A Comparative Study of Helicopter Engine Particle Separators

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Particle separators are fitted to helicopter engine intakes to remove potentially harmful dust from the influent air. Their use is necessary in desert environments to eliminate the risk of rapid engine wear and subsequent power deterioration. However, their employment is concomitant with an inherent loss in inlet pressure, and in some cases auxiliary power. There are three main technologies: vortex tubes; barrier filters; and integrated inlet particle separators. The present study compares the pros and cons of each device, applying where possible analytical theory, and using computational methods to generate performance data. The vortex tube separators are found to achieve the lowest pressure drop, while the barrier filters exhibit the highest particle removal rate. The integrated inlet particle separator creates the lowest drag. The barrier filter and vortex tube separators are much superior to the integrated particle separator in improving the engine lifetime, based on erosion by uncaptured particles. The erosion rate predicted when vortex tube separators are used is two times that of a barrier filter, however the latter experiences a temporal (but recoverable post-cleaning) loss of approximately 1% power.

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## Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>AC</td>
<td>Air Cleaner</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<tr>
<td>EAPS</td>
<td>Engine Air Particle Separator</td>
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<tr>
<td>IBF</td>
<td>Inlet Barrier Filter</td>
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<tr>
<td>IPS</td>
<td>Integrated Inlet Particle Separator</td>
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<tr>
<td>LIF</td>
<td>Life Improvement Factor</td>
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<tr>
<td>MGT</td>
<td>Mean Gas Temperature</td>
</tr>
<tr>
<td>MTBO</td>
<td>Mean Time Between Overhaul</td>
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<tr>
<td>MTBR</td>
<td>Mean Time Between Removal</td>
</tr>
<tr>
<td>PSD</td>
<td>Particle Size Distribution</td>
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<tr>
<td>RANS</td>
<td>Reynolds-Averaged Navier-Stokes</td>
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<tr>
<td>RPM</td>
<td>Revolutions Per Minute</td>
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<tr>
<td>VTS</td>
<td>Vortex Tube Separator</td>
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</tbody>
</table>

- \( A \) = area \( (m^2) \)
- \( c_m \) = particulate mass concentration by mass (-)
- \( c_v \) = particulate mass concentration by volume \( (kgm^{-3}) \)
- \( C \) = viscous resistance coefficient \( (m^{-2}) \)
- \( d \) = diameter \( (m) \)
- \( D \) = drag \( (N) \)
- \( D \) = inertial resistance coefficient \( (m^{-1}) \)
- \( D_H \) = hydraulic diameter \( (m) \)
- \( E \) = overall efficiency (-)
- \( H \) = pitch \( (m) \)
- \( k_r \) = engine erosion factor (-)
- \( k_v \) = volume shape coefficient (-)
- \( \dot{m} \) = mass flow rate \( (kgs^{-1}) \)
- \( n \) = number of particles (-)
\( N_p \) = number of particle size groups (-)

\( P \) = total pressure (Pa)

\( q \) = dynamic pressure (Pa)

\( Q \) = volume flow rate (m\(^{-3}\)s\(^{-1}\))

\( r \) = radial position (m)

\( R \) = radius (m)

\( Re \) = Reynolds number (-)

\( S \) = scavenge proportion (-)

\( U \) = velocity (ms\(^{-1}\))

\( W \) = power (W)

\( W_r \) = power degradation rate (Ws\(^{-1}\))

\( x \) = particle diameter (m)

\( Z \) = depth (m)

\( \alpha \) = filter packing fraction (-)

\( \beta \) = engine erosion correlation component (-)

\( \epsilon \) = porosity (-)

\( \phi \) = ingested particle diameter (m)

\( \eta \) = grade efficiency (-)

\( \kappa \) = dynamic shape factor (-)

\( \mu_g \) = gas viscosity (kgm\(^{-1}\)s\(^{-1}\))

\( \rho \) = density (kgm\(^{-3}\))

\( \sigma_g \) = geometric standard deviation (-)

\( \nu \) = void function (-)

\( .0 \) = initial

\( .a \) = of engine inlet

\( .co \) = of collector

\( .core \) = of core flow
\[ C \] = of cake
\[ d \] = diffusional
\[ eff \] = effective
\[ E \] = of single fibre (efficiency)
\[ f \] = of fibre
\[ fed \] = quantity fed
\[ F \] = of filter
\[ h \] = of helix
\[ i \] = inertial
\[ m \] = by mass
\[ p \] = of particle
\[ pc \] = of collected particulate
\[ pe \] = escaped/unfiltered particulate
\[ e \] = recovered
\[ s \] = sieving
\[ scav \] = scavenge
\[ t \] = of tube
\[ v \] = of separating region
\[ v \] = by volume
\[ v g \] = volume geometric
\[ z \] = axial component
\[ \theta \] = tangential component
\[ \infty \] = freestream
\[ ^{+} \] = dimensionless
\[ ^{'} \] = corrected
I. Introduction

Dusty environments are found all across the globe, as a result of millions of years of wind erosion and other geomorphological processes. Thanks to their operational versatility and ability to land on unprepared sites, helicopters frequently encounter such environments. In certain areas of operation the dry and dusty conditions are found at high altitudes, where the air is less dense and sometimes hotter. This medley of harsh conditions can be particularly troublesome to a helicopter engine, which must continue to deliver required power for the task in hand. If no protection is provided to the engine, the performance deteriorates rapidly due to damage by sand and dust. If there is any loose sediment around the landing site, it is likely to be disturbed from rest by the rotor downwash as the helicopter lands or takes off. If the sediment is small enough, a dust cloud forms and the chances of particle ingestion are increased. The degree of ingestion is dependent on a number of factors that relate to the properties of the sand, the properties of the rotorcraft, and the location of the intake with respect to the rotor disk. Once it is established that a helicopter needs protection from sand ingestion, there are three main technologies available to implement at the engine intake, all of which vary in their method of separating particles. The technologies are commonly referred to as Engine Air Particle Separators (EAPS) or eeps. Two are retro-fit devices integrated into the engine intake architecture as an option for the operators, while the third type is designed into the engine inlet as an integral component. The three devices are:

1. Vortex Tube Separators (VTS), that rely on centrifugal forces created by cyclone-like systems (Fig. 1a).

2. Integrated Inlet Particle Separators (IPS), that rely on rapid change in curvature of the inlet geometry (Fig. 1b).

3. Inlet Barrier Filters (IBF), that rely on a permeable fabric panel in front of the inlets to arrest the particles (Fig. 1c).
The mechanism of capture or scavenge, the typical flow rates, and the size of each device is different. Therefore, it is unsurprising that device performance varies. Table 1 gives a qualitative overview of each device’s advantages and disadvantages. However, from an engineering perspective, qualitative analysis will not suffice. The aim of this study is to implement the results of the prediction of each device’s performance into a new comprehensive method for quantitative comparison. New EAPS performance indices are then used to ascertain the most suitable form of engine protection in dusty environments.

The two key variables used to assess device performance are separation efficiency and pressure drop, from which further performance indicators can be extrapolated. The separation efficiency is often quoted as a single figure for a particular test sand, but the effectiveness of a device at removing a particle is dependent on the particle size and shape, of which there is a great range within the spectra of dusts around the globe. The design of an effective particle separating device should therefore consider a target dust size to be filtered, as superior separation efficiency is invariably attained at the expense of pressure loss. In the present work, theory is presented to calculate the separation efficiency and resultant pressure drop of an assumed EAPS design, when used to protect a test case engine from damage by a fixed composition test dust. A method is then presented to determine the size distribution of the particulate that evades capture by each device and subsequently degrades the engine.
### Table 1 The main advantages and disadvantages of each EAPS system.

<table>
<thead>
<tr>
<th>EAPS Device</th>
<th>Advantages</th>
<th>Disadvantages</th>
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</thead>
<tbody>
<tr>
<td>Vortex Tube Separators (VTS)</td>
<td>• Low pressure drop.</td>
<td>• High drag since large area required to achieve mass flow.</td>
</tr>
<tr>
<td></td>
<td>• High separation efficiency.</td>
<td>• Icing issues.</td>
</tr>
<tr>
<td></td>
<td>• Bypass door available if needed.</td>
<td>• Susceptible to FOD.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Scavenge pump required.</td>
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<tr>
<td></td>
<td></td>
<td>• Inlet mass flow extracted to scavenge particles (≃ 5-10%).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Integration difficulties.</td>
</tr>
<tr>
<td>Integrated Inlet Particle Separators (IPS)</td>
<td>• High airflow per unit area, hence low drag.</td>
<td>• Relatively low separation efficiency.</td>
</tr>
<tr>
<td></td>
<td>• Easily integrated to engine inlet face.</td>
<td>• Inlet mass flow extracted to scavenge particles (≃ 15-20%).</td>
</tr>
<tr>
<td></td>
<td>• Low total pressure distortion.</td>
<td>• No bypass capability.</td>
</tr>
<tr>
<td></td>
<td>• Ease of optimisation.</td>
<td>• Scavenge pump required.</td>
</tr>
<tr>
<td>Inlet Barrier Filters (IBF)</td>
<td>• Very high, temporally increasing separation efficiency.</td>
<td>• Temporally increasing pressure drop due to particle accumulation.</td>
</tr>
<tr>
<td></td>
<td>• Reduction of total pressure distortion.</td>
<td>• Maintenance heavy, thus more time-on-ground (for cleaning).</td>
</tr>
<tr>
<td></td>
<td>• No scavenge mass flow.</td>
<td>• Large surface area required to minimise pressure drop.</td>
</tr>
<tr>
<td></td>
<td>• No bleed flow required thus lower MGT over engine lifetime.</td>
<td>• Integration difficulties.</td>
</tr>
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</table>

Engine degradation by particle ingestion takes many forms, afflicting each stage of the engine. The compressor blades bear the brunt of the damage, suffering erosion of leading and trailing edges, blunting of tips, and roughening of pressure surfaces. At the combustor, impurities in the dust can reach temperatures high enough to change state and adhere to the walls leaving a layer of glaze, which reduces the flow area. A similar process occurs at the turbine blades, whose cooling vents may also become clogged, leading to an increase in the mean gas temperature (MGT). Aside from the obvious loss in efficiency caused by particle agglomeration on the blades, the higher working temperature also reduces component lifetime, leading to increased rejections, overhauls, and ultimately heightened...
cost. EAPS device are therefore of great benefit to operators. The present work demonstrates this benefit by comparing the degradation of an unprotected engine with the loss in power experienced when employing a particle separator.

II. Background

The issue of particulate ingestion is synonymous with an operational situation known as “brownout”. Brownout is a very serious problem for helicopter pilots. It occurs when the helicopter is landing or taking off above a loose sediment bed such as the desert floor. In dusty environments, the impingement of the wake flow and the tip vortices on the ground causes particles to be disturbed from the sediment bed, leading to the formation of a dust cloud. The dust cloud is a dangerous event for the pilot. As the intensity increases, a situation known as degraded visual environment (DVE) occurs, whereby the pilot loses the spatial orientation cues required to safely fly the aircraft.

It has been reported that the occurrence of brownout is the primary cause of human factor related mishaps during military operations [1], causing losses of aircraft and personnel [2]. The problem is not limited to airworthiness issues; blade erosion and wear on various mechanical parts, and a deterioration of engine performance due to the ingestion of particulate are also caused by brownout clouds. The latter of these is of the greatest interest in the present work.

If viewed under a microscope, a sample of desert sand would exhibit a dispersion of particle diameter, shape, hardness and mineral composition, all of which are important properties for the prediction of EAPS performance and engine deterioration. The range of diameters is represented by a particle size distribution (PSD) which describes the proportion by mass, number or other dimension of a given particle size. The PSD at the engine intake is dependent on the mechanisms causing the formation of the brownout cloud. There is a great multitude of variables involved in the generation of the brownout cloud, and in practice it takes good pilot handling to mitigate the associated risks. Certainly in any event, it is likely that some particles will arrive at the engine intake, and must be removed before reaching the engine to at least ensure that the power supplied does not rapidly degrade. The EAPS devices available to perform this task are described in the foregoing.
A. Particulate Ingestion

If the diameter of each particle in a dust sample be determined, then a range of diameters of varying quantity would be found. This is called a particle size distribution. The common approach is to split the sample into size bands and measure the number or mass of particles within a size band. The result is a curve that illustrates the proportion of each size band relative to the whole sample. This curve can be expressed algebraically, or manipulated to show other properties of the distribution. This data is important to EAPS design because it can inform the designer of which are the most abundant particles in a given area, allowing the device to be tailored accordingly. It may also permit more accurate predictions of engine wear. This information is used to estimate the mass of dust reaching the engine. If incompressible flow is assumed, the mass flow of air-particle mix entering the engine intake system is given by:

\[ \dot{m}_p = c_m \dot{m}_a \]  

(1)

where \( c_m \) is the particulate mass concentration and \( \dot{m}_a \) is the engine mass flow rate. The particulate mass concentration is related to the brownout dust concentration as:

\[ c_m = \frac{1}{\rho_g/c_v + (1 - \rho_g/\rho_p)} \]  

(2)

where \( c_v \) is the particulate volume concentration expressed as mass of particles per unit volume of air-particle mix, and \( \rho_p \) and \( \rho_g \) refer to the particle and air density respectively. Thence Eq. 2 can be used with Eq. 1 to determine the mass of particles reaching the engine based on the local dust concentration, constituent densities (assumed constant) and engine inlet conditions. The mass of all particles in a given size range is:

\[ m_p = k_v d_p^3 \rho_p n \]  

(3)

where \( d_p \) is the particle diameter, \( n \) is the number of particles in that size range, and \( k_v \) is the volume shape coefficient. For spheres, the volume shape coefficient is \( \pi/6 \) (\( \approx 0.524 \)); i.e. it is the
factor that the diameter cubed must be multiplied by in order to give the volume of the shape. For sand it is said to be in the region of 0.26 to 0.28. The mass fraction \( m_{p,i}^+ \), within a size range and compared to the total mass of the distribution, is the mass in the size range divided by the mass of the entire distribution:

\[
m_{p,i}^+ = \frac{k_v d_{p,i}^3 \rho_p n_i}{\sum k_v d_{p,i}^3 \rho_p n_i} = \frac{d_{p,i}^3 n_i}{\sum d_{p,i}^3 n_i}
\]

in which the density and volume shape coefficient are assumed to be constant throughout the all the size grades and can therefore be cancelled. The index \( i \) corresponds to the size range. This is the same expression for volume distribution, since mass scales proportionally with volume. To use Eq. 4, a representative particle diameter is required for the size band; this is usually the mid-point of the grade.

B. Vortex Tube Separators

A single vortex tube, typical of those use to construct the device shown in Fig. 1a is schematically illustrated in Fig. 2. As particulate-laden air enters a vortex tube separator, it is first met by a set of helical vanes, which impart a radial and tangential component of velocity to the flow, inducing swirl. Particles in the air are of greater specific gravity, and so experience a greater centrifugal force in this rotation. Owing to the effects of inertia, this causes the particles to be thrown outwards towards the periphery of the tube. The vanes bestow a similar fate to heavier particles too, by virtue of a design which deflects or trains particles on impact radially outwards. A second, narrower tube in the base of the device physically separates the flow into two streams; the cleaner core air flow continues to the engine inlet whilst the particulate-laden “dirty air” is scavenged to the atmosphere.
As a starting point for low order models and qualitative descriptions of particle separation by vortices, Holdich [3] is a valuable resource. The flow inside a vortex tube separator is complex and not fully understood. Empirical and semi-empirical models have been developed, but their usefulness is often limited to the geometry. Additionally, there are many factors that affect the device performance. The key geometrical design parameters are the helix pitch, number of blades, outer tube diameter, inner tube (known as the collector) diameter, and axial distance between the helix and the collector. Furthermore, the behaviour changes according to the axial velocity, which is a function of mass flow rate. Owing to this large array, much of the literature contains case-specific computational fluid dynamics (CFD) studies verified with experimental results. Klujszo et al. [4] conducted a parametric study on an inline cyclone separator, concluding: that increasing the blade pitch angle improved separation at the expense of pressure drop; that there is a limiting axial velocity for a given tube beyond which separation efficiency does not improve; that gradual turning of the flow reduces pressure loss; and that the implementation of a back cone aft of the helix can enhance performance by displacing a separated flow region in which inadvertent mixing would otherwise draw unwanted particles into the core. However unlike the VTS in Fig. 2, the scavenge chamber in Klujszo’s work was not fluidised. A similar study by Hobbs [5] on a much larger scale demonstrated the case-specific nature of CFD of vortex tubes.

In the present work, the vortex tubes are required to supply a sufficient mass flow of clean air to a helicopter engine. Due to the wide range of intake geometries and engine sizes, it is probable...
that no single design is optimum for all rotorcraft. Therefore a more general analytical model is required that can be used for an initial, low order prediction of VTS performance and can be applied to numerous embodiments of the vortex tube separator. Such a mathematical model was derived by Ramachandran et al. [6] to predict the separation efficiency and pressure drop of an inline cyclone separator. The authors verified the model with experimental data and illustrated a good prediction, despite using simplifying assumptions. The validation was conducted with aerosol particles that migrated radially under centrifugal force, and adhered to the tube walls where they could be counted. This differs from the embodiment shown in Fig. 2, in which particles are captured once they breach a radial position equal to the radius of the inner tube (collector).

1. Pressure Drop

The pressure drop is derived by longitudinally demarcating the tube and summing the losses of each part. In this low order model, the losses are attributed only to wall friction, hence a key dimension of each section is the hydraulic diameter. The loss is calculated from the Darcy-Weisbach relationship for flow through a cylinder:

$$\Delta P = \rho g \frac{fLU^2}{2D_H}$$  \hspace{1cm} (5)

where \( f \) is the friction factor, \( L \) is the section length, \( U \) is the average gas velocity through the section, and \( D_H \) is the section hydraulic diameter. The friction factor is given by [7]:

$$\frac{1}{f} = -1.8 \log \left( \frac{6.9}{\text{Re}_g} \right)$$  \hspace{1cm} (6)

where \( \text{Re}_g \) is the Reynolds number of the cylinder flow, given as:

$$\text{Re}_g = \frac{\rho_g U D_H}{\mu_g}$$  \hspace{1cm} (7)

The tangential component of velocity is set by the pitch of the vanes. The flow velocity thus varies from a minimum at \( r = 0 \) to a maximum at \( r = R_t \), but has an invariant axial velocity component.
The net velocity of the gas is the vector sum of these two components:

\[ u_{VT} = \sqrt{u_t^2 + u_{\theta}^2} = u_t \sqrt{1 + \frac{2\pi r^2}{H_t}} \]  

(8)

where \( H_t \) is the helix pitch, defined as the axial distance travelled by the gas in one revolution of the helix. The average velocity \( u_{avg} \) through the helical section of the tube can be calculated as an area-weighted average of \( u_{VT} \), which simplifies to:

\[ u_{avg} = u_t \frac{4\pi}{3R_t^2 H_t^2} \left[ \left( \frac{H_t^2}{4\pi^2} + R_t^2 \right)^{3/2} - \left( \frac{H_t}{4\pi^2} \right)^{3/2} \right] \]  

(9)

The pressure drop due to the required dynamic pressure through the helix is given by:

\[ \Delta q_h = \rho g \frac{u_{avg}^2 - u_t^2}{2} \]  

(10)

To facilitate calculation of the power required to service the vortex tube, it is split radially into two parts: the core air flow that continues to the engine, and the scavenge flow containing the separated particles. It assumed that the pressure distribution at the collector face is uniform, hence the pressure loss at the entry to both the collector and the scavenge is a summation of the helix pressure loss and the separating region pressure loss; the remaining pressure loss for the collector and scavenge are calculated from Eq. 5 using the respective hydraulic diameters. The pressure drop of the tube core is thus:

\[ \Delta P_{core} = \Delta P_h + \Delta q_h + \Delta P_v + \Delta P_{co} - \Delta P_{ram} \]  

(11)

while the pressure drop of the scavenged proportion of the flow is:

\[ \Delta P_{scav} = \Delta P_h + \Delta q_h + \Delta P_v + \Delta P_s - \Delta P_{ram} \]  

(12)

where the subscript \( h \) refers to the helix section, \( v \) is the separating region (between the helix and the collector), the subscript \( co \) is the collector, and \( s \) refers to the scavenge conduit. \( \Delta P_{ram} \) represents
any static pressure increase gained through ram effects, which occurs if the tubes are facing into
the flow in forward flight. If one considers an array of tubes lying parallel, increasing the number
of tubes per unit area will increase the pressure lost to friction by virtue of the additional internal
surface area.

2. Separation Efficiency

The separation efficiency of a vortex tube is again governed by the pitch of the helix: a larger
turning moment applied to the gas creates a larger tangential drag force on the particle, which
translates to a greater centrifugal force. If the particle tracks far enough radially, beyond the radius
of the collector, it will be separated. The theory is adapted from Ramachandran et al. [6] for
scavenged vortex tubes; a complete derivation is given in [8]. The grade efficiency is defined as the
fraction of particles of a single diameter departing the tube via the scavenge line:

\[
E(x)_{VTS} = 1 - \exp \left( -Q_g \frac{8\pi}{18\mu_g} x^2 \frac{L_v}{R_{VTS}^2 H_t^2} \right)
\]  

(13)

where \( x \) is the particle diameter, and \( Q_g \) is the tube volume flow rate. From this it can be seen
that the separation efficiency of a vortex tube increases as a function of tube mass flow rate and
separating region length, and decreases as the collector radius and helix pitch are lengthened. In
sum, smaller tubes afford a higher separation efficiency, as the particles have less distance to traverse
to reach the periphery of the tube. However, as was shown above there is a balance to be met with
pressure loss, which also increases with tube number. This represents just one of many compromises
in EAPS design.

C. Inlet Barrier Filters

An barrier filter captures particles from the air by one of a number of mechanisms. The first,
more obvious mechanism, when the particle is too large to pass through a filter pore. As the
particle size becomes comparable in magnitude to the fibre diameter, it may be captured by failing
to negotiate the change in curvature of the fluid streamline around the fibre by virtue of its inertia.
At the submicron level, particles may wander in Brownian before being picked up by a fibre, or
may be drawn to a fibre under the influence of van der Waals force. In addition to the van der Waals force and electro-static charge, particles that are not trapped by their bulk adhere to the fibres under surface tension. Before installation, and every as part of each cleaning schedule, the filter is impregnated with an oil, which both serves as a tacking agent and a hydrophobic barrier. The filter medium is folded into pleats to increase the surface area, and held in formation by a wire mesh. It is inserted into a panel, whose area must be large enough to lower the throughput velocity to a level that does not cause a large loss of pressure through the filter. All engine-bound air must pass through the filter panel in order to be filter. A typical IBF-intake arrangement is depicted in Fig. 3.

![Diagram of Inlet Barrier Filter](image)

**Fig. 3 Diagrammatic representation of one embodiment of an Inlet Barrier Filter.**

Other than those of the present authors, of the literature pertaining to IBF there are two notable pieces of work. The first is a joint presentation by Scimone & Frey et al. [9] presented at the 56th Annual Forum of the American Helicopter Society. In this paper the authors detail the background, filter media technology, design considerations, and predict the effect on engine performance and lifetime increase using simulation programs. While providing useful insight into the state of the art, no allusion is made to the design particulars of the IBF and no real test results are given. Instead the focus is on comparing the IBF technology to the other particle separators and describing the main IBF design considerations. Furthermore, the transient state (due to clogging) is only discussed
in relation to activation of the bypass door - a necessary safety feature which allows unfiltered air to the engine in the event of IBF failure. The second is a contribution by Ockier et al. [10] in which the flight testing and certification of an IBF for the Eurocopter EC145 is given. No parametric analysis is given, nor is provided any theoretical derivations for the calculation of pressure loss and separation, which limits the results’ extrapolation to further cases. In contrast, a parametric study by Bojdo & Filippone [11] investigates the effect of particle size and incident flow direction on the rate of solids accumulation on the filter, while an earlier contribution by the same authors investigates the consequences of altering the internal filter fabric properties, and the effect of cake growth on IBF performance [12].

1. Pressure Drop

The loss in pressure across a porous medium arises from fluid drag on the constituent fibres. As the filter collects particles, these too contribute to the drag. The loss can be split into viscous and inertial losses; inertial losses appear at a fibre Reynolds number of around 10. Expressed in terms of the volume flow rate, the pressure drop across a porous medium at all Reynolds number can be expressed as:

$$\Delta P_F = \mu g \left(\frac{Q}{A}\right) Z_F C + \frac{1}{2} \rho g \left(\frac{Q}{A}\right)^2 Z_F D$$

(14)

where $Q$ is the volume flow rate, $A$ is the filtration area, $Z_F$ is the filter thickness, and the constants $C$ and $D$ represent the viscous and inertial resistance coefficients, respectively. Much of the research found in the field of Filtration & Separation pertains to determining the resistance coefficients, which are found to vary between materials and filter structure. In some cases, models take a slightly varied form of Eq. 14; for a comprehensive review see Bear [13]. In the current analysis it is assumed that the filter is non-woven, containing an arrangement of randomly assorted fibres of constant diameter. The viscous and inertial resistance terms as given by Ergun [13] for the filter medium are:

$$C = \frac{150(1 - \epsilon_F)^2}{\epsilon_F \rho_d^2}$$

(15)
\[
D = \frac{3.5(1 - \epsilon_F)}{\epsilon^4_F}
\]

(16)

where \(d_f\) is the fibre diameter and \(\epsilon\) is the medium porosity, or volume proportion of void space.

The process of particle capture within the filter is by no means straightforward. The likelihood of particle capture may be increased as the filter clogs, due to the formation of particulate dendrites on the fibre surface; a filter may begin life capturing particles throughout its depth, but over time the accumulation tends towards the front surface. However, the process depends on both particle size, flow velocity and filter structure; some media are composed of layers of varying property to achieve a more homogeneous accumulation, which alleviates the rate of increase of pressure loss. In this simple model, the pressure rise is accounted for by varying the filter porosity as a function of time:

\[
\epsilon_F(m_{pc}) = \epsilon_F(0) - \frac{\rho_p m_{pc}}{Z_F A_F}
\]

(17)

where \(\epsilon_F(0)\) is the initial filter porosity (clean state), \(A_F\) is the total filtration area and \(m_{pc}\) is the mass collected over the period of time spent ingesting particulates, which is related to the efficiency of the filter by:

\[
\dot{m}_{pc} = E_{IBF} \dot{m}_p
\]

(18)

where \(E_{IBF}\) is the overall capture efficiency of the IBF and \(\dot{m}_p\) is the mass flow rate of particles reaching the filter, given by Eq. 1. When the filter has reached capacity, it no longer captures particle internally. This transition is gradual when assessed over the whole filtration area, and during the removal of a polydisperse size distribution. However, the product of this transition is the gradual buildup of a surface cake, which replaces the fibres as the principle filtering medium. Cake filtration, as it is known, represents another large area of research. Much of the research concentrates on determining cake porosity as a function of particulate properties, and the ease of slurry break-up during reverse-flow cleaning (Refs. [14–17]. Many of the studies in the literature use low Reynolds number Stokesian flow through the cake, which maybe typical of the application.

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on which they are based. In extension of any theory to IBF, the Reynolds number is expected to be higher, hence the inertial term cannot be neglected. A study by Endo et al. [18] develops a general theory for a cake composed of a polydisperse distribution of particle size in high Reynolds number flow. The pressure drop across the cake is given as:

\[
\Delta P_c = 0.2269 \rho_g \left( \frac{Q}{A} \right)^2 Z_c \frac{(1 - \epsilon_c) v(\epsilon_c)}{e^2_c} \kappa \frac{\chi_{vg}}{x_{vg} \exp \left( \frac{5}{2} \ln^2 \sigma_g \right)} + 3.96 \sqrt{\frac{\rho_g \mu_g}{\sigma_g}} \left( \frac{Q}{A} \right)^{1.5} Z_c \frac{(1 - \epsilon_c) v(\epsilon_c)}{e^{2.5}_c} \kappa \frac{\chi_{vg}}{x_{vg}^{1.5} \exp \left( \frac{27}{8} \ln^2 \sigma_g \right)} + 17.28 \mu_g \left( \frac{Q}{A} \right) Z_c \frac{(1 - \epsilon_c) v(\epsilon_c)}{e^2_c} \kappa \frac{\chi_{vg}}{x_{vg}^2 \exp \left( \frac{4 \ln^2 \sigma_g}{19} \right)}
\]

where \( Z_c \) is the cake thickness, \( x_{vg} \) is the geometric mean diameter by volume/mass of the particle size distribution, and \( \sigma_g \) is the geometric standard deviation, \( \epsilon_c \) is the cake porosity, \( \kappa \) is the dynamic shape factor, which is defined as the ratio of the drag force on the particle in question to that on a sphere of the volume equivalent diameter, and \( v(\epsilon) \) is the void function. The void function is a function of only the porosity but seems to depend on the particle size distribution and shape. Hence it is an important parameter of the cake which should be determined experimentally for a given dust if Eq. 19 is to be applied with confidence. In the absence of data from the field, an estimate for the void function is used:

\[
v(\epsilon) = 165 \frac{(1 - \epsilon_c)}{e^2_c}
\]

This is derived from an experimental study by Choi et al. [19] in which the dust cake compressibility of fine fly ashes (from a coal power plant of fluidized bed combustor) was investigated. The particle size distributions were represented by geometric mean diameters of 1.2, 2.2, and 3.6 \( \mu m \), geometric standard deviations of 1.4 1.6 and 1.6, and adjusted dynamic shape factors of 1.15, 1.28 and 1.64 respectively. The cakes were tested at face velocities of 0.02 to 0.08 ms\(^{-1}\). A wider size distribution is expected in desert conditions, while a typical filtration velocity in an IBF system is around 1.5 ms\(^{-1}\).

Equations 14 and 19 represent two of three sources of pressure loss across an IBF. The action
of pleating introduces the third source of pressure loss, which arises due to contraction of the flow in the pleat channels. This is more difficult to predict. At low Reynolds numbers it is possible to estimate the loss to fluid shear by virtue of the channel $x$-velocity profile, which resembles channel flow with wall suction. As Reynolds number increases, the velocity profile more closely resembles a turbulent boundary layer; in such examples some authors (Refs. [20, 21]) assume a similarity solution to estimate the fluid shear. However, in these examples the pleat channels are modelled as simplified geometries. In application to IBF, it is found that the pleat folds are more rounded and the flow rates much greater. A study by this author (Ref. [22]) revealed through CFD analysis of pleat channels, that the velocity profile varies considerably with depth, and is difficult to predict as a function of pleat shape. In this regard, CFD is a useful tool, in predicting the third source of pressure loss.

In this study, the Navier-Stokes equations were solved for the flow through a two-dimensional pleat section. To represent the resistance of the filter and cake, areas of the computational domain were designated as “porous”. A momentum sink term corresponding to the pressure drop given by Equations 14 and 19 was added to the Navier-Stokes equations in the cells of these zones. The sink term was prescribed with the resistance coefficients expressed by Equations 15, 16 and 19. The flow was assumed to be turbulent and fully-developed. Turbulence was solved using the Reynolds Stress Model; a segregated solver was used to solve the governing equations for the conservation of momentum and mass; a 1st Order Upwind scheme was used to discretise the momentum and turbulence terms; the PRESTO! scheme was used for pressure discretisation; and the PISO algorithm was selected for pressure-velocity coupling. For more details of the solution setup, see Chapter 4 of Ref. [8]. The results of the study are extrapolated to the present work to determine the transient pressure drop across the inlet barrier filter EAPS system.

2. Separation Efficiency

The separation efficiency is calculated by quantifying the capture mechanisms detailed above. The derivation is taken from the “Single Fibre Theory” described by Brown [23]. Consider a single fibre lying within a fibrous filter. The capture efficiency of the fibre is mainly a combination of three
capture mechanisms:

\[ \eta_E = 1 - (1 - \eta_d)(1 - \eta_i)(1 - \eta_s) \]  

(21)

where \( \eta \) is the capture efficiency, and the subscripts \( E, d, i, \) and \( s \) refer to the total, Brownian diffusion, interception, and sieving mechanisms respectively. In addition to many other variables, it is a function of particle diameter. Each efficiency is determined separately using well-established empirical or analytical theory; an improvement in the accuracy of such models is constantly being sought in the literature. For a full derivation of the separate efficiencies is given in Ref. [8]. The relationship between single fibre efficiency and the capture efficiency of the whole filter is calculated by considering the number of fibres per unit volume, which is determined by the fibre diameter and filter porosity (or packing fraction, as it is known when considering the solid proportion of volume). Recalling the transiency of the porosity, the general relationship for the separation efficiency of a homogeneous fibrous filter expressed in terms of the key filter parameters, as a function of particle size and collected mass is:

\[ E_F(x, m_{pc}) = 1 - \exp \left( -\frac{4\alpha(m_{pc})Z\eta_E(x)}{\pi(1 - \alpha(m_{pc}))d_f} \right) \]  

(22)

where \( x \) refers to the particle diameter, \( m_{pc} \) refers to the total mass of particles collected within the filter, and \( \alpha_F \) is the filter packing fraction \((\alpha_F = 1 - \epsilon_F)\), which increases as a function of mass collected.

D. Integrated Inlet Particle Separators

The integrated inlet particle separator performs its duty by imparting a radially outward velocity component to fast-flowing engine inlet air, before requiring the air to follow a sharp turn radially inward to continue to the engine. This is depicted in Fig. 4. Particles that fail to negotiate the turn air are scavenged away with approximately 15-20% of the influent mass flow. Several variations on this technique, including a version for radial inlet compressors, and the inclusion of turning vanes to impart an additional tangential component of velocity, are described in a review.
by Filippone & Bojdo [24]. The device also relies quite heavily on rebound mechanics, which can be difficult to predict with an analytical model. This type of EAPS device has a much richer history of research than the other two technologies, developing from a need to protect helicopter engines in increasingly harsh environments across the Middle East and Southwest Asia. More recently, CFD has been used as a tool to optimise IPS design.

One such example of using CFD is available in Hamed et al. [25]. These authors used a combination of deterministic and stochastic particle bounce models with Lagrangian tracking on a fully turbulent solution of the Reynolds-averaged Navier-Stokes (RANS) equations. The particle’s path was integrated within the RANS solution up to the collision or bouncing point. The rebound was stochastic and produced new initial conditions for particle tracking. To calculate the separation efficiency, several thousand particles have to be tracked from the inlet. The work of Vittal et al. [26] follows a similar approach, and focuses on the concept of a “vaneless” separator. Particle paths were predicted through a Lagrangian tracking, although the method only accounted for boundary layer corrections. The comparisons with tests indicate that the separation efficiency was up to 90% with a fine sand and a scavenge flow rate in excess of 14%. For a coarse sand the efficiency was 5% higher. The most recent theoretical work on IPS is that of Taslim & Spring et al. [27]. These authors used CFD methods coupled with particle dynamics to predict the scavenge efficiency of a

Fig. 4 Diagrammatic representation of a generic Integrated Inlet Particle Separator.
conventional inlet design. The main contribution of this work was the model of the particle impact, in particular the restitution coefficient and the inelastic effects. They also investigated the effect of sand properties such as shape and density, and inlet geometry. They concluded that extremely fine particles (smaller than 10µm) cannot be practically separated.

The performance of an IPS is very much dependent on the local flow conditions, which in turn are determined by the engine mass flow requirements. Therefore each study case is limited to the engine for which the IPS system is designed. The sensitivity of IPS design to local conditions renders universal analysis even more difficult when considering the real life situation, in which the particulate will undoubtedly differ from those test sands used to verify CFD data. While this may be a common problem in all areas of particle separator analysis, it highlights the case-specific techniques that are needed for IPS theoretical analysis. Therefore no analytical theory is presented in the current work. Instead, the performance results of the study by Taslim & Spring are adopted to compare with the other EAPS technologies.

E. Engine Degradation

There are numerous examples of just how damaging particle ingestion can be for an engine. Severe erosion during military operations in the 1970s led to engines being withdrawn after just 100 hours of service, while more recently (1990s), unprotected Lycoming T-53 engines lasted as little as 20 hours [25]. Similarly, during operations Desert Storm and Desert Shield in the early nineties saw GE T-64 engines lasting around 120 hours between removals [28]. A two-part study by van der Walt & Nurick [29, 30] proposes and validates a first-order approach for predicting the engine life of helicopters operating in dusty environments. Since most of the erosion occurs on the compressor and especially on the first stage, the analysis is concentrated on (and indeed limited to) this part of the turboshaft engine. It links the erosion rate of metal plates to key variables, such as blade material properties, quartz content, particle hardness, and particle shape. In particular, it reports that erosion rate is almost directly proportional to the percentage of quartz in the dust. It also finds that erosion rate is increased at higher impact velocities, and climbs linearly with particle size up to a critical diameter. The study is introduced by justifying the employment of EAPS, but continues.
to develop a theory of erosion per unit mass of particulate ingested to account for particles that *evade* capture in the separation process. Notably, the trends observed highlight the importance of knowing the dust properties of the environment of operation when predicting engine deterioration. The power deterioration rate for a filtered helicopter engine is given as:

\[ W_r = k_r \phi U^\beta \]  

(23)

where \( U \) is the impact velocity, \( \phi \) is the ingested particle diameter, and \( \beta \) is a correlation exponent. The constant \( k_r \) is dependent on the engine and erodent properties that are all assumed to be constant for a specific engine and dust type, hence Eq. 23 describes a linear relationship between the mass ingested and the power lost to erosional effects. This linear relationship is proven in van der Walt & Nurick’s study for up to 10% power deterioration after an initial unsteady stage in which power is actually observed to increase. (This is due to dust polishing of the blade surface at the very beginning of erosion). For the case of a sparse dust distribution in which particle-on-particle interactions are negligible, the engine power loss is given by:

\[ \Delta W = k_r m_{pe} U^\beta \phi \]  

(24)

where \( m_{pe} \) is the mass of ingested particles. If the ingested particulate contains a range of particle diameters split into \( i \) size bands, Eq. 24 can be written more generally as:

\[ \Delta W = k_r U^\beta \sum_{i=x_{min}}^{x_{max}} (1 - E_{EAPS}(x_i)) m_i^p x_i \]  

(25)

where \( x_i \) is the representative diameter of the \( i \)th size group in the dust cloud PSD and \( E_{EAPS}(x_i) \) is the corresponding separation efficiency. Hence for a given sample of dust broken down into a series of representative size bands, application of the separation efficiency prediction models stated thus far can be combined with the erosion theory put forward by van der Walt & Nurick to ascertain the damage sustained whilst using each type of engine protection, and compare this with the power lost to pressure drop by each system.
III. Theory

The emergence of the three different particle separating systems over the last thirty years or so raises the question of which device is the most efficacious in enhancing engine performance. System efficacy can be measured by a number of criteria; two have been visited in the preceding section, namely pressure drop and efficiency. The best EAPS system will remove 100% of the particles from the dusty air passing through it for no loss of pressure. It will not require any additional power from the engine in order to operate, and will not contribute to airframe drag. The ideal EAPS system would also be lightweight, low-cost and low maintenance. Clearly a device that matches these criteria does not exist, but in the comparison of particle separators these drivers act as barometers to assessing EAPS efficacy. The following section presents low-order theoretical models used to compare the EAPS devices.

A. Overall Separation Efficiency

The IBF and VTS separation efficiencies given by Eqs. 22 and 13 are expressed as a function of particle size. For a simpler comparison, it would be useful to express the efficiency as a single figure, as is favoured by EAPS manufacturers. To achieve this, a mean separation efficiency can be calculated for the whole distribution, for a given device. Suppose the size mass fraction of a dust is represented by a function \( f(x) \). The mean efficiency can be expressed in terms of fractional size groups as:

\[
E_{EAPS} = \sum_{i=1}^{N_p} m_i (1 - E_{EAPS}(x_i))
\]

where \( N_p \) is the number of size bands, \( x_i \) is the diameter of the size band, and \( m_i \) is the mass expressed as a fraction of the total distribution mass.

For devices that scavenge, rather than collect particles, a correction must be applied to determine the true separation efficiency, since a portion of the air is removed from the influent mass flow. The overall efficiency given by the equations above calculates the mass of particles removed from the total mass fed, which is greater than what would have ordinarily been sucked into the engine. The correction is quite straightforward: the particle mass flow in the scavenge line post separation is
a summation of the mass of particles originally within the scavenge proportion, and the mass of particles extracted from the core mass flow proportion by way of the corrected separation efficiency, $E'$:

$$\dot{m}_{p,scav} = S\dot{m}_{p,fed} + E'_{EAPS}(1 - S)\dot{m}_{p,fed}$$  \hspace{1cm} (27)$$

where $\dot{m}_{p,fed}$ is the particle mass flow rate fed into the vortex tube and $\dot{m}_{p,scav}$ is the mass of particles scavenged. The equations used to derived the efficiencies stated above involved the whole system architecture, and therefore refer to the fraction of mass extracted from the total mass fed, or:

$$E_{EAPS} = \frac{\dot{m}_{p,scav}}{\dot{m}_{p,fed}}$$  \hspace{1cm} (28)$$

Dividing Eq. 27 through by $\dot{m}_{p,fed}$, substituting in Eq. 28, and rearranging thus gives an expression for the corrected separation efficiency as a function of the overall efficiency and the scavenge proportion:

$$E'_{EAPS} = \frac{1}{1 - S}(E_{EAPS} - S)$$  \hspace{1cm} (29)$$

This means that the corrected separation efficiency is lower than the overall efficiency calculated in Eq. 26. For example an EAPS device that scavenges 10% of the flow, and achieves an overall separation efficiency of 90% will achieve a corrected efficiency of 88.8%. Note, however, that the “unfiltered” 11.2% will be split between the scavenge line and the core mass flow; the corrected efficiency should only be used to compare devices, as it does not calculate how much dust will be ingested by the engine. For this, the prior equations relating to grade efficiency must be used.

B. Power Required

Another basis for comparison is the total additional power required by the engine to cater for all requirements of the EAPS system. There are three sources of power loss, not all of which are
present for every EAPS device:

1. **EAPS Scavenge Pumps** which require power to suck particles away from the core air flow as part of the separation mechanism.

2. **Device Pressure Loss** which is a form of drag arising from the air passing through the EAPS system and being resisted by friction from integral parts of the device.

3. **Drag** which arises from an enlargement of the airframe to accommodate and support the EAPS system.

### 1. VTS Power Required

The vortex tube arrays carry the biggest potential for power consumption, as all three sources are present. Drag arises from the box-like structure that is required to support the tubes (see Fig. 1); a scavenge pump is required to energise the separated particulate stream; and pressure loss arises from friction with the walls of the multiple tubes that comprise the array. The work done per unit time can be expressed in a number of ways. Firstly, the scavenge power required is given as:

\[
W_{scav,VTS} = \dot{m}_s \Delta P_{scav}
\]  

(30)

where \(\Delta P_{scav}\) is given by Eq. 12, and \(\dot{m}_s\) is the scavenge mass flow rate, of which the scavenged particles make up a large proportion and contribute to the density of the fluid in that region. It is given as:

\[
\dot{m}_s = \dot{m}_{g,s} + \dot{m}_{p,s} = \dot{m}_g (S + \eta_{VTS} \epsilon_m)
\]  

(31)

where \(S\) is the scavenge proportion. It is likely that Eq. 30 does not account for all the power required. In the arrangement shown in Fig. 1 and in other such embodiments there is a “scavenge chamber” into which the scavenge conduits exhaust the particles. It is in essence a tube bundle in cross flow, as the scavenge pump draws air from the chamber tangentially across all the tubes that carry the clean air to the engine. The additional drag and pressure loss through detached
flow is assumed to be non-negligible, but cannot be reasonable theorised without prior knowledge of the chamber’s geometry. In this low-order analysis it is catered for by simply doubling the power required expressed by Eq. 30.

The power required to maintain core mass flow when overcoming the pressure loss through the VTS adopts a similar method:

$$W_{\text{core},\text{VTS}} = \dot{m}_g (1 - S) \Delta P_{\text{core}}$$  \hspace{1cm} (32)

where $\Delta P_{\text{core}}$ is given by Eq. 11.

The device drag is calculated by considering the total surface area occupied by the tubes and the supporting planform area. Assuming that all vortex tubes collectively are designed to supply a design point mass flow $\dot{m}_E$ of air to the engine via each one of their collectors, the number of tubes required is:

$$N_t = \frac{\dot{m}_E}{\dot{m}_{c0}} = \frac{\dot{m}_E}{\rho_g u_g \pi R_c^2}$$  \hspace{1cm} (33)

It can be inferred visually from Fig. 1a that a panel of vortex tubes has a larger area than the total tube area, due to the requirements for support. If the total frontal area is $A_P$, the total drag acting on the panel is:

$$D_{\text{VTS}} = \begin{cases} \frac{1}{2} \rho_g (A_P - N_t A_t) U_\infty^2 + (N_t A_t)(U_\infty - u_g)^2 & \text{if } U_\infty > u_g \\ \frac{1}{2} \rho_g (A_P - N_t A_t) U_\infty^2 & \text{if } U_\infty \leq u_g \end{cases}$$  \hspace{1cm} (34)

where $A_P$ is the VTS panel projected area. The power required to overcome drag is:

$$W_{D,\text{VTS}} = D_{\text{VTS}} U_\infty$$  \hspace{1cm} (35)
Summing Eqs. 30, 32, and 35 yields the total power required for the VTS system:

\[ W_{VTS} = 2W_{\text{scav,VTS}} + W_{\text{core,VTS}} + W_{\text{D,VTS}} \]  

(36)

2. **IBF Power Required**

The power requirements of the IBF differ to the VTS by the lack of a scavenge pump. There is a considerable and transient pressure loss across the filter that must be opposed by the engine:

\[ W_{F,IBF}(m_{pc}) = \dot{m}_g(\Delta P_{IBF}(m_{pc}) + \Delta P_{re}) \]  

(37)

where \( \Delta P_{IBF} \) is the total loss across the IBF filter, and \( \Delta P_{re} \) is any pressure recovered due to the forward motion of the aircraft. It is assumed that unlike the VTS, the supporting structure for the IBF does not contribute a significant amount to the device drag. The pressure recovery exists at forward speeds greater than the engine face velocity, or:

\[ \Delta P_{re} = \begin{cases} \frac{1}{2} \rho g (U_\infty - U_a)^2 & \text{if } U_\infty > U_a \\ 0 & \text{if } U_\infty \leq U_a \end{cases} \]  

(38)

The IBF drag is assumed to be a form drag created by the deceleration of air into the intake, hence can be calculated similarly:

\[ D_{IBF} = \begin{cases} \frac{1}{2} \rho g A_F (U_\infty - U_a)^2 & \text{if } U_\infty > U_a \\ 0 & \text{if } U_\infty \leq U_a \end{cases} \]  

(39)

The power required to overcome this drag is:

\[ W_{D,IBF} = D_{IBF} U_\infty \]  

(40)

Summing Eqs. 37 and 40 gives an expression for the total power required to service the IBF:

\[ W_{IBF}(m_{pc}) = W_{F,IBF}(m_{pc}) + W_{D,IBF} \]  

(41)
It should be remembered that owing to the build up of particles on the filter’s surface, the power required to overcome the pressure drop given by Eq. 37 is a function of the total mass collected. Importantly, this means Eq. 41 is transient: the power required to employ an IBF device increases over time.

3. IPS Power Required

The IPS is mounted to the front of the engine and is therefore assumed to pose no additional drag to the airframe; there are no significant adjustments to the intake to accommodate the IPS that would increase the drag. Therefore, the power requirement to counter drag is neglected here. However, like the VTS, a scavenge pump is required to extract the separated particles from the core air flow which requires power. The pressure loss across an IPS is mainly attributable to skin friction at the walls of the separator, but as the flow turn angle increases, the contribution to pressure drop of form drag increases [27]. The total pressure loss can be segregated into core and scavenge flows and combined with respective mass flow rates to calculate the total power required:

\[
W_{IPS} = W_{core,IPS} + W_{scav,IPS} = \dot{m}_g (1 - S) \Delta P_{core} + \dot{m}_g S \Delta P_{scav} \tag{42}
\]

4. EAPS Power Required

From the above it is clear that the power required to employ a particle separating device depends on the system chosen. At least one technology requires an increasing dedication of engine power, while two others draw power for scavenge pumps. In summary, the power lost to the EAPS system is given by:

\[
W_{EAPS}(m_{pc}) = \begin{cases} 
W_{VTS} & \text{if Vortex Tube Separator used} \\
W_{IBF}(m_{pc}) & \text{if Inlet Barrier Filter used} \\
W_{IPS} & \text{if Integrated Inlet Particle Separator used}
\end{cases} \tag{43}
\]

where \(W_{VTS}, W_{IBF}(m_{pc})\) and \(W_{IPS}\) are given by Eqs. 36, 41 and 42 respectively. This permits an assessment of the devices based on their power demand from the engine.
C. Engine Longevity

There are now two identified sources of engine power loss for a helicopter operating in dusty environment with particle separating technology:

1. Power required to overcome EAPS.

2. Power lost due to erosion by ingested particulate.

Since each EAPS system will carry different power penalties but will achieve varying levels of separation efficiency, the power loss provides a useful metric in comparing the key technologies. Summing the sources of loss, the rate of reduction in available engine power for an EAPS-fitted rotorcraft, as a function of dust mass fed is:

$$W_E(m_p) = W_r(m_{pe}) + W_{EAPS}(m_{pc})$$

where $m_p$ is the mass of particles entering the intake as given by Eq. 1, $m_{pc}$ is the mass collected by an EAPS device (only applicable to IBF) as given by Eq. 18, and $m_{pe}$ is the mass of particle that evade capture and is ingested by the engine. The latter quantity is related to $m_p$ by the efficiency of the EAPS system in a similar way to the mass captured by an IBF:

$$m_{pe} = (1 - E_{EAPS})m_p$$

When the system features dual flow paths, it must be remembered that $m_p$ refers to the mass of particles entering the device. Since a portion of the mass flow is scavenged, this is greater than the mass that would enter an unprotected engine of the same mass flow. However, Eq. 13 accounts for this by including the scavenged flow portion $S$ in the efficiency expression given for VTS and IPS devices. For completeness, the three EAPS devices’ efficiencies are summarily given as:

$$E_{EAPS} = \begin{cases} 
E_{VTS} & \text{if Vortex Tube Separator used} \\
E_{IBF} & \text{if Inlet Barrier Filter used} \\
E_{IPS} & \text{if Integrated Inlet Particle Separator used}
\end{cases}$$
where $E_{VTS}$ and $E_{IBF}$ are given by Eqs. 13 and 22 respectively. The IPS efficiency $E_{IPS}$ is not given analytically in the present work, but takes the same form as Eq. 13 and its value can be taken from test cases in the literature. All are functions of the particle size. The IBF separation efficiency here is also function of mass collected.

D. Engine Improvement Index

A perhaps simpler method for comparing EAPS devices is to calculate the resulting extension to engine life over unprotected engines. Scimone & Frey [9] discuss a study by Textron Lycoming which investigated the potential gains offered by EAPS employment. It used a Life Cycle Cost Model to predict the increased Mean Time Between Removal (MTBR) offered by installing a particle separator. It found a hundredfold increase in MTBR can be achieved when using an IBF. In a similar study, mentioned in the contribution by van der Walt & Nurick [30], the VTS is quoted as been able to achieve an MTBR of between 10 and 25 times the unprotected engine. An important point is made: that such predicted values are sensitive to local conditions, dust type, and dust concentration, so such figures need to be treated as benchmark figures.

From an analytical standpoint, however, verified models can be useful to cross-compare EAPS devices. A simple method is to express life extension as the ratio of the erosion rate of an unprotected engine to the erosion rate of a protected engine. If the mass fractions of ingested particulate in Eq. 24 are instead represented by a effective mean diameter by mass proportion, $\phi_{eff}$, the erosion rate for a protected engine simplifies to:

$$\left( \frac{\Delta W_r}{m_{pe}} \right) = (1 - E_{EAPS})\phi_{eff}$$ (47)

The erosion rate of an unprotected engine takes the same form as this, but omits the separation efficiency term (or simply $E_{EAPS} = 0$) and uses the effective (arithmetic) mean diameter by mass of the dust cloud, $x_{eff}$. Hence the lifetime improvement factor, LIF, is given by:

$$LIF = \frac{d_{eff}}{(1 - E_{EAPS})\phi_{eff}}$$ (48)
This can be used as a quick and effective tool to compare EAPS devices in many environments, provided the PSD data are known.

IV. Results & Discussion

The theory outlined above is applicable if three operational parameters are known: the engine mass flow rate; the particle size distribution of the dust to be filtered; and the erosion factor of the engine’s compressor. Since real data are available relating to the erosion coefficient of a Turbomeca Turmo engine in the study by van der Walt et al. [29], it is selected as a test case. The Turbomeca Turmo is an axial gas turbine turboshaft engine designed to deliver approximately 1200 kW shaft power. The design point engine mass flow is around 5.3 kgs$^{-1}$, which conveniently lies within the range of mass flow rates tested in the IPS study by Taslim & Spring et al. [27]. It is assumed that a similar solution would be met if an IPS were to be designed for the Turmo, which allows the results from Taslim & Spring’s work to be adopted in the present work. For the VTS and IBF theory application, hypothetical solutions were proposed based on the Turmo design engine mass flow rate. For example, a desirable throughput velocity for well-performing IBF is around 8 ms$^{-1}$. To achieve such a flow rate for a mass flow of 5.3 kgs$^{-1}$ at static sea level conditions requires a projected IBF panel surface area of 0.54 m$^{-2}$. For more details of device sizing see Chapter 7.2 of Ref. [8].

To assess separation efficiency fairly requires internationally recognised standard test dusts. Several exist, representing specific size distributions that represent or replicate the typical environments in which the device may be required to operate. Arizona sand has been used for testing turboshaft particle separators and other heavy equipment components for decades. A number of sub-categories of Arizona sand exist, including: Arizona Road Dust, Arizona Silica, AC Fine and AC Coarse Test Dusts, J726 Test Dusts, and more recently ISO Ultrafine, ISO Fine, ISO Medium and ISO Coarse Test Dusts. Many military and industrial specifications require the use of Arizona Test Dust and refer to one or more of the above names. In the current work, AC Coarse test dust specifications is used throughout to quantify EAPS separation efficiency, due to its resemblance to typical desert environments of helicopter operation. The properties of the distribution can be found in Ref. [30].
A. Separation Efficiency

To calculate the efficiency of the VTS and IBF solutions of separating AC Coarse test dust, the PSD data can be implemented into the theory. For the IPS however, there is no theory; the results are adopted from a CFD study. This study tested an IPS solution with three test dusts, one of which was AC Coarse dust. The size bands were not as refined as those used in van der Walt’s study, but the two closely resemble one another, as demonstrated by Fig. 5, which superimposes the cumulative mass fractions of the test dust used in each study.

![Cumulative mass fraction curves of AC Coarse PSD data used in the studies of van der Walt & Nurick [30], and Taslim & Spring [27].](image)

1. Grade Efficiency

The grade efficiency is first compared. The results are shown in Fig. 6. Both the VTS and IBF separate fully the majority of the range, although the IBF performs better at removing the smallest particles in the range. This is significant given that damage can be caused by particle a small as 1μm in diameter. The data for the IPS are displayed separately due the misalignment of sample size groups, but illustrate a similar trend, in that beyond a certain particle diameter all particles are
removed from the flow. Notably, the value at which this occurs is a much larger diameter, around 20 \( \mu m \), than the maximum size that evades capture by the VTS (9.0 \( \mu m \)) and IBF (4.6 \( \mu m \)) devices.

![Diagram showing mass scavenged or captured for the range of particle sizes that comprise AC Coarse test dust, when filtered by VTS and IBF or IPS.](image)

**Fig. 6** Proportion of mass scavenged or captured for the range of particle sizes that comprise AC Coarse test dust, when filtered by a. VTS and IBF; b. IPS.

The difference in separation efficiency between the three devices becomes meaningful when it is considered how much of the ingested mass evades capture to reach the engine. Figure 7 displays the cumulative mass fraction of particles that evade capture to be ingested by the engine. A steeper gradient indicates the portion of size range that will most dominate the PSD of the ingested particulate, while a flat section indicates that no particles of that size are ingested (since the cumulative total does not rise). The last ordinate value on the curve represents the fraction of total mass fed that escapes capture. Clearly from this plot, the IBF performs best, closely followed by the VTS and then the IBF. A diagnosis of the ingested particulate will be dealt with in the foregoing sections.
2. Overall Efficiency

The total mass ingested indirectly leads to assessing the overall efficiency of the device. Figure 8 shows the variation in overall separation efficiency as a function of engine mass flow rate for the VTS and IBF devices. The comparison with IPS cannot be made due to a lack of data. Both devices illustrate a dependency on engine mass flow rate, with the IBF outperforming the VTS by approximately 3.5%, which is consistent across the range. The plot shows that even at low mass flow rates both devices perform well although the most crucial times for EAPS use are when the helicopter engine is performing at close to full power, during landing and takeoff.
Fig. 8 Overall separation efficiency of VTS and IBF devices as a function of engine mass flow.

The transient performance of the EAPS systems is also compared. In comparison with the other technologies, the IBF possesses the advantage of a temporally increasing separation efficiency, due to the captured particles decreasing the medium porosity. Figure 9 shows the temporal characteristic of the overall separation efficiency of each EAPS device. The abscissa relates to the time spent in a brownout cloud of constant concentration of 1.16 kg m$^{-3}$, comprising a composition resembling AC Coarse test dust. Of course this is an idealised situation: in practice the concentration itself is likely to be unsteady, as indeed will be the size distribution. Expressing the temporal characteristic as a function of collected mass may be more appropriate for comparison with other filters, but from a helicopter operations perspective, expressing it in this way provides context.

Clearly the only time-variant device is the IBF; the apparent “jump” to an efficiency of 100% is a modelling assumption. This point represents the transition to cake filtration, when the filter medium has reached capacity. At this clogging stage the efficiency is assumed to be unity due to the creation of much lower porosity cake (compare a typical cake porosity of 0.65 with the filter medium porosity of 0.95). The transition occurs here once the filter has spent approximately 3 minutes in...
the brownout cloud.

Fig. 9 Transient overall separation of EAPS devices, in particular showing the temporal increase in IBF efficiency.

B. Power Requirements

While separation efficiency assess the proficiency of each device at performing the main task, the power required to enact the forces of separation is a measure of the cost. The main source of power is the pressure lost by the flow through the device, however in some devices power is also required to service a pump to scavenge a portion of the flow and extracted particles away from the core flow. Additionally, the size and location of the device on the airframe has an impact on the extra work required by the engine in the form of accompanying drag. Therefore the method of comparing devices by power consumed affords a practical assessment of the main drawback of employing EAPS technology.
1. Pressure Drop

An initial comparison of the pressure loss across each EAPS device is presented first. Figure 10 shows the variation of pressure drop across a range of Turmo engine mass flow rates for each device. The results suggest that the VTS suffers the least loss of pressure at the design point mass flow rate of 5.3 kg/s, and is least sensitive to changes in mass flow. The IBF performs best at low mass flow rates, although there are data missing for the IPS at the same operating point. The IPS pressure loss rises sharply with mass flow rate and is more than double the IBF pressure loss at a mass flow rate of 6 kg/s. Expressed as a percentage of the total pressure available, the total pressure loss at the design mass flow rate of 5.3 kg/s for the VTS, IBF and IPS devices is 0.42%, 0.54% and 0.96% respectively. This of course is only true of one engine speed, during hover, and excludes the capture of particles.

Fig. 10 Effect of engine mass flow rate on EAPS device total pressure loss normalised with available pressure in hover at Standard Sea Level conditions.
2. Power Consumption

A more complete picture of the effect of the EAPS system on engine performance is found by collecting all sources of loss together, and plotting the power expended on servicing the EAPS as a fraction of the maximum power that the engine can deliver, in two scenarios. The first scenario is the transient condition, in which the helicopter is hovering in a brownout cloud and the engine working at the design point mass flow. The second scenario investigates the power required to service the EAPS in forward flight in order to consider the effect of device drag, although an assumption is made in that the engine mass flow rate remains constant, when in practice the engine power requirement (ergo mass flow) reduces with helicopter forward speed (up to a point).

The results are shown in Fig. 11. In Fig. 11a the abscissa refers to the total time spent in the brownout cloud. The fluctuating power required by the IBF is a manifestation of the cleaning cycles discussed throughout the present work: the pressure drop across the filter is monitored by a sensor, which notifies the pilot when the difference reaches an unacceptable level. This may differ between aircraft, depending on the size of the engine. In the current example a pressure drop limit of 3,000 Pa was assigned. It can be seen that the power required at this limit reaches a peak of 1.27% before the IBF panel is cleaned or replaced after 10 minutes. This equates to 6 filter cycles per hour in a brownout cloud. Incidentally, the manufacturers of IBF recommend replacing the filter after 15 wash cycles, which at the current rate is every 2.5 hours total time spent in a brownout cloud. Of course, the constant conditions are unlikely to prevail for longer than the 10 or 20 seconds it takes to land or takeoff, but this figure gives some indication of IBF endurance.

The evolution of the IBF curve is interesting: initially it is the least power-hungry device, but after approximately 5 minutes its state pushes the IBF beyond the requirements of even the IPS. The IPS and VTS are invariant in time, with the VTS requiring approximately half the power of the IPS. In transition to forward flight, all devices are assumed to recover pressure from the forward motion of the helicopter with 100% efficiency, while the drag is seen to act on the area containing the streamtube when the freestream velocity exceeds the core flow velocity. Pressure recovery is possible if the axial flow velocity through the device is less than the freestream velocity. When the engine face velocity exceeds the freestream velocity, a small amount of thrust (or negative drag) is
produced in effect; this thrust is neglected here.

The IPS is positioned just in front of the engine inlet, and therefore does not contain any components that could cause additional drag. The decrease in power required is attributable to pressure recovery, which relieves the work of the scavenge pump. For the same reason, a initial decrease in required power is seen to service the VTS up to a forward speed of around 18 knots, beyond which the power increases due to the emergence of form drag. The form drag appears at a freestream velocity greater than the average capture streamtube velocity, hence for much of the range the power required to service the IBF is constant. The assessment of performance in forward flight is important in determining the performance of the helicopter in cruise when EAPS are fitted, which may help to justify the use of engine protection.

![Graph](image)

**Fig. 11** Comparison of the power required by each system in two operational scenarios: a. hover in a brownout cloud of concentration $1.16 \text{ kgm}^{-3}$; b. transition from hover to forward flight up to 30 knots, with clean IBF and constant engine mass flow.

From this relatively simple analysis, it is established that the IPS requires the most power for the range studied. However, if the data were extrapolated to higher cruise speeds, there may be a switching of this trend. Furthermore, the simple modelling excludes the additional airframe drag created as a consequence of the EAPS device’s presence, which would become significant at high freestream velocities. Investigation of this requires further work beyond the remit of the current study. A final point to make is that it could be argued that since the IPS is integrated into the engine
from the outset by the manufacturers, its effect on engine performance has already been accounted for. It is the engine manufacturers obligation to deliver the power requested by the client. If optional extras are included in the specification, they must already be catered for by the power output of the engine. From a performance loss standpoint, this may make the IPS more favourable over the other devices, but as will be seen in the forthcoming section, the costs of an inferior separation efficiency may still dominate the comparison.

C. Engine Life

In the preceding section, the three EAPS devices were shown to achieve differing separation efficiencies. The separation efficiency of a device can be expressed as a single number for a given dust, but such detail is not sufficient to assess the efficacy of a device. By looking instead at the grade efficiency that can be achieved by a particle separator, it is possible to ascertain the size distribution of the particles that evade capture. No device is 100% efficient, therefore it can be expected that some damage will be incurred by the engine as a result of erosion or otherwise. Therefore it is important to know the properties of the particles that are not removed by the EAPS. The size distribution of the unfiltered particulate can be determined using the same methods used to ascertain the PSD of the initial dust, and can be calculated theoretically as the opposite of the captured mass of a given particle size.

1. Engine Lifetime Extension

The financial worth of employing an EAPS system can be quickly established by estimating the extension to engine life over the unprotected case. The Engine Improvement Index is a metric proposed by van der Walt & Nurick [29] which gives a single number to express the factor by which an engine life can be extended due to the removal of particles. The simple metric may also be used to compare EAPS devices with other protection methods such as blade coatings. Using the same expressions for grade efficiency that were used to create Fig. 6, the PSD of the particles that evade captured can be found. From this, an effective mean diameter of the unfiltered particles can be determined and implemented into Eq. 48 along with the overall separation efficiency of the device to yield the Lifetime Improvement Factor (LIF). The results are summarised in Table 2. The
condition of hover in a brownout cloud of AC Coarse test dust at the engine design mass flow rate is used as the test case.

Table 2 Summary of Lifetime Improvement Factors of the three EAPS devices, with mass mean diameters ($\phi_{eff}$) of escaped particulate.

<table>
<thead>
<tr>
<th>EAPS Type</th>
<th>$E_{EAPS}$</th>
<th>$d_{eff}$ (AC Coarse)</th>
<th>$\phi_{eff}$</th>
<th>LIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTS</td>
<td>95.06 %</td>
<td>38.74 µm</td>
<td>1.79 µm</td>
<td>530</td>
</tr>
<tr>
<td>IBF</td>
<td>98.36 %</td>
<td>38.74 µm</td>
<td>1.48 µm</td>
<td>1325</td>
</tr>
<tr>
<td>IPS</td>
<td>79.08 %</td>
<td>49.38 µm</td>
<td>6.24 µm</td>
<td>38</td>
</tr>
</tbody>
</table>

Looking firstly at the Lifetime Improvement Factor, there is a stark contrast between the three devices. The VTS and IBF eclipse the IPS in terms of extending engine life, by over ten and twenty times respectively. Thanks to its superior overall separation efficiency, the IBF also outperforms the VTS by more than double, although the mean particle size of the escaped particulate is slightly larger than the VTS. This can be explained by examining more closely the grade efficiency of the IBF at these conditions: across the range of particle sizes, even the largest sizes in the distribution of 100 µm, the efficiency does not reach unity, unlike its counterpart. Theoretically, a very small fraction of larger-diameter particulate evade capture and contribute to the mean diameter seen in Table 2. Over time the efficiency does reach 100%, which will gradually decrease the mean particle size, however the transient case is not considered here. As a point of clarity, the mean particle size of the initial AC Coarse dust is larger for the case of the IPS due to use of different data for the PSD.

Clearly, employment of any device is favourable from a financial perspective, although it would be interesting to carry out a full fiscal comparison study that also included life extension due to blade coating. It is true that these are unverified theoretical estimates, and reflective of just one operational condition, but if it is considered that an unprotected engine can last just 25 hours in such conditions, a LIF of just 150 can push the engine lifetime due to erosion to a level that is on parity with the regular Mean Time Between Overhauls.
2. Engine Power Deterioration

The main objective of the experiment conducted by van der Walt & Nurick was to predict the rate of power loss as a function of ingested mass. After an initial unsteady phase, during which the power was actually observed to increase due to surface polishing, their results showed a linear decrease of engine power with total mass ingested, but the rate of decrease was observed to lessen with decreasing particle size. This linearity is observed for up to 10% power loss. The reduction in power was fully attributed to erosion of the compressor; in practice the smaller particles can impact and coalesce with the turbine blades at the hot end, causing further deterioration of power, but this aspect of damage is not modelled here. The proposed formula for engine deterioration rate is given in Eq. 47. It requires knowledge of the size distribution of the particulate that evades capture, and knowledge of the erosion factor $kU^\beta$, which is dependent on the impact velocity of the erodent, the properties of the erodent, and the properties of the compressor blade. The erosion factor is essentially the ratio of the power deterioration rate and the effective ingested particle size. It was calculated after two experiments: firstly after recording the power loss due to the ingestion of unfiltered SAE Coarse test, and secondly after ingesting particulate unscavenged by a Donaldson vortex tube separator array; and found to be very similar ($-1.40$ and $-1.45$, respectively), suggesting that while some dust properties may influence $k$, the effect is minimal.

The findings from the study are applied in the present work. The grade efficiency of each device gives the mass fraction of each particle size group removed from the initial test dust; what is not removed contributes to the “ingested” dust particle size distribution. These data are inputted into Eq. 47 to give the power deterioration rate as a function of particulate mass fed into the system. Combining this with the power required to operate the EAPS systems allows a holistic assessment of the impact of EAPS on prolonging engine life in harsh environments. The results are given in Fig. 12.

The ordinate of Fig. 12 expresses the power loss as a percentage of the initial power, while the abscissa provides a reference for the total mass fed. The mass fed refers to the mass of particulate reaching the intake before passing through the EAPS. Expressing the power loss as a function of mass fed eliminates the need to know the local dust concentration. However, it must still be assumed
that the engine is working at the design mass flow rate, as this affects the separation efficiency. A striking trend visible in Fig. 12 is the rate at which the unprotected engine loses power. After ingesting just 2 kg of AC Coarse test dust the power is reduced by 8.4%. In contrast, all EAPS systems exhibit a saving of engine power, even after filtering as much as 30 kg of dust. At this point, the dust that was not scavenged by the IPS and VTS systems has contributed to a power loss of 6.1% and 0.6%, which includes the initial power required to service the device.

![Fig. 12 Engine power deterioration as a function of mass fed, as predicted by van der Walt & Nurick comparing case of no protection with longevity achieved by the three EAPS devices.](image)

The power loss signature of the IBF displays the characteristic fluctuations symptomatic of the cleaning cycles. Interestingly the gradient of the power loss during a cycle is steeper than the IPS slope. If the maximum permissible pressure loss were greater, the troughs would extend lower. The power loss of the IBF generally varies between a minimum of 0.25% to a maximum of 1.25%, with only a slight decrease in the average quantity. The power loss of the VTS appears to encroach increasingly into the trend of the IBF, but over the range shown remains less than the average power lost due to use of an IBF. Extrapolation of the data suggests that the IBF will outperform
the VTS after around 50 kg of dust fed. For a dust concentration of $1.16 \text{ gm}^{-3}$, this equates to 166 minutes of brownout landing time.

V. Conclusions

The present work pits the three main EAPS devices against each other using theoretical models of varying levels of fidelity. The EAPS are assessed on a number of performance indicators: grade efficiency, separation efficiency, pressure drop, power required, engine lifetime extension and engine erosion rate. To facilitate the cross examination, a test case was set up using the Turbomeca Turmo engine and the properties of AC Coarse test dust.

The results show that the VTS is the superior device when assessed on pressure loss alone at the design point conditions, but show that it is outperformed by the separation efficiency offered by the IBF. The IPS performance falls short of both the retrofit technologies in terms of particulate removal, but if the pressure loss is already catered for in the engine design, the presence of the IPS does not directly affect engine performance. However, both the IPS and VTS require power to service a scavenge pump to extract the particulate, which depreciates their worthiness somewhat over their passive counterpart. The IBF differs from the other technologies by exhibiting a time-variant power loss, but its superior separation efficiency translates to a much longer lifetime extension than the VTS and IPS.

All devices permit a fraction of the ingested mass through their systems, which means the engine does not completely escape damage by erosion. However the extension to life in harsh environments offered by the VTS and IBF devices would return the MTBO to more recognisable levels, inasmuch as their removal is scheduled for reasons other than erosion by particle ingestion. The effect of the power penalty on rotorcraft performance is not modelled here, but if investigated could provide enough information to more-holistically assess the financial benefits of employing an engine air particle separation device.

References


