such contaminants affects the thermal performance of cooling systems and leads to component failure, expensive repairs and loss of service of an aircraft.
Although there have been many publications of material pertaining to heat exchangers and fouling, very little publications specifically to aircraft air-conditioning systems or failures have been published. Nonetheless, the literature review indicates that sizes and distribution of particulate matter including Reynolds numbers and rates of deposition have been established in previous papers.
The novel approach to this industrial problem has been to evaluate the operational problem of aircraft air conditioning systems, identify local factors, and to consider the use of means of protection employed in other non-aerospace industries. It is believed the application of electrostatic precipitation could potentially aid prevention of fouling particulate matter on aircraft air conditioning heat exchangers.

1. Introduction

Large commercial aircraft employ a system known as an *environmental control system (ECS)* to provide conditions in flight that allow passengers to travel in relative comfort. The ECS provides both cooling or hot air to pressurise the passenger cabin, which controls temperature, fresh air ventilation and cabin altitude (via pressurisation, by moderating the outflow valves).

The source of air used by the ECS is typically taken from the gas turbine compressor, known as *bleed air* (between stations P2.5 and P3 in a gas turbine), and is both high pressure and temperature.

Prior to allowing hot bleed air into the passenger cabin, the air must first be cooled to an acceptable value. This is performed using a unit known as an *aircraft pack.* The pack is comprised of several units, including a number of heat exchangers cooled by ambient *ram air*, air that is ducted from outside the aircraft and post cooling, is vented back to atmosphere. The *pack heat exchangers* are the main units of interest, and comprise typically of a fin and plate assemblies, co-flow single pass units. The hot bleed air (from the gas turbine) is cooled to measured value by the pack which in turn is controlled by the ECS. The external ram cooling airflow passing into the pack heat exchangers contains debris, which is deposited on the forward face of the fin and plate single pass exchanger. The majority of debris is believed to be deposited on the outermost surface – namely as the air passes further into the pack exchanger, the level of contamination decreases. Note, this review is not concerned with passenger air quality.

Major aircraft manufacturers and a UK airline have recently suggested that air conditioning system overheat poses regular failures under given operational conditions, which has a considerable effect on aircraft technical dispatch reliability of aircraft.

One specific airline operates their fleets currently in a single class layout of the passenger cabin, which is known as high passenger density configuration. This relies on the air conditioning system running constantly in “Hi Flow” mode to provides sufficient ventilation for the additional passengers. Such an

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airlines high passenger density must meet the legislated requirements to provide a minimum quantity of fresh conditioned air to each passenger.

1.1 Fresh Cabin Air requirements

Until 1996, both the Federal Aviation Authority (FAA, USA) and Joint Aviation Authority (JAA, Europe) had the same basic requirement for cabin ventilation rates. FAR 25.831 and JAR 25.831 **[1]** required a minimum supply of 10 cubic feet per minute (cfm) of fresh air per flight crew member, which "must be free from harmful or hazardous concentrations of gases or vapours."

The resulting high flow operation causes the air conditioning system to operate at 120% of the "normal" manufacturers flow rate **[1]**. High flow operation of levels greater than "normal operation" may be required to provide additional levels of ventilation during abnormal situations/ operations. One such operation would be smoke in the passenger cabin, where additional air is required to prevent asphyxiation. Another abnormal operation could be high density single economy class configurations.
The higher than average air conditioning system failures are observed in the aircraft pack, caused by overheating whilst the aircraft is either on the ground, or during take off/ landing.
During these specific operations, large volumes of ambient ram air do not flow over the primary and secondary heat exchangers, rather a mechanical fan operates to assist in the transfer of heat between the system and ambient.

The overheating in the system is due to particulate matter accretion in the air conditioning pack heat exchanger matrix. When excessive levels of particulate are deposited in the matrix, the thermal performance of the heat exchanger decrease: the pack reaches higher than acceptable operational temperatures and must be isolated. This system failure results in the flight crew "shutting down" the overheating pack to prevent further damage and the possibility of a fire. It is worth noting that the ECS unit and packs are typically located on narrow and wide bodied aircraft, below the water line normally close to the wing box section. A centre fuel tank is normally in close vicinity to this system.
Rectification can only be achieved by removing the pack from the aircraft, returning the unit back to the original equipment manufacturer (OEM) for deep clean to remove operational contaminants.

Fig. 1 **[2]** shows hot bleed air from the engine compressors is metered through a bleed air valve and being passed to the primary heat exchanger. After primary cooling, the air passes to the air cycle machine and latterly into the secondary heat exchanger before being distributed into the cabin air system.

Ambient air provides cooling at both the primary and secondary exchangers.

In this paper, a review of the known pollutants at airfields is considered, along with non-aviation industry publications in dealing with the field of particulate matter fouling applied to heat exchangers. The potential of electrostatic filtering will be finally considered as a solution to prevent airborne particulate fouling on the aircraft pack heat exchangers.

2. Sources of Airborne pollutants

Department for Transport (DoT) UK published a white paper **[3]**, theorising air transportation development over the next 30 years**.** The paper and content is of specific importance to academic study, as it is believed that increased levels of growth will lead to higher levels of airborne debris, thus potentially effecting the operations of aircraft heat exchangers. The numbers of aircraft operating at a given period of time will not be correlated to the levels of technical dispatch reliability, but it would be expected that increased levels of operation will lead to higher rates of failure.

2.1 Particulate Matter (PM_{10})

The Department for the Environment, Food and Rural Affairs UK defines particulate matter being *“classified according to its size and this classification is used in concentration measurements. For example, PM_{10} is – to a good approximation – the concentration of particles that are approximately equal to 10 µm.”* **[4]**

Airborne particulate matter is made up of a collection of solid and/or liquid materials of various sizes that range from a few nanometres in diameter (about the size of a virus) to around 100 µm (about the thickness of a human hair). It consists of both primary components, which are released directly from the source into the atmosphere, and secondary components, which are formed in the atmosphere by chemical reactions. Particulate matter comes from both human made and natural sources. It contains a range of chemical compounds and the identity of these compounds is dependant on the source materials (as per Table 1).

Measurements of the concentration of particulate matter in air are made by recording the mass of particulate matter in one cubic metre of air, using the units micrograms per cubic metre, µg m^{-3}.

The Particulate Matter **[5]** is described by the Department of Transport (DoT) publication “Project for sustainable development at London Heathrow” as one of the main particulate contribution to airborne fouling, and therefore particular attention will be given in this review to its particle size, distribution, sources and effects. It makes reference to dispersion modelling close to airfields and the types of measured emissions found close to the airfield (London Heathrow). London Heathrow International Airport, located in West London adjacent to the M25. Pollutants monitored included concentrations of NO_2 (gas) and particulate matter (including PM_{10}).

The inclusion of particulate matter is of specific interest to this review, as it is believed that such materials are likely to accrue on heat exchanger surfaces with the potential to affect the heat transfer ability. The paper **[5]** does not include details of future pollutant models or content that would enable one to calculate/ generate the emissions that would be required should this task need evaluation and further consideration. The methodology the DoT employed was via the appointment of panel members (selected by DoT) providing written details of recommendations on how to set up detailed “Bottom up inventory.” This approach is considered too qualitative/ subjective, therefore considered to be limited to this academic study.

2.2 Particulate Matter sources

The mean UK limit for particulate matter PM_{10} is 40 µg m^{-3}, across the UK as a whole: The report stated that the maximum value measured was 27.3 µg m^{-3} with an estimated mean average around the London Heathrow vicinity of 24-25 µg m^{-3}. Measurements of smaller particles namely $PM_{2.5}$ were estimated to be between 17-21 µg m^{-3}. Sources of PM_{10} pollution are known to include:

- Aircraft from both ground and flight operations including operation of Auxiliary Power Units (APU’s), operations of tyres and brakes and ground engine tests
- Airside vehicles - both supportive and service vehicles (air start equipment, ground power units)
- Road vehicles, at both landside and airside. (Airside is the within the security perimeter of the airfield, landside are all other areas not subject to strict security controls)
- Airport car parks, bus stations and taxi cues.
- Airport building heating and ventilation air conditioning (HVAC) (including boiler plant)
- Airport fire training exercises

Further sources of emissions are later discussed including critical phases of flight, namely take off and landing, however quantified values of emission types are not given. A general approach trend is suggested in accordance with the International Civil Aviation Operation documentation, that at a distance of 10 nautical miles (20Km) from the threshold (of the runway) the aircraft will be approximately at 3000ft. At this time a moderate flap setting is likely to be made resulting in the deceleration of the aircraft. At approximately 6.5 nautical miles (13km) the undercarriage is extended and the aircraft is then

approximately at 2000ft. The final flap setting is made at 5 nautical miles (10km) at an approximate altitude of 1500ft.
This account is particularly important to this study as the operational failure observed by commercial airlines of the air-conditioning systems is not in flight, but whilst the aircraft is on the ground, typically after the aircraft has flown a sector and then is performing ground operations. It is believed that the initial and final phases of flight where the aircraft is known to fly at reduced speeds, reduces the mass airflow through the air conditioning heat exchangers and coupled with this is the ambient air containing higher values of particulate matter, namely PM_{10} as shown in fig. 2.

2.3 Particulate Matter (PM_{10}) at London Heathrow

Fig. 2 clearly shows two areas of higher than expected levels of PM_{10} in West London – as indicated by the brightly colour shaded regions representing high PM concentration: The sites are believed to be London Heathrow (West London) and RAF Northolt which displayed very high levels of PM_{10} pollution located in North West London. It should also be noted that aircraft take-off and/ or approach is likely to track the aircraft across central London, which is also high in PM_{10} aerosol material – thus further affecting the deposit of debris on the heat exchangers.

Auxiliary Power Unit, APU, emissions are briefly discussed and their use is significantly less complex than the emission of aircraft as APU operation is typically whilst the aircraft is on ground without ground services. The APU may be used in early and late phases of flight namely take off and landing, but generally the use of APU in flight in not necessary.
Equation 1 shows the relationship for total APU emissions which suggests that the means of operation for a given APU coupled with the rate of fuel flow and an emission index of the respective mode.

$$APUemissions = \sum_{\mathrm{mod}\,e=1}^{\mathrm{mod}\,e=4} Time_{\mathrm{mod}\,e} \times FuelFlow_{\mathrm{mod}\,e} \times EmissionsIndex_{\mathrm{mod}\,e} \tag{1}$$

The mode conditions contained within formula 1 are defined as:
1. No load,
2. Electric,
3. Full ECS + electric,
4. MES + electric.
Where ECS = environmental condition services, MES = main engine start.

The report **[5]** noted that mode 2 and 3 produced similar levels of NO_x and PM_{10} values, modes 4 and 1 were distinct. The report however does not include reference to particulate matter composition or of size distribution of average particulate size. This is because the mandated measurement for particulates at present is only mandated for PM_{10}. The inclusion of a size distribution of particulates including analysis of the Volatile Organic Content would be beneficial to this field.

The report states that APU emissions are higher than modern gas turbine main engines. This statement suggests that APU use will have a significantly higher impact on the reliability of air conditioning heat exchangers than modern gas turbines due to the PM_{10} levels produced. Additional APU use being restricted to very low altitude use which also suggest slower aircraft operating speeds thus lower mass airflow though the respective heat exchanger matrixes.
Airside traffic contributes to PM_{10} being measured, but due to the lack of exact data values for distances travelled the report is unable to given an exact breakdown of vehicle type and PM_{10} mass production.
This will not hinder the investigation, as values of PM_{10} have been monitored at various sites both inside and outside the airport vicinity, thus trends of PM_{10} pollution are known from observations.

3 Heat exchanger findings in other non-aircraft industries

Publications on aircraft heat exchanger fouling is very limited. The approach employed is to review other non-aircraft industrial experiences from papers/ publication to better understand non- aviation industry knowledge.
General Electric Water Company has considered the commercial effects of heat exchanger efficiency **[6]**, and as such has developed commercial software CHeX, which contains a predictive algorithm to estimate the heat exchanger efficiency. The publication suggests the field of heat exchanger fouling has a significant financial effect on US industry, circa $10 billion per annum in 1985. *Although the period of data is now significantly out of date, the inclusion and consideration of such a unit is useful in understanding the commercial value fouling has to play in better managing heat exchanger assets*. CHeX software has various inputs and can address fouling detection, fouling prediction and fouling diagnosis, within the application of the water industry. Calculations are performed in the software by a hybrid Kalman filter which models fouling prediction data, thus an element of reliability can be established. The model and software relies heavily on a number of sensor values being acquired and then considered. The full detail of the model inputs/ weightings and algorithm is not shown due to the commercial value of the product, however, Kalman filtering is a very valuable and current tool employed by other industries, including the aircraft maintenance field. The approach of CHeX would not be applicable to the scope of the this research, as the aircraft heat exchangers do not contain sensors detecting debris, nor are there a data acquisition module attached. Should either sensors and data acquisition units be considered to be fitted, the heat exchanger unit (OEM) and the aircraft would require an element of re-certification and such costs would need to be considered against the potential savings increased levels of technical dispatch reliability of the air-conditioning system.

Numerical simulation of the fouling process has been considered by Brahim et al. **[7]**. The fouling process was simulated by CFD code FLUENT subsequent models based on the crystallisation fouling of calcium sulfate on flat heat transfer surfaces. The study made some simplification assumptions of the real crystalline growth, namely a real system requires continuous variation of the geometric flow model. This was overcome by the authors introduction of crystal growth rates in the simulation, thus a realistic model of the temporal modification of both flow and heat transfer field due to the continuous crystal growth.

The experimental set up used in Brahim's **[7]** publication differs from the operational scope of the this aircraft academic study, as debris is material dissolved in solution, compared to particulate matter suspended in an aerosol that affects the aircraft heat exchangers. Brahim's simulation of the crystalline growth rate, shown in figure 3, would be a logical model to consider for this study, as consideration is given to rates of deposition and removal, flow rates and temperature fields, total mass flow rates with a temporal consideration.
A specific consideration of fouling and calculations has been given by Riverol and Napolitano **[8]**, based on the milk pasteurization process, being subject to alterations stemming from the variation in the temperature, pH and raw milk quality. Although milk fouling is not directly linked to the aircraft pressurisation system, the considerations given to the fouling mechanisms and rate of formation were considered carefully as a relevant body of academic research. The variability may manifest itself in changes in the formation of the deposit (fouling) in the pasteurization unit, such that there is a need for tools, both instrumentation and computational, to help in monitoring the process and keeping it on the desired course. General fouling application to heat exchangers are considered for similar food applications, petrochemical industry and neural network control and simulation **[9 to 18]**, whereas Riverol and Napolitano's paper **[8]** described a practical procedure based on neural networks that allowed prediction of the temporal variance of deposit thickness, the overall heat transfer coefficient and critical time (the time that the unit has to be stopped for cleaning) for reducing the impact of fouling.

The four assumptions made in the paper were:

- The number of hot streams, cold streams and heat exchangers were the same.
- Each stream exchanges heat once, and only once.
- The heat exchanger operates continuously.
- A fouling profile of the equipment is estimated using a fouling model.

The paper does not contain details of the neural network model, but the results shown demonstrate the variance of thermal conductivity at differing temperatures with temporal shift. This was due to physical

properties of milk, and the effect of temperature with the denaturisation process of protein (and subsequent rates of sedimentation).
Such considerations of variance of temperature should be investigated in this field of study, to ensure that variance of temperature does not influence the physical properties of deposit on the heat exchanger plates.
Actual units in service are subject to variation of temperature: typically on the ground the air inlet temperature to the heat exchangers may be as high as 80˚ C, however if the outside ambient conditions are severe, additional external cabin heated air will be required to provide heat to the aircraft to prevent the airframe from becoming too cold during ground operations.

A logical method of experimental fouling investigation on aircraft would be to pass PM_{10} material (in aerosol form) over sample plates at differing temperatures – temperatures similar to those experienced at the heat exchanger inlet temperature, and view the soiled plate faces with an electron microscope to ensure consistency of material properties. The likely temperature range is between 30 to 80 ˚ C, as supported by technical literature.
Additionally, sample heat exchanger matrixes containing in service debris could be viewed using the same apparatus to ensure consistency with the test materials. Any such variance (if any) could be investigated further.

Siegel and Nazaroff's research **[19]** was of specific interest as the paper links the thermal performance of a heat exchanger with particle deposition of materials of varying sizes. The acknowledgement of existing materials that discuss cleaning and maintaining HVAC heat exchangers, cite little has been written about the factors controlling HVAC heat-exchanger fouling by deposition of particulate matter. Researchers have modelled particulate fouling for heat exchangers used in industrial processes. The authors further state that significant strides in the modelling fouling mechanisms, such as in dairy processing, nuclear reactor cooling systems, crude oil distillation, and other process and industrial heat exchangers, thus suggesting that the process of fouling is common to many applications. The objective of the authors paper was to develop and test a model of particle deposition in typical HVAC heat exchangers. The development of such a model represented a step toward the evaluation of energy and indoor air quality effects of heat-exchanger fouling,
The model used three major inputs (air velocity, particle size, and fin spacing) and several minor inputs to determine the likelihood that a particle will deposit in a heat exchanger.
Siegel and Nazaroff's **[19]** study was restricted to isothermal conditions with major output of the model being the deposition fraction, Z; defined as the likelihood that a particle of a given size will deposit on a heat exchanger. The mass deposition rate of particles of a given diameter was the product of the deposition fraction, the flow rate of air through the heat exchanger, and the concentration of particles in the air upstream of the heat exchanger. Owing to the importance of particle diameter on deposition processes, the deposition fraction was a function of particle size.
Air velocity also affected the deposition fraction by altering the inertial impaction of particles as well as the residence time of particles in the heat exchanger. This was latterly considered as a function of Reynolds number, where it was found that very high **Re** values (from turbulent flows) coupled with large particulate matter, produced high values of deposition. Fin spacing, a geometric parameter that is related to heat-exchanger thermal efficiency and pressure drop, influences the deposition fraction by changing the distance that a particle must travel to contact a surface.
The paper additionally estimated the deposition fraction and the factors that influence it. The primary focus was a mathematical model of deposition in a fin-and tube-heat exchanger that accounted for inertial impaction, gravitation settling, air turbulence and Brownian diffusion.
In light of Siegel and Nazaroff's **[19]** findings, the air conditioning heat exchanger flow rates need to be quantified to establish where the cooling air flow rate does provide high **Re** values , as this would result in higher rates of particulate deposition.

This could be established by viewing an OEM's publication which states the operational characteristics of a given aircrafts air conditioning heat exchanger performance values.

General particulate fouling has been discussed by various publications **[20- 24]**, with the consensus of opinion based upon observations from industrial applications. Gas side fouling of a heat exchanger was the focus of Bouris et al. **[25]** paper, considering the design and evaluation of a novel heat rube bundle heat exchanger that achieved higher heat transfer levels at lower levels of pressure drop, whilst remaining less susceptible to gas side fouling. The paper demonstrated that the novel design of tube and reduced transverse spacing permitted reduced levels of fouling. The design of the specified tube is a symmetrical aerofoil type arrangement (fig.4), design c.

The inline bundle arrangement with DDEFORM tubes placed at half the transverse spacing of the standard in-line arrangement is shown in fig. 5

Further to the simulations and practical experimentation, the authors noted that that heat transfer decreased (using DDEFORM tubes) due to reduced levels of mixing and turbulence in the modified bundles, therefore a reduction in the transverse spacing was considered. The subsequent results form the latter studies showed that the new closely spaced bundles showed a higher heat transfer level with a 75% lower deposition level, with a 40% lower pressure drop.
Although this research has academic merit, the application of redesign to existing aircraft heat exchangers is not a feasible solution considered, as such a process would require considerable OEM research, aircraft manufacturer certification followed by local National Aviation Authority approvals (for both fitment of the new component and the increased time between maintenance). Such activities would be very expensive, and the new component would need to demonstrate a clear financial saving, which would be unlikely in this authors opinion.

3.1 Domestic air conditioning fouling – a similar problem to aircraft

Ahn and Lee **[26]** investigated the characteristics of the air side particulate fouling materials in finned-tube heat exchangers of air conditioners. The research is of specific interest as the authors considered three types of heat exchanger matrix sites, namely an office, a restaurant and latterly a seaside inn by employing an “API Aerosizer” equipment to size the particulate fouling material on respective matrixes. The use of pre-filters was noted, and the sizing of the pre-filter mesh was defined as 30 mesh - 600μm. Fouled filters (3 yrs service) were inspected and it was determined materials off less than 100 μm passed through the filter due to the large size of the pre-filter pore size. Fouled pre-filters are shown in figure 6.
Figures 7 to 9. consider the sized distribution of defined the average aerodynamic diameter of fouling materials for:

- office – 6.6 μm, fig. 7
- restaurant – 9.8 μm, fig 8
- seaside inn -20.9 μm fig 9

All three heat exchangers were further investigated for the type of fouling material, and it was noted that the seaside unit contained additional quantities of Na and Cl elements were observed for the outdoor seaside inn unit, which would be as expected for a saline environment. It would be anticipated that commercial aircraft operating in a similar environment would also exhibit similar NaCl fouling accretion due to the marine environmental conditions.
The authors noted that the office conditioner contained smaller particulate fouling, due to high concentrations of small particulate matter from indoor domestic conditions. This is accounted for by skin debris, clothing fibres and such particles are more likely to be deposited on the evaporator when operating in “conditioning mode,” namely the water condensate is bled over the heat exchanger to aid in cooling. The additional of water condensate appears to greatly increase the fouling rate – and such an observation is important to this study as aircraft typically follow a similar practice of spraying water condensate from the air cycle machine onto the heat exchanger matrix to increase the rate of cooling. Condenser fouling is shown in figures 10, to 12, from images produced from a scanning electron microscope (SEM).

The restaurant analysis appears to exhibit similar fouling trends to that of air quality studies **[3,4,5]** and it is believed this might be due to the restaurant conditioned air containing larger quantities of organic materials: this is plausible as South Korean restaurants typically cook food on hot plates at the table of customers with a charcoal heat source. This would produce larger than expected airborne particulate matter containing organic fumes (from cooked meats) and products of combustion. Analysis of the fouling material is shown in **table 2**.

The chemical components were analysed using a dispersive X-ray spectrometer. Carbon readings are not recorded, due to materials being collected and captured on the spectrometer using carbon based adhesive tape – as confirmed by the author.
The paper stated that if corrosion of the heat exchanger is considered (such as a condenser used for 6 years), the combined effect of particulate debris and corrosion severely effects the performance of the condenser. This observation is unlikely to be of assistance to this study, as units are typically removed an overhauled at regular intervals (c. 15 months) and as such corrosion accretion is unlikely due to time between overhaul.

Particulate matter is known to have a size distribution – aerosols have been considered by Lekhtmakher and Sharpiro **[27]** suggesting two characteristics of aerosols namely size distribution f (r) and probability density function (pdf) (r) as shown in fig. 13.

3.2 Fouling factors and distribution

The concepts of size distribution and size probability density function are usually not distinguished **[28 to 32]**. Uncertainty was considered dependent on the total number of aerosol particles measured, thus an estimation was made of the variances of the aerosol size-dependent properties was considered.

A more recent approach to utilise adaptive filtering in detecting fouling of heat exchangers was considered by Jonsson et al**. [33]**. Jonsson's paper considered how a non-linear physical state space model can be applied to an on-line detection of fouling in a heat exchanger application. The model was based on parameters of inlet and outlet temperature and mass flow rate, and in doing so was able to make subtle calculations during transient operations. The filter is optimised initially with a clean heat exchanger, and results gained appear to suggest that Jonsson's filter is sensitive and has applicability to fouling detection.
A fouling factor was considered as part of the kalman filter model, as shown in fig 14. Note that fig. 14 suggests that the time interval range between 0.663 and 0.949 shows a significant change in the fouling factor which would also be associated with a change of the thermal conductivity.

Such a measurement and latterly in this research the ability to predict significant changes in thermal conductivity would be very valuable to this research as the results could be considered as a function of performance and therefore when a thermal conductivity threshold is achieved, a trigger is performed to alert the aircraft operator to schedule an aircraft heat exchanger replacement at the earliest opportunity. In doing so in a timely fashion, the heat exchanger matrix would be changed and the effects of in service failure would be avoided, thus the reliability of the system would show improvement, and technical dispatch reliability would cease to be effected by fouling.

3.3 Fouling factors – a diverse approach

Different applications to industries other than aerospace and food processing have been considered. Rummens et al. **[34]** considered fouling mechanisms specific to supports from nuclear steam generators based on experimental data (pressure loss, local velocity, turbulence intensity, local void fraction). Their approach allowed for considerations to be given to a proposed fouling mechanism, criteria's supporting fouling propensity, correlation of fouling with mass flux with an analytical simulation once data was gathered. Such an approach is logical should the authors have access to live on-condition equipments and data, so models can be suggested and subsequently validated. Although it must be considered that such academic study would be subject to normal operational condition.
Laboratory heat exchanger experiments and scaled up applications have been considered by Schreier and Fryer **[35]** where they understood a number of laboratory simulations have been conducted, yet application of knowledge of fouling to industrial practices is often seldom: Problems identified included the multiple conditions affecting fouling rates, and even with an approach to use computational models of a simple heat exchanger to predict rates of fouling, the scaled up results differ significantly. The authors'

approach to the process was centred about a rapid fouling heat exchanger which fouls in a matter of hours, rather than days. This is a significant variance with the research presently being considered, as the aircraft heat exchangers foul in approximately 12 months or less dependant on operational use.

Thermal effectiveness of a fouled heat exchanger was considered by Jeronimo et al. **[36]** who monitored heat exchangers of a petrochemical plant. The plant contained various changing feed-stocks in the refinery, and it was noted that changing the feed-stock affected the performance factors measured. An approach to assess the fouling levels, the daily thermal properties and efficiencies were not compared to the design calculations. Rather, new values of heat transfers, flow rates were measured resulting in revised heat transfer coefficients, but the overall process for recalculation was considered too timely and onerous. The authors concluded that the measured parameters for an effective study are the inlet and outlet temperatures of the heat exchanger and the mass flow rate: Changing the physical properties of the feed-stock did not appear to significantly effect the results gained, thus a simple approach to estimating fouling levels was considered.
The paper however did not specify what the feed-stocks were, nor did the authors specify the method of fouling of heat exchanger. The approach is consistent with other publications, namely to gather operational data and to consider and suggest theorems subsequently. The approach of gather industrial operation data is however subject to data availability (on- wing performance values are not currently available for this study) and also the academics ability to vary conditions are strictly limited to the normal operating procedures of the plant.

Hot and cold stream fouling in a continuous heat exchanger network (HEN) plant operations have been considered **[37, 38]**, thermal analysis **[39]** and energy balance equations established on heat transfer coefficients including fouling factors **[40]**. Optimisation of a planning and cleaning schedule of a HEN was considered by Sanaye and Niroomand **[41]**. Data from operation petrochemical sites were obtained; areas investigated were the operational HEN of the Urea and Ammonia plant.
Parameters supplied from the plants included variations of inlet and outlet temperatures, exchanger type and arrangement, heat transfer surface areas, mass flow rates for both hot and cold streams and heat transfer coefficients and variation of fouling with time.
The author’s objective was to provide an optimal cleaning schedule for the HEN that provided maximum operational output with minimal effect to operational cost.
The rate of fouling was considered, as was the objective function, and the final solution was able to model a cost efficient cleaning schedule.

Jun and Puri **[42]** investigated and successfully predicted the rate of fouling on plate heat exchangers for milk pasteurisation. The model calculations were validated by experimental results with small variations in predicted mass – which was temperature dependant. Food processes are known to have different propagation fouling processes, but the validation and prediction of deposition was positive. Roumeliotis and Marthioudakis **[43],** discussed the effects of an aircraft air-conditioning systems, specifically as condensation gives rise to several problems in materialization of the air cycle: It was shown to result in a temperature rise thus lead to different conditions than the expected at the turbine exit. Additionally, as liquid water must be removed from the air stream prior to passing regions of cold temperatures. In the case that turbine exit temperature is very low; there was the possibility of ice particles formation, and significant damage resulting from ice accretion and shedding.
Thermodynamic equilibrium methods for predicting the occurrence of condensation and calculating the mixture properties were considered, once condensation has occurred. This method was validated against the experimental results from a turbocharger turbine; the experimental results demonstrated condensation could cause significant variation to the turbine exit conditions. It was shown that condensation regions could be predicted and the mixture properties after condensation could also be evaluated.

Merheb et al. **[44]** has took a novel approach to measuring fouling of plate heat exchangers. Their investigations have centred on using low frequency acoustic waves passed/ propagated through the plate heat exchangers and results measured. It was shown that levels of fouling were affected by low frequency waves, thus a measurement could made in situ.

Although the application of this principle was aimed at the food industry, it may be possible to apply such principles to aircraft heat exchangers if it could be determined that PM_{10} was similarly susceptible to acoustic wave energy.
Such an observation could be of interest later during the research should new methods for analysing total deposition on a heat exchanger become of importance.
Intellectual consideration, research and study to fouling of heat exchangers has been cited by Bott **[45]** as a result of the 1970's oil crisis, where the effects of heat exchanger fouling became of commercial interest due to the increase of unit cost of energy. Maintenance is known to have an operational effect on heat exchanger fouling rates, specifically considered by Kuoasa et al. **[46].** The heat exchanger used recovered kinetic energy (heat) from Biomass combustion, with a Stirling engine (fig. 15), yet the efficiencies of such a system are limited due to the fouling nature of the exhaust gases within the heat exchanger. Kuoasa considered the optimal cleaning interval of the heat exchangers for the system comparing some simulation with practical results. The model considered included weighting for power demand and the unit cost of electricity.

The effects of gas speed particulate fouling was investigated by Abd-Elhady et al. **[47]** where it was shown that fouling fluid has a minimum velocity below which, significant rates of fouling occur due to the matter settling on the heat exchanger.
Their observation is in keeping with the operational aircraft failures, where fouling appears to be most significant whilst the aircraft is on the ground due to high rates of particulate matter in the ambient air and low speeds of mechanical fans blowing ambient air over the heat exchanger matrixes.

3.4 Fouling and a cleaning routine

An optimal cleaning schedule was considered by Markowski and Urbaniec **[48]** based upon the knowledge that process plants incorporating heat exchangers networks for heat recovery, fouling of heat-transfer surfaces, hindered the correct production activities and latterly increased energy consumption thus giving rise to higher than acceptable costs. Such costs (or losses if considering profit and loss accounting) could be reduced if on-line cleaning of heat exchangers would be considered.
The scheduling of cleaning interventions on the individual exchangers in the Heat Exchanger Network (HEN) was based on a prior knowledge of the time behaviour of the thermal resistance of fouling. The mathematical model of the influence of fouling on heat exchanger and HEN operation was discussed and an example of its application was included in the publication.
The application of this academic work is likely to be helpful once a greater understanding of the fouling models have been established and validated for the project. The validated models could then be used to predict the optimal cleaning schedule for the operational aircraft to maximise technical dispatch reliability.
Leo and Perez-Grande **[49]** considered the optimisation of a aircraft environmental controls. A latter and more significant paper by Leo and Perez-Grande **[50]** considered the thermodynamic/ economic operation of an aircraft environmental system, as shown in fig. 16.

The environmental control system (ECS) of an aircraft was treated by the authors to be considered as a single component (a black box unit), and the cost per unit of energy of the conditioning stream entering the passenger cabin was considered for a range of aircraft engine bleed pressure values. A minimum cost was suggested for a given pressure, which was close to the nominal bleed pressure. The thermodynamic and economic data discussed were values obtained from live operations – from in-service equipment. The model proposed suggested that the operating costs were due primarily to the fact the ECS has a given mass, and therefore an associated weight fuel burn associated as such: The authors stated that onboard aircraft ECS is a special feature of this system (namely not being a fixed static device) and it was proposed that as such they were significantly different from other thermal devices.

4. Electrostatics

Electrostatics filters are used in a range of applications including domestic air conditioning. However, their application to aircraft heat exchangers within an aircraft pack, to prevent fouling, has not been investigated.

4.1 Electrostatic attraction/ precipitation

Barona, Cha and Jung **[51]** investigated negatively charged Polyvinylidene Difluoride (PVDF) microfiltration membranes were prepared using direct sulfonation with chlorosulfonic acid. The fouling phenomena and rejection was observed to increase on the membrane, when it was electrostatically charged. The World Bank Group **[52]** considered the effects of airborne particulate matter, in terms of pollution prevention and control. The Bank cites emission control using electrostatic precipitors (ESPs) being specifically effective removing/ collecting fine particulates. Recognition by the World Bank using ESP to remove fine airborne particulate does suggest that the technology and equipment is available and should be considered as means to prevent fouling of the heat exchanger in this study.

A commercially available industrial system is made by Wheelabrator Air Pollution Control Inc. (USA) **[53]**, being a modification of the ESP process with an enhancement using irrigation to clear the collector plates, as shown in fig. 17.

4.2 Electrostatic precipitation in transportation

Saiyasitpanich et al. **[54]** investigated the removal of diesel particulate matter using wet ESP. The paper is of specific interest as experimental conditions are cited: An applied DC voltage 70kV, the corona current 3 mA, collecting area $0.312m^2$ and latterly the effect of gas velocity on particulate removal efficiency. It was found that at a constant ESP voltage and diesel particulate production rate (constant load on test engine) an increase of gas residence within the wet ESP led to a significant increase in total particulate removal efficiency. The need for new methods employing ESP to remove particulate matter from PM_{10} to $PM_{2.5}$ was identified by Chang **[55]**, where current industrial methods were reviewed for their suitability. As Chang's paper focused mostly on industrial coal fired plants, the proposed means of removal of fine $PM_{2.5}$ was identified by use of several systems (Pulsed corona, corona shower, electron beam). A multi-system approach to remove $PM_{2.5}$ is unlikely to be proposed by this review as a final solution due to regulations regarding to weight constraints. Schmatloch and Rauch **[56]**, employed a single wire electrode to form an ESP in an exhaust flue: At voltages above 20 kV, the paper comments that unwanted sparking and electrical discharge occurred. This difficulty will need to be considered carefully, as the possibility of sparking (due to an excessive voltage) in an aircraft would potentially limit the solution and produce erosion of materials leading to further material fouling the heat exchanger surfaces.

4.3 Electrostatic attraction/ precipitation

Ahn YC **[57],** further investigated fouling for domestic air conditioning heat exchangers and experimentally considered the effects of loss of pressure on a heat exchanger (due to fouling), the rate of fouling and latterly means of employing protection including the use of electrostatic filtration. Ahn found that the additional costs of fouling included a loss of thermal performance, cost of cleaning the fouled exchangers and cost of protective means employed. Invisible costs due to fouling included a loss of service of the unit, bacterial infections leading to decontamination, contingency costs for replacement units and the cost of maintenance. Ahn suggests that the ESP means provided significant means of preventing fouling, but the cost of employing such means from additional energy consumptions was only financially feasible after an operation period of seven years in the domestic environment, as shown in fig. 18.

Clearly, the domestic operation environment of Ahn's heat exchangers is significantly less hostile than the external conditions as described previously around an airfield, which would validate operational aircraft exchanger failure at present being in operational service for periods of less than a year and "failing" due to exchanger fouling.

4.4 Electrostatic precipitation potential application to aircraft heat exchanger pack fouling in the ram air stream

It is the authors' belief that condensed water (that is presently discharged directly onto the cooling fins of the aircraft heat exchanger), could be redirected to the proposed electrostatic collector plate forward of the exchanger, thus a similar irrigation process would ensure the continued reliability of the proposed system (modification) with little or no moving parts or required human intervention.
Careful consideration however must be given to the possible effects of multiple corona discharge wires and respective plates, given the likely location of the unit to other aircraft systems. It would seems likely that high intensity radio frequency interference may be caused should such a unit become operational, and this in turn could pose a safety concern to radio communication fitted to the aircraft. Likewise, the proximity of the fuel tanks and pipes containing kerosene (Jet A-1) must not be discounted.

5. Conclusion

This paper initially considered the fouled heat exchangers and associated effects of thermal resistance.

The following points of conclusions can be drawn:

- The deposition materials on the heat exchanger are small aerosol particles from ultra fine to larger PM_{10}
- Government monitored levels of airborne PM_{10} around London City and Heathrow airport, defined sources of PM_{10} produced by the transportation sector (and aviation sector) namely road traffic, aircraft operations & associate aircraft equipment.
- The velocity of air containing particulate matter affects the rate of deposition in that at low Re values deposition rates increase. Furthermore, electrostatic filters work more effectively at low Re values, as the charging process is inversely proportional to Re.
- Electrostatic protection filtration employed domestically/ commercially have long "break even" periods due to the relatively clean environment. It is expected, however, that such filters will be more economically viable, in terms of shorter payback periods, in the more hostile environment in which aircrafts operate.
- The aircraft heat exchanger systems are significantly more sensitive to fouling and effects that other known systems, therefore further study in this field is required especially to examine the benefits of using electrostatic filters.

Although there is a wealth of papers pertaining to HVAC and heat exchanger plate fouling, there is minimal material directly written pertaining to the field of aerospace, specifically in air-conditioning systems.
The employment of electrostatic precipitation (ESP) as a means of prevention does appear to be a proven industrial method in non-aerospace applications. Special consideration should therefore be given to employing ESP to remove particulate matter that is known to cause operational aircraft problems.
Specific consideration when using ESP as means of protection must include additional effects, such as production of ozone gas and other unwanted compounds (ionisation of volatile organic compounds) from the charged plates, and sparking/ arcing of plates (due to excessive potential voltages) which would introduce new pollutants.

Further experimental work is required to establish the rates of fouling of PM on aircraft heat exchangers so a correlation could then be made to understand the rate with temporal variation effecting thermal resistance. Once this is achieved, a comparison to ESP could be made, to evaluate the effectiveness of this system, which in turn could lead to predictions on operational "on-wing" air conditioning system reliability.

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Figures

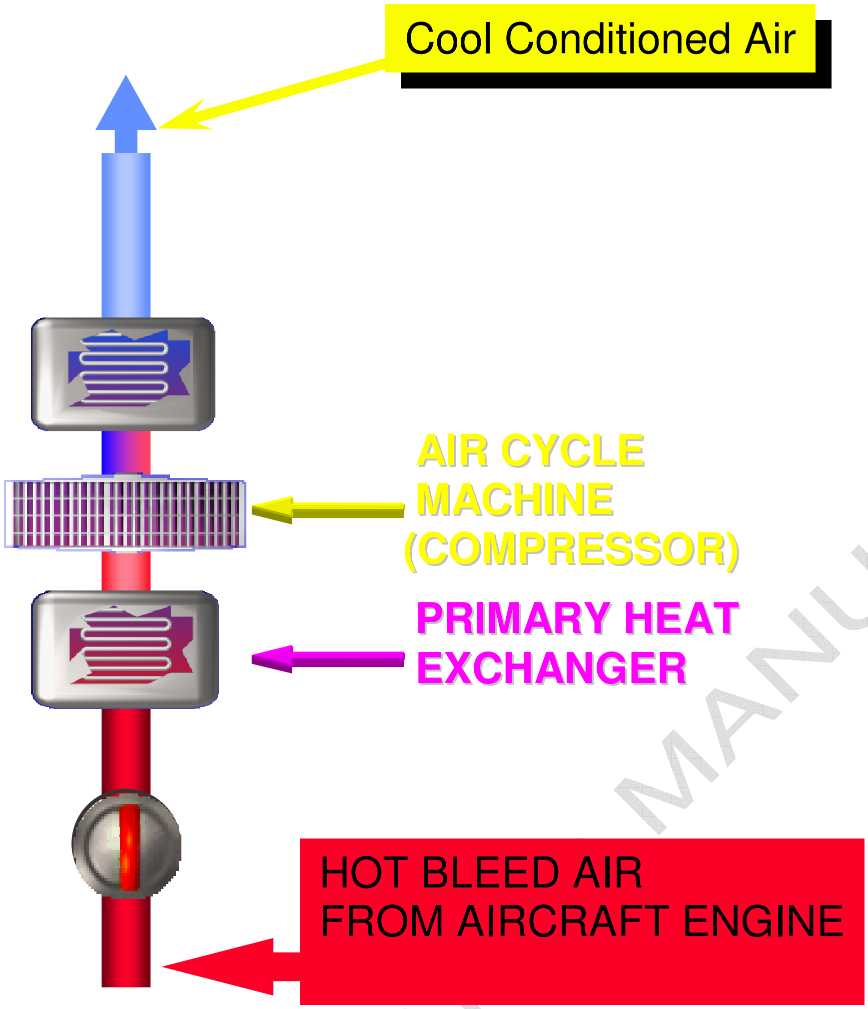


Figure 1 – Airbus air conditioning schematic VACBI [2]

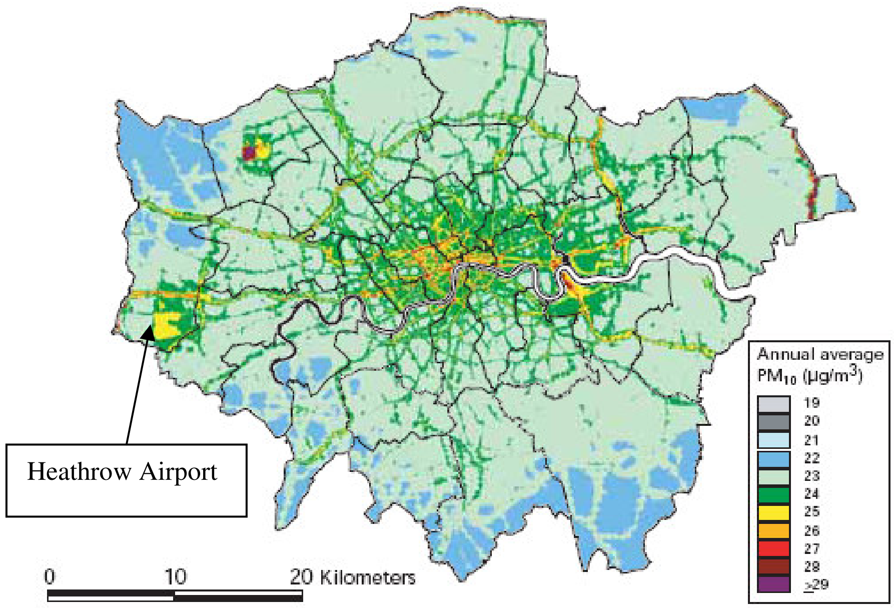


Fig. 2 – 2004 PM_{10} concentrations London [5]

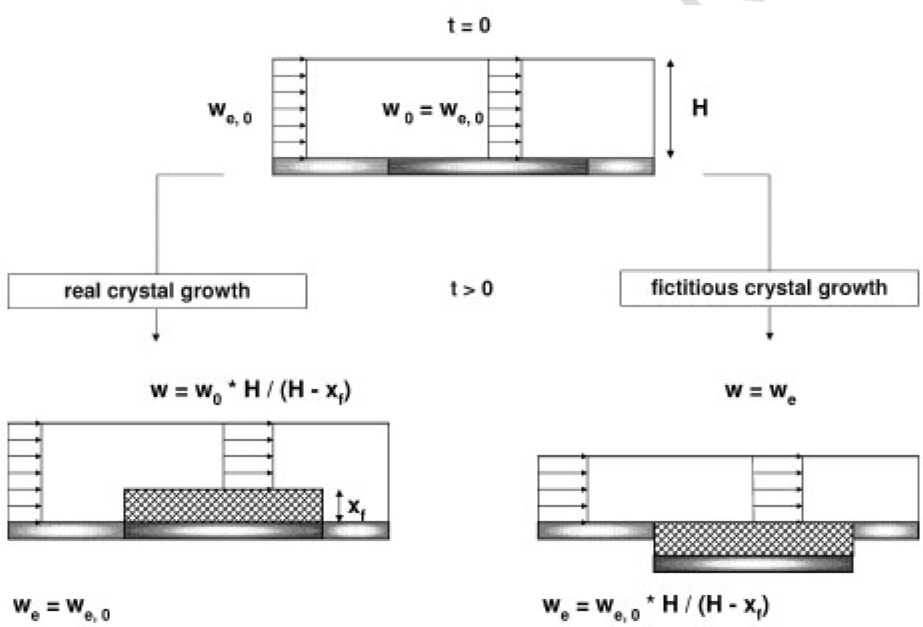


Fig 3. Schematic presentation of the fictitious crystal growth. [7]

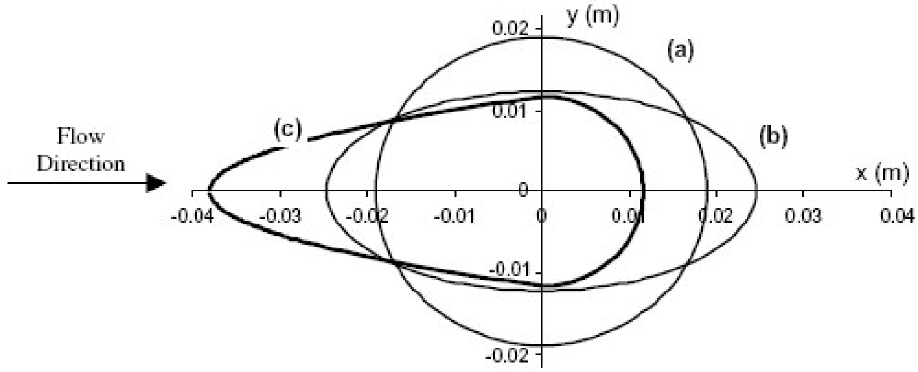


Fig. 4 Three different tube cross-sections: (a) Standard circular tube, (b) elliptic cross-section with a 2:1 axis ratio and (c) the proposed deposit determined tube shape (DDEFORM) [25]

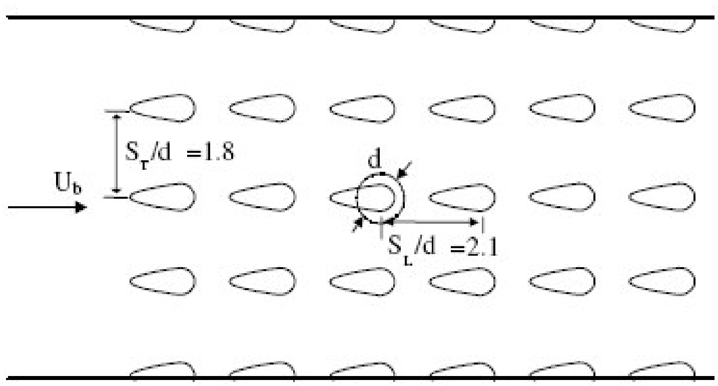


Fig 5. DDEFORM tubes at half transverse spacing [25]

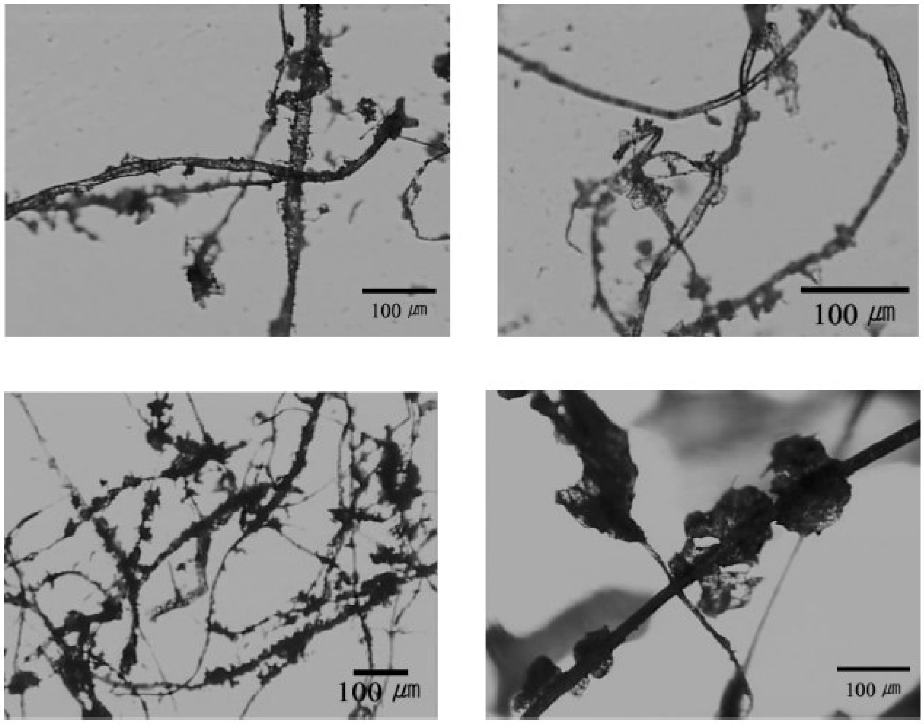


Fig. 6 – fouling particles attached to pre-filters[26].

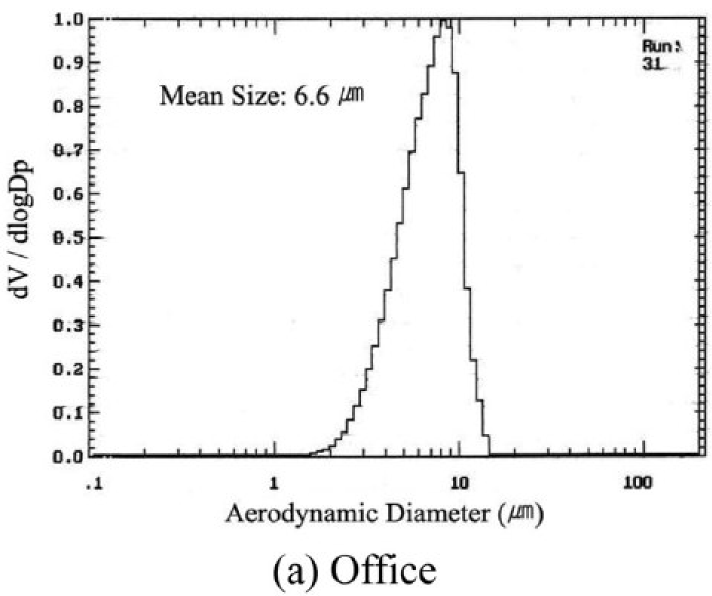
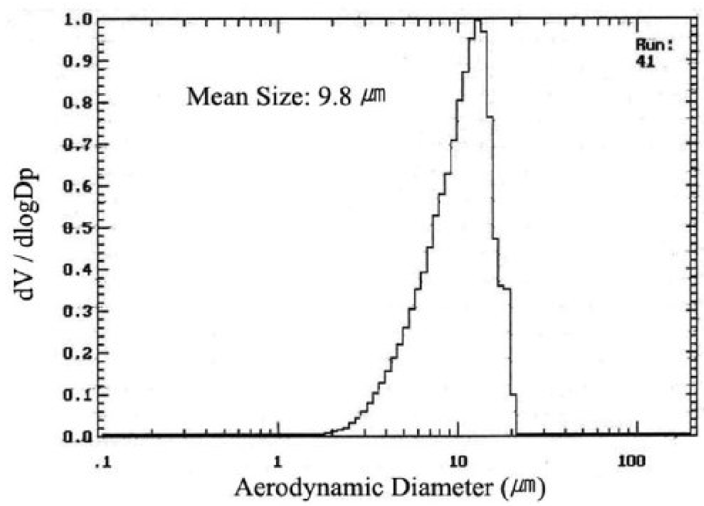
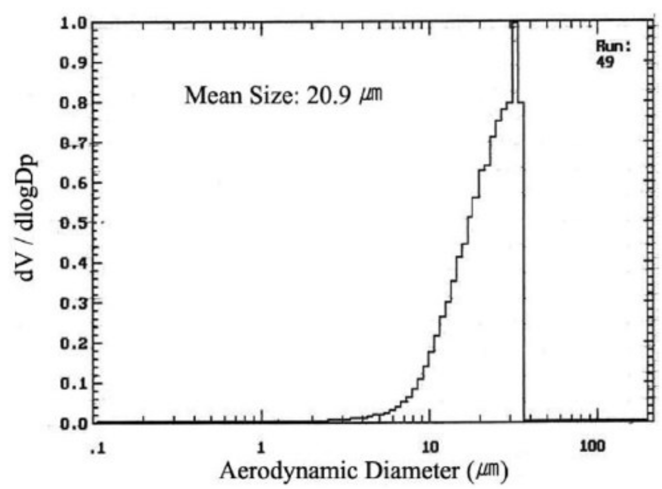


Fig. 7 – Size distribution of fouling in an office heat exchanger [26]



(b) Restaurant

Fig. 8 – Size distribution of fouling in an restaurant heat exchanger [26]



(c) Seaside inn

Fig. 9 – Size distribution of fouling in a seaside inn heat exchanger [26]

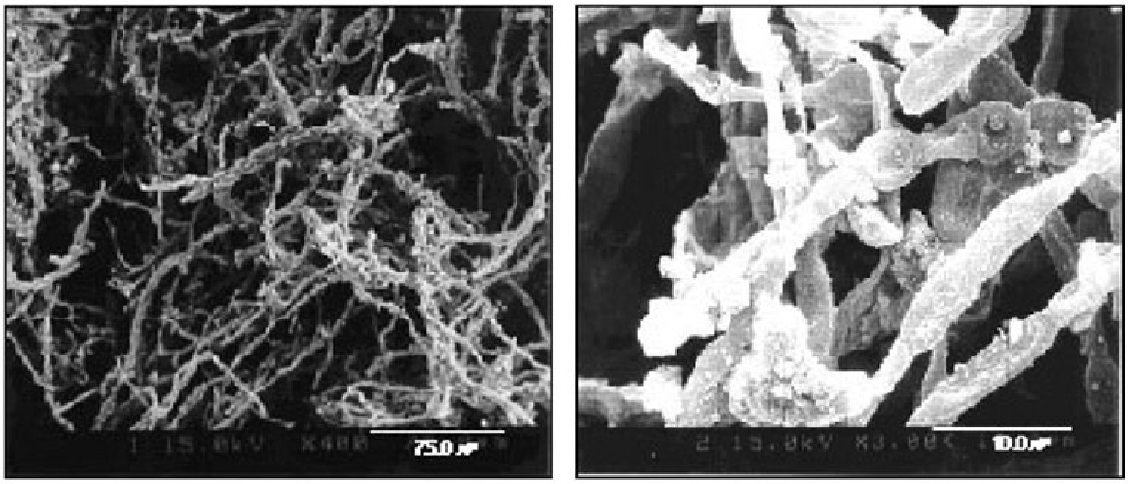


Fig. 10 – SEM images (varying magnification) of office fouled evaporator [26]

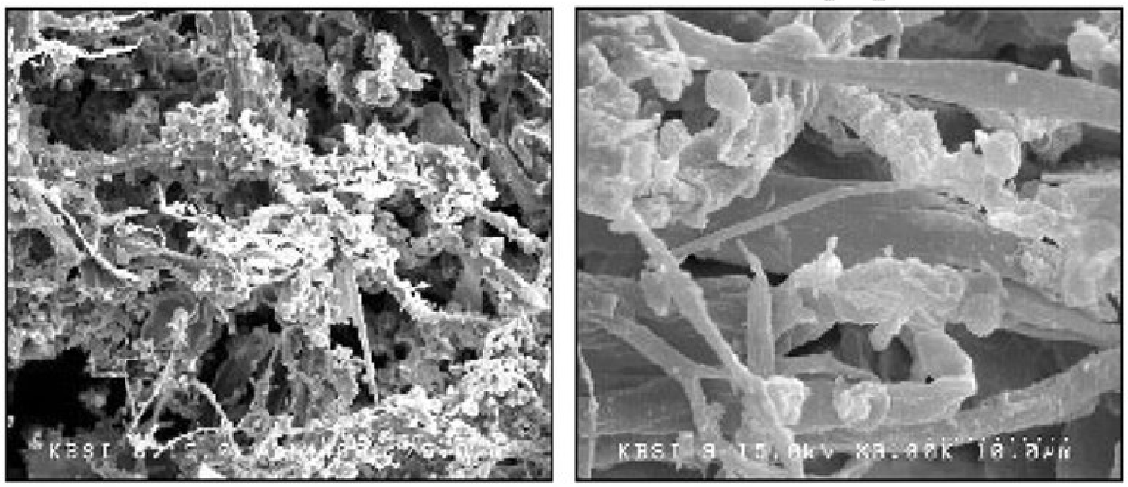


Fig. 11 – SEM images (varying magnification) of restaurant fouled evaporator [26]

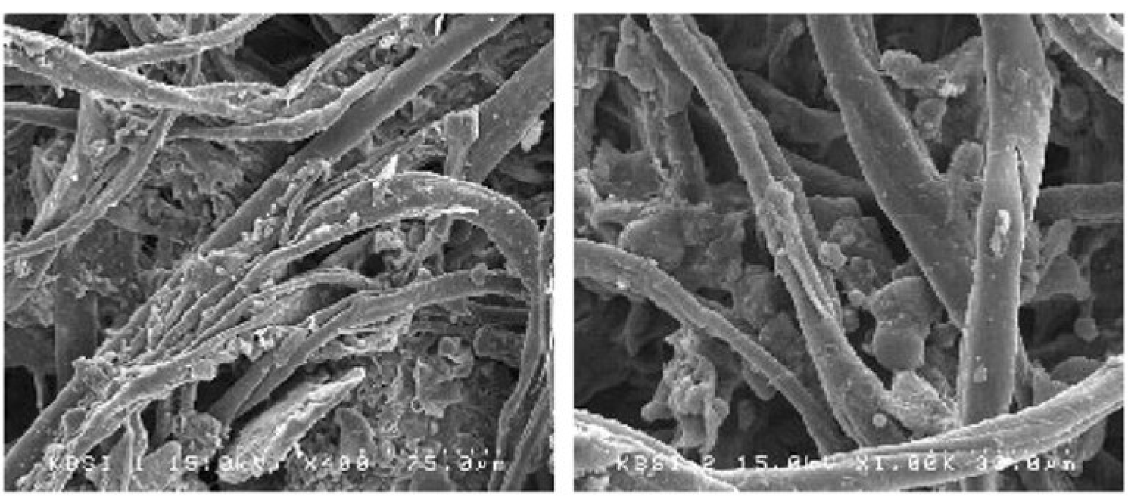


Fig. 12 – SEM images (varying magnification) of seaside fouled evaporator [26]

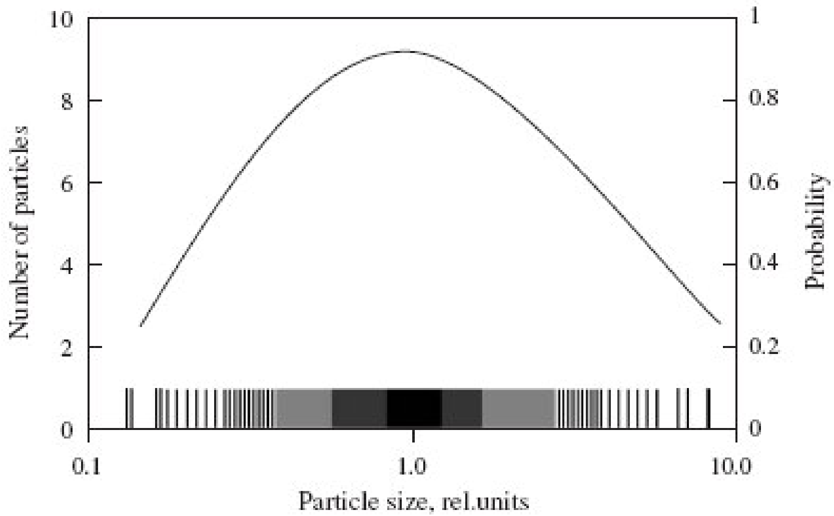


Fig. 13 - Continuous probability density function and discrete size distribution function: solid line—pdf (r) (right axis) [27]

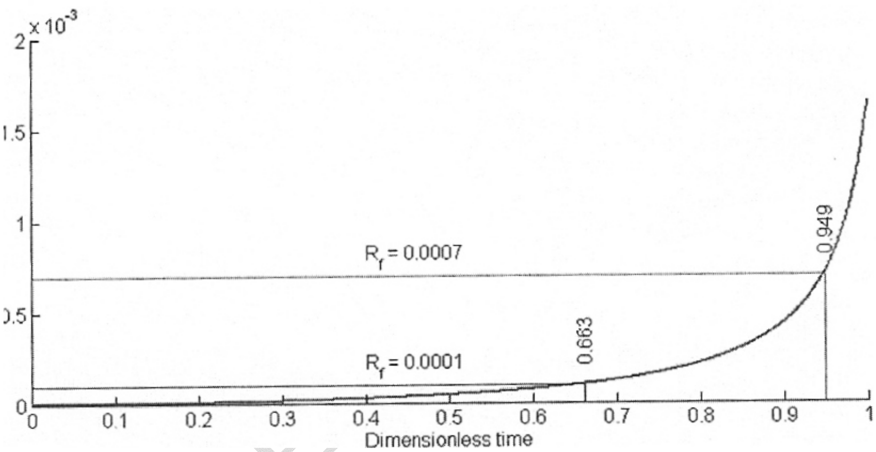


Fig. 14 – Fouling factor verses time (dimensionless time) [33]

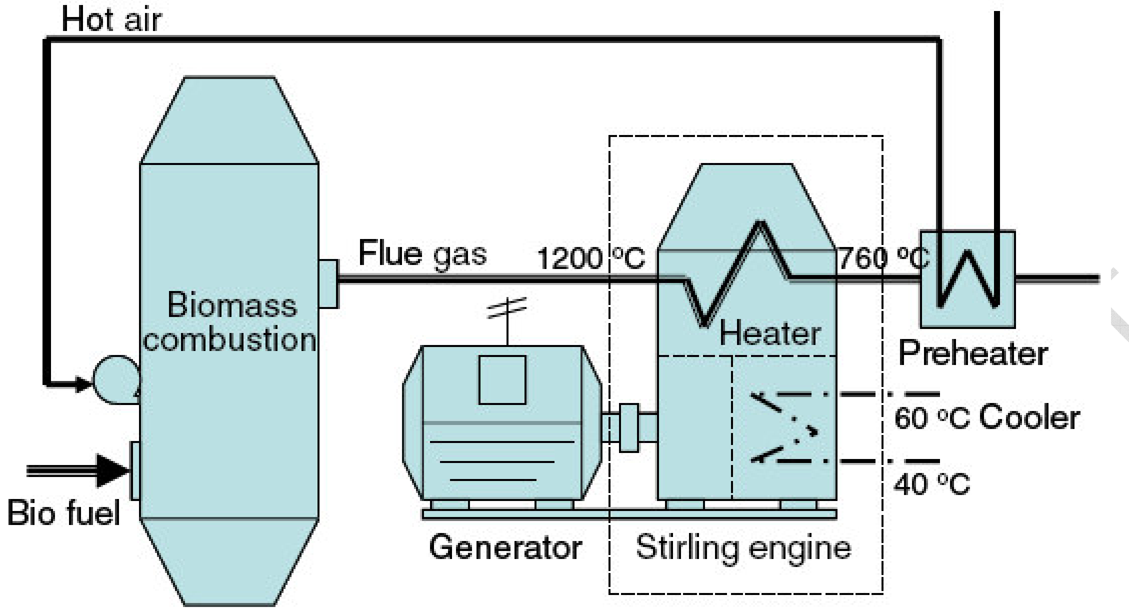


Fig. 15 – The Stirling engine and generation source [46]

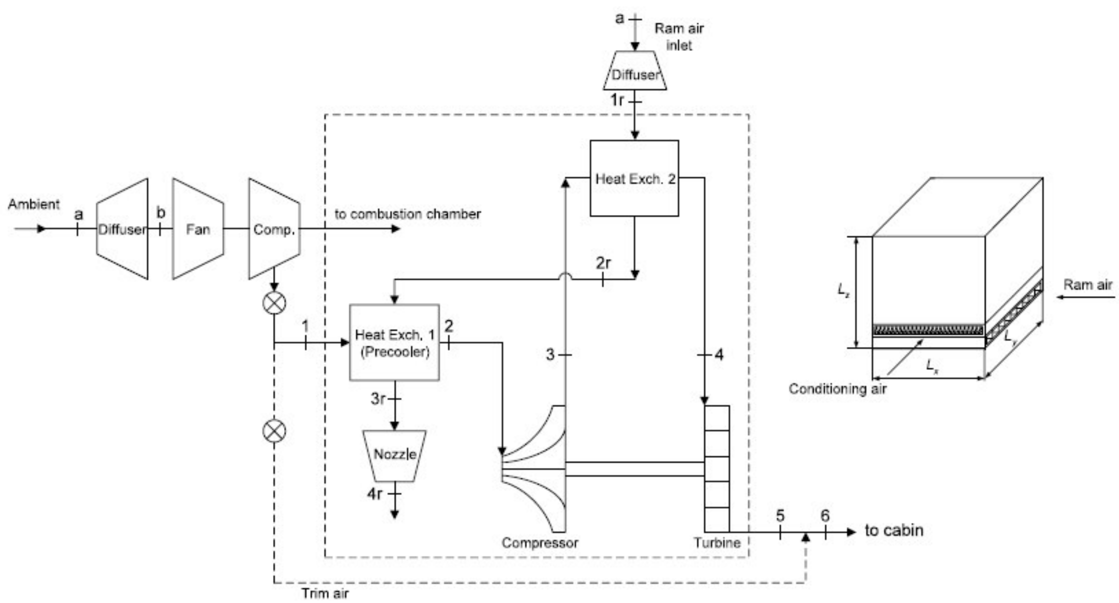


Fig. 16 – Typical Environmental Control System of an aircraft, and detailed view of the cross flow heat exchanger [50].

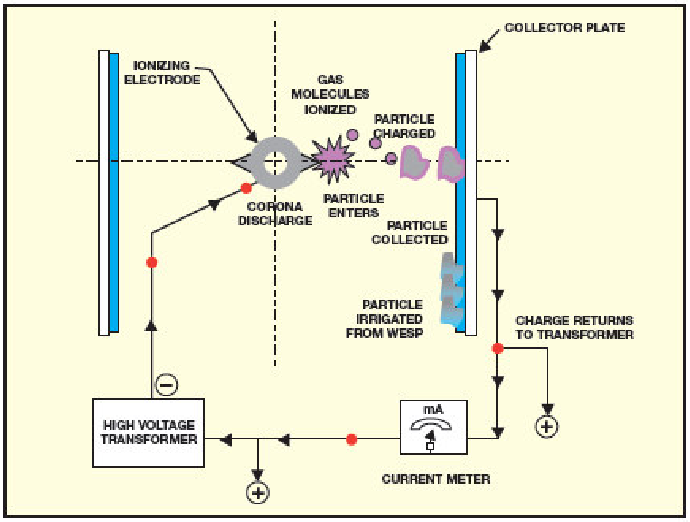


Fig. 17– Wet Electrostatic Precipitation, Wheelabrator Air Pollution Control Inc [53]

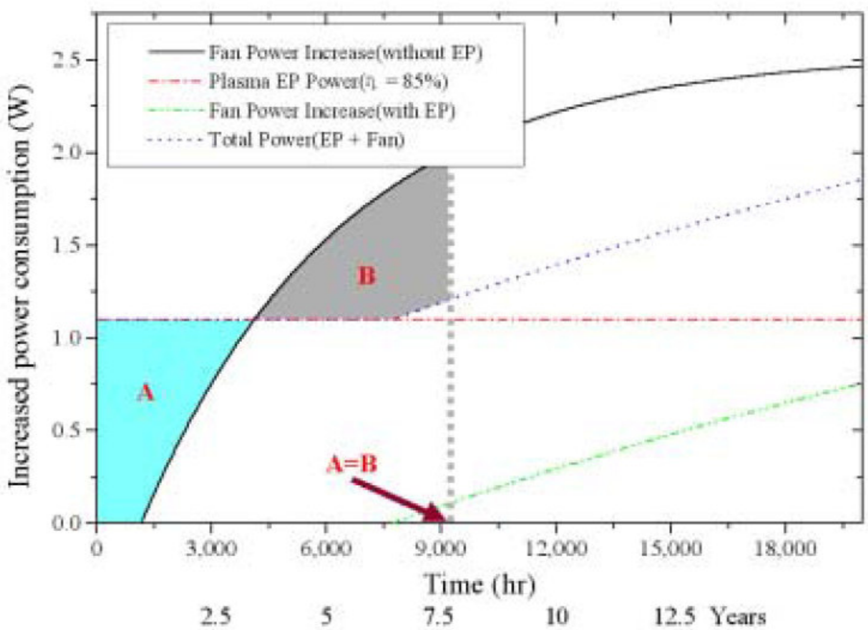


Fig. 18. Power consumption with and without anti fouling [57]

Tables

Primary components	Sources
Sodium chloride	Sea salt.
Elemental carbon	Black carbon (soot) is formed during high temperature combustion of fossil fuels such as coal, natural gas and oil (diesel and petrol) and biomass fuels such as wood chips.
Trace metals	These metals are present at very low concentrationsand include lead, cadmium, nickel, chromium, zinc and manganese. They are generated by metallurgical processes, such as steel making, or by impurities found in or additives mixed into fuels used by industry. Metals in particles are also derived from mechanical abrasion processes, e.g. during vehicle motion and break and tyre wear.
Mineral components	These minerals are found in coarse dusts from quarrying, construction and demolition work and from wind-driven dusts. They include aluminium, silicon, iron and calcium.
Secondary components	**Sources**
Sulphate	Formed by the oxidation of sulphur dioxide (SO_2) in the atmosphere to form sulphuric acid, which can react with ammonia (NH_3) to give ammonium sulphate.
Nitrate	Formed by the oxidation of nitrogen oxides (NO_x – which consists of nitric oxide (nitrogen monoxide, NO) and nitrogen dioxide (NO_2) in the atmosphere to form nitric acid, which can react with NH_3 to give ammonium nitrate. Also present as sodium nitrate.
Water	Some components of the aerosol form of particulate matter, such as ammonium sulphates and ammonium nitrates, take up water from the atmosphere.
Primary and secondary components	**Sources**
Organic carbon	Primary organic carbon comes rom traffic or industrial combustion sources. Secondary organic carbon comes from the oxidation of volatile organic compounds (VOCs). There may be several hundred individual components. Some of these trace organic compounds, such as certain polycyclic aromatic hydrocarbons, are highly toxic.

Table 1 – Sources of Particulate Matter [5]

	Applications			
	Indoor unit		Outdoor unit	
Elements	Office	Restaurant	Seaside inn	Seaside inn
O	64.29	44.59	52.40	46.37
Al	10.58	11.67	11.11	19.25
Si	13.36	21.42	21.41	8.58
K	2.16	1.91	3.40	1.13
S	—	2.80	—	3.70
Na	—	—	—	2.97
Cl	—	—	—	1.83
Ca	3.05	4.06	1.55	3.90
Fe	6.56	13.54	10.14	6.55
Zn	—	—	—	5.72
Total	100	100	100	100

Table 2 – Chemical components of fouling in heat exchangers [26]