Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT

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SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	Reducing Energy Consumption in Air Filtration Systems (RECAFS)
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Report Submission Date	31/08/22

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Project Summary (max 500 words)
The built environment has been widely recognised as one of the largest energy consumers in the modern world. A disaggregation of the energy consuming sub sectors within the built environment, attributes heating, ventilation and air conditioning (HVAC) services as the most intensive, consuming 20% to 70% of the total energy used by commercial buildings. Therefore, the development of abatement strategies through technological innovations or guidelines for building services installation is vital. In particular, natural and anthropogenic sources of particulate matter (PM) have a detrimental impact on energy consumption and indoor air quality (IAQ) in buildings. The delivery of treated air into indoor microenvironments typically involves filtration systems. As particle accumulation on the filter increases, the differential pressures across the filter rise and so to the resistance to airflow, incurring higher energy consumptions. The transportation of ambient PM from outdoor air into the inlet of a mechanical building ventilation system is poorly understood. Through numerical methods, the differences in concentration of PM in ambient air and within air handling units (AHUs) were determined, more commonly referred to as Aspiration Efficiency (AE %). This quantity assesses the ratio of the ambient concentration to the in-AHU concentration where for a large ventilation system, an AE of 0% is most desirable. The initial study was concerned with understanding the related building and environmental variables. By establishing the AE of existing AHU inlet rainhood designs, the dynamics of PM concentrations passing from the ambient

environment to indoor spaces can be used in the development of novel PM control technology known as aspiration efficiency reducers (AERs). We also aimed to create the baseline AE of existing rainhoods, which have not been designed with PM control in mind, but nevertheless possess an AE. Results found facing the AHU inlets away from the particle laden wind resulted in substantially different filter loading rates across a range of particle diameters. This study was followed by developing sustainable AERs to reduce the ambient PM concentration entering an AHU, and minimise filter loading. Results showed that AERs could reduce AE for PM_{10} concentrations by 5-35%, corresponding to 3.2-9.3% energy savings compared to commercial rainhoods.

Furthermore the project was also concerned with expanding our understanding of how $PM_{2.5}$ emissions from local traffic pollution sources effects filter loading. Considering the AHU rooftop location and orientation relative to the wind, and the PM source could lead to further optimisation of a ventilation systems performance. This study found that increasing the distance from the local source reduces PM filter loading for an AHU inlet facing into the wind. Rotating the inlet away from the prevailing wind results in the lowest AE and energy savings of up to 25%.

Finally field tests in an urban environment have been performed using AER attachments and compared with a commercial rainhood. The pressure drop across both an ePM1 70% fabric bag filter and a coarse 60% efficiency panel filter was monitored in addition to the system pressure and compared. Results show that AER technology resulted in a reduction in filter loading.

Keywords (min 3 and max 10)	Aspiration Efficiency, Air Handling Unit, Particulate Matter, Filtration system, Mechanical ventilation, Energy consumption, Aspiration Efficiency Reducer, Urban Canyon.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

The built environment is one of the largest sectors for energy consumption worldwide with a significant portion attributed to heating, ventilation and air conditioning (HVAC) services. To mitigate against climate change and improve the operating efficiency of buildings, novel solutions are required to combat the effects of environmental pollution on building operating efficiency. Specifically, airborne particulate matter (PM) has a negative impact on energy consumption and indoor air quality (IAQ) in buildings. Typically, two-stage filtration is used to maintain an acceptable IAQ at the expense of increased energy consumption as the filters are loaded with PM. The systems resistance rises and as a consequence, increasing the fan load in order to maintain the required ventilation flow rates.

This research was focused on developing sustainable low carbon and low-cost PM control technology known as aspiration efficiency reducers (AERs) to reduce the ambient PM concentration entering an air handling unit (AHU) and minimise filter loading. Novel AER technology was designed and evaluated using aspiration efficiency (AE) theory which measures the ratio of the ambient concentration to the in-AHU concentration. Conventional AE studies were conducted for aerosol samplers with the goal of measuring 100% of the ambient environment, in contrast AERs were designed by reverse-engineering AE to approach 0%. To determine the effectiveness of AER technology as a form of PM control, the results must be compared with the AE of the current AHU inlet attachments, commercial rainhoods. Establishing the AE of existing AHU inlet designs, the dynamics of PM concentrations passing from the ambient environment to indoor spaces can be used in the development of novel AERs. We also aimed to establish the baseline AE of existing rainhoods, which have not been designed with PM control in mind, but nevertheless possess an AE. Localised vehicular fine particulate matter ($PM_{2.5}$) emissions in an urban street canyon can also influence the energy performance and IAQ of a building ventilation system at roof level. A study was conducted on the rooftop positioning of AHUs and $PM_{2.5}$

dispersion across the building rooftop. By examining the energy demands of air filtration through an AHU located in different positions and orientations, best practice guidelines for building service installation can be developed with the intention of improving the building operating efficiency.

The project aims required numerical modelling due to time constraints associated with field monitoring for a parametric investigation of the building and environmental variables that impact AE. This study modelled two commercial AHU rainhoods across a range of PM diameters, flow rates, wind speeds and directions. A 20-50% difference in particle concentrations between ambient air and the in-AHU concentration was observed between forward and rear-facing AHUs, with respect to ambient wind direction. Furthermore, a decrease in the ventilation flow rates resulted in a significant reduction in PM concentrations entering the rear-facing AHU. The follow-up AER investigation focused on technology designed to prevent the occurrence of a forward-facing AHU which had incurred the highest AE for commercial rainhoods. The study found that the engineering of wind flow around the AHU and its inlet resulted in lower PM concentrations across a range of particle diameters. The difference in AE for particles within the PM_{10} range for the passive AER prototypes in comparison to a commercial rainhood ranged from 5-35% for various inlet designs. This translated into increased energy savings of 15.2-20.6% and extended fabric filter lifespan of up to an additional 100 hundred days until saturation.

The last numerical study examined the influence of AE on the filter loading rates as the distance from the source increases, and for varying wind speed, and AHU orientation relative to the ambient wind direction. The investigation found the ventilation $PM_{2.5}$ concentration was equal to the ambient when positioned near the windward wall of the target building. A decrease of 33 % and 60 % in the filter loading rate at a wind speed of 7.5 m/s and 2.5 m/s was found at the leeward wall. Therefore there were no energy savings when the AHU is positioned on the windward side of the target building but savings in energy consumption of 9.8 % at the building centre and 19.4 % at the leeward side. Comparing the effect of the wind orientation for identical AHU positions on the rooftop centre resulted in a 26-35 % reduction in AE when the AHU inlet is not facing into the particle laden wind and led to the largest energy savings of 25.8 %.

Finally, post numerical investigations, field studies were performed in an urban environment comparing the developed AER technology with commercial rainhoods and their filter performances were measured over several months. The study showed that AERs reduced energy consumption leading to minimal waste generation and presented cost savings whilst improving IAQ, through a reduction in maintenance activities and the number of filter replacements. This novel technology requires low-capital investment to deliver environmental, energy and economic savings in this sector.

2.2 Introduction to Project

The generation of air pollutants and greenhouse gases through the use of fossil fuels is a major anthropogenic cause of global warming and also has a significant effect on human health. The rapid expansion in populations and industrialisation over the past century has a led to a large increase in the use of fossil fuels, especially in urban centres. The rate of global emissions has been increasing at an exponential rate and the current trends are unsustainable. Further research and investment is required to increase the use of renewable technology for energy generation and innovative pollution control technology. This fact has led to modern society identifying and creating mechanisms that ensure countries are taking a pro-active and legally binding approach to the reduction of their carbon footprint, and to human health protection. This is enshrined in the Paris 2020 accord. In response to the Paris 2020 accord, building energy consumption has been identified as one of the leading contributors in the total global emissions; particularly the HVAC systems components of a building. Therefore, this project is concerned with the development of innovative technologies and guidelines that target and strive towards the goal of mass-produced zero energy buildings. The filtration systems which are associated with all aspects of a buildings HVAC system are loaded with PM and induce significant energy losses as particle accumulation increases. The filters act as a barrier, whereby particles are trapped and prevented from entering the ventilation system but in the process the ventilation systems energy consumption increases.

This project is concerned with the development of sustainable energy efficient technology by reverse engineering the principles of AE. The AER will deflect and/or restrict a significant proportion of ambient PM away from the fresh air inlets of the ventilation system, thus increasing the life span of the filter and reducing fan motor loading. AE theory was originally used in the performance assessment of air pollution sampling devices where various environmental and design characteristics were examined to improve AE toward 100% and thus increase air sampling accuracy. AE is defined as the sampled fraction of particles relative to the total concentration of particles dispersed in ambient air. It was later applied to human mouth and nose aspiration studies and most recently adapted for building ventilation intakes. McNabola et al. [1] first addressed building ventilation pollution control technology by applying an AE index to a ventilation system intake in order to develop novel PM control technology.

AERs are sustainable technology designed to reduce the ventilation systems PM concentrations relative to the ambient concentration upstream of the air filtration system contained within a building AHU and therefore acts as a prefilter. AER technology to date, has been designed with an array of cylindrical orifices that have large orifice surface areas to induce low ventilation velocities. Current traditional HVAC infrastructure at the inlet upstream of the filtration system incorporate rainhoods as shown in Figure 1 whose sole function is to prevent the ingress of rain droplets into the ventilation system and subsequent deposition on the filters. Rainhoods are not designed to restrict PM particles from entering the AHU or lower the PM concentration entering the AHU. Moreover the replacement of rainhoods with AERs as an AHU inlet attachment are advantageous as they will (a) reduce the PM concentrations drawn into the ventilation system (b) lower a building energy consumption (c) less maintenance costs due to increased filter life (d) improve IAQ (e) possess low capital costs (e) be easily retrofitted and (f) comprise a low carbon technology. Finally AE concepts can also be adapted to assess and modify urban planning guidelines and stipulate best practices for AHU installations by aiming to reduce AE. Considering the surrounding urban environment the AHU is situated in and assessing how AE changes from the local source, location of the AHU in the PM transportation path, and filter loading (i.e. receptor) could also lead to the improvements outlined from (a)-(e) for AERs. The project is therefore concerned with the creation of sustainable energy infrastructure for HVAC industry in the form of AERs and improving future urban development strategies that improve the operations of buildings.

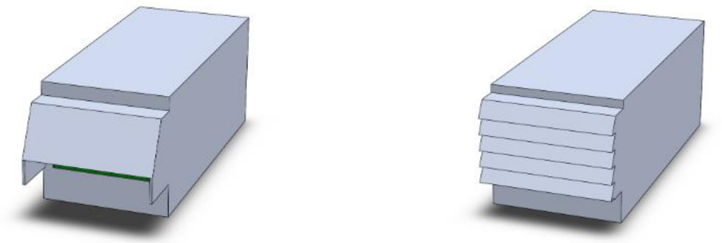

Figure 1 CAD model of an AHU fitted with a (a) single orifice rainhood (Inlet 1) (b) louvre rainhood (Inlet 2) [2].

2.3 Project Objectives

The overall aim of this project is to develop passive PM control technology that can be installed onto new and existing building ventilation system inlets. The project is focused on examining the effects of an AER device on PM of various aerodynamic diameters and its effectiveness at reducing PM concentrations within an AHU. The variables that effect the process are poorly understood and identifying the dominant building and environmental variables will inform the optimisation and design of said device. The project also aims to establish the optimum position of the AHU inlet upon a rooftop and the inlet orientation relative to the oncoming wind, to minimise energy consumption and improve IAQ. Combining innovative technology and urban planning considerations by placing the AHU in low concentration zones should drastically reduce AE and as a consequence incoming PM concentrations. This will provide an energy efficient solution to reducing the built environments energy demands, lowering operating costs and improving IAQ. To achieve the aim of developing a fully functioning prototype the following objectives were proposed to increase the depth of knowledge:

1. Review of current PM and AE literature.
2. Advance our knowledge of AE for the purpose of air pollution control in an AHU.

3. Determine the effect of varying meteorological and building operating conditions on AE of existing commercial AHU rainhoods.
4. Analyse the effect on AE, IAQ and energy consumption of altering the orientation of the AHU intake relative to the wind direction.
5. Analysis of the relationship between AE and Stokes number (St) for large ventilation systems.
6. Development and optimisation of numerous AER prototypes which includes various configurations of circular orifices in an array, and strategically placed baffle plates/deflectors.
7. Determine the effect of pollutant dispersion to roof-top level on an AHU filtration system in an urban environment with a ground level vehicular pollution emission source
8. Analysis of the corresponding energy consumption of HVAC systems within an urban street canyon configuration, and assess the optimum location and orientation for placement of the AHU upon the rooftop.
9. Full scale field test of the final optimised AER prototypes and AHU in comparison to a commercial rainhood and its filter loading in an urban environment.

2.4 Summary of Key Findings/Outcomes

The first numerical models developed were concerned with evaluating the AE of existing AHU rainhood attachments used in the Irish HVAC market today. Two designs were chosen, a single orifice rainhood (Inlet 1) and the more commonly used louvre rainhood (Inlet 2). No studies had examined the effect commonly used commercial AHU rainhood designs have upon the migration of PM from the ambient environment into the building ventilation system, and the implications of this on building energy consumption and IAQ. The AHU was modelled facing into the particle laden wind (forward-facing, FF) and away (rear-facing, RF) across a range of wind speeds, particle diameters and building ventilation flow rates in order to quantify their effect on AE.

- *Innovation 1: Development of AE knowledge for a large aspiration system (i.e. AHU fresh air intake) Previous numerical AE studies only focussed on PM aerosol samplers and human aspiration studies, and never as a control mechanism. This numerical study was the first for a full-sized AHU and determined the dominant environmental and building operating variables that impact AE.*
- *Innovation 2: Confirmation that the wind orientation, wind speed and particle diameter are the main factors that affect the AE of an AHU.*
  The FF AHU results in AE of approximately 100%, only at high wind speeds and with increasing particle diameter does AE exceed this value. The RF-AHU is less than 100% for all scenarios and conversely approaches zero with increasing diameter and wind speed.
- *Innovation 3: Determination of the relationship between the AE of an AHU and the building ventilation flow rates.*
  The effect on AE when increasing the building ventilation flow rates for an FF AHU was negligible and typically produced similar results regardless of the ventilation velocity. Whereas AE was reduced for a RF AHU with less demand and consequently low ventilation velocities.

The second numerical study incorporated the findings from the rainhood analysis in the design of next generation AERs. The first AER prototype (Case 1) as shown in Figure 2 sought to follow on from previous research paths based around an array of cylindrical orifices being more effective than single orifice designs associated with traditional rainhood infrastructure. AER Case 2 and 3 were designed to prevent a FF AHU occurring as the particle laden wind was found to flow directly onto the filter with little to no impedance, generating high AE values. The former orientated the cylindrical array to coincide with the gravity vectors and the latter utilises a barrier in front of the cylindrical orifice array. Finally, AER Case 4 is a concept constructed as an active system that responds to the wind direction by closing a damper system preventing the FF conditions. Furthermore several 2D models were simulated with orifice size of 25mm and deflectors placed around the AHU inlet.

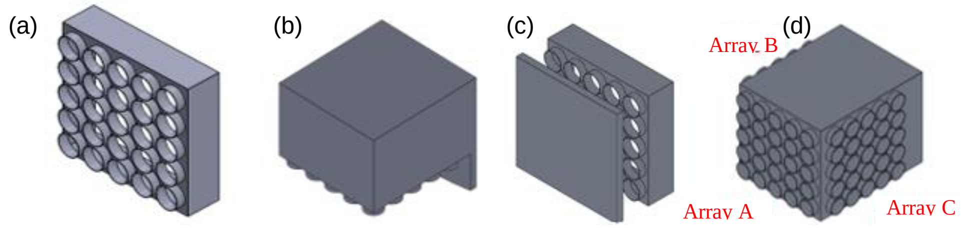

Figure 2 CAD model of novel AER attachments for a full sized AHU where (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 [3].

- *Innovation 4: Assessment of AER technology design with an array of cylindrical inlets and comparison with rainhood technology*
  AER technology was developed based on previous literature and designed to match the AHU bodies dimensions and minimise increases in footprint requirement. Results showed that AER Case 1 had relatively similar AE trends with minor gains in energy performance as an AHU equipped with rainhood technology.
- *Innovation 5: Improvement in the building energy consumption and IAQ by reducing the ventilation PM emissions using passive AER prototypes Case 2 and 3.*
  Major gains were achieved with AER Case 2 and 3 as the highest AE occurs with an FF AHU and those designs prevented this. Both prototypes resulted in a lower energy consumption for particles within the PM_{10} range and very low aspiration for large diameter particles.

Table 1 Energy and economic cost estimation for particle loading rates of a filter with an AHU attachment [3].

	$\overline{\mathbf{AE}}_{\leq 10\mu m}$	**Filter saturation**	$\overline{\Delta P}$	**Energy consumption**	**Energy cost**	**Energy cost savings per filter**		**AER vs Louvre Energy cost savings**	
	%	Days	Pa	KW/h	0.22 € Kw/h	€	%	€	%
Filter		321	198*	2888.9	635.6	-	-	-	-
Louvre	77.5	414	173.4*	2529.3	556.5	79.11	12.4	-	-
AER Case 1	74.0	435	168*	2449.4	538.9	96.69	15.2	13.66	3.2
AER Case 2	70.7	455	165.8*	2417.7	531.9	103.66	16.3	23.58	4.4
AER Case 3	71.2	452	167.3*	2439.6	536.7	98.85	15.6	15.38	3.5
AER Case 4	62.6	514	157.4*	2294.8	504.9	130.70	20.6	24.77	9.3

- *Innovation 6: Demonstration of the potential active control technology (AER Case 4)*
  The active system had the lowest AE values across a range of particle diameters and wind conditions as the FF AHU has again been prevented and the performances upheld for a RF AHU compared to RF AER Case 2 and 3 which incurred higher AE than RF Case 1.

The final numerical study was concerned with furthering our understanding of the effect a local vehicular $PM_{2.5}$ source and an AHUs position and orientation, on AE. By considering the surrounding environment and planning appropriately, significant savings could be made on a buildings energy consumption and as a consequence, improvement in IAQ. An urban street canyon was modelled with a PM source at street level. A wind profile representing the urban environment was used and the AHU placed on a three storey building rooftop in three different positions as illustrated in Figure 3.

- *Innovation 7: Planning for building design should include a mapping of local PM sources and the AHU rooftop location proximity to any pollutant sources.*
  Positioning the AHU at its furthest point to the PM source compared to the nearest resulted in a 33% difference in AE when facing into the wind as shown in Table 2. Energy saving of approximately 20% could be achieved with consideration for positioning.
- *Innovation 8: Additionally, considering the AHU inlet orientation to the prevailing wind direction results in lower filter loading rates regardless of the AHUs rooftop position.*
  A further reduction in energy consumption occurs for a RF AHU where an AE of 58% occurred compared to its counterpart AE of 84% also at the rooftop centre, FF-pos-2. Furthermore AE was found to average around RF-pos-2 for both other location at pos-1 and pos-2.

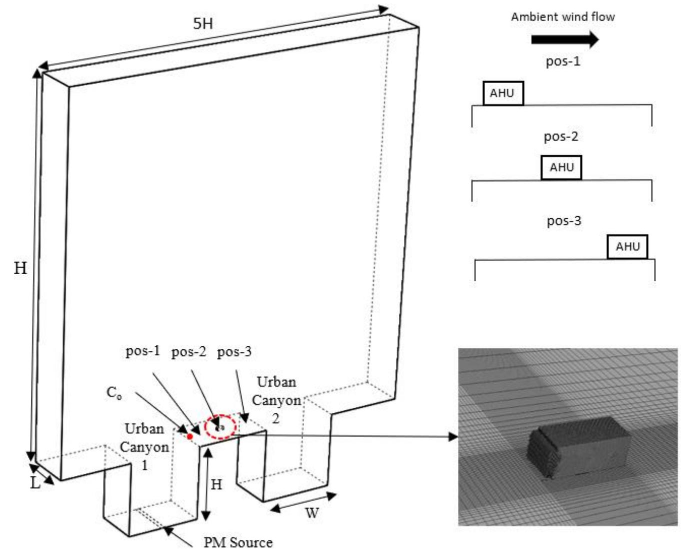

Figure 3 Computational domain of symmetrical urban street canyons with a PM2.5 source and rooftop AHU (Note: W=L=H=12m).

Table 2 Assessment of the impact vehicular emitted PM2.5 emissions have on the energy and economic cost estimations as the AHU location and orientation changes at a wind speed of 7.5 m/s.

	AE	**Filter saturation**	$\overline{\Delta P}$	**Energy consumption**	**Energy cost**	**Energy cost savings per filter**	
	%	Days	Pa	kWh	0.22 € kWh	€	%
Filter		321	198*	2888.9	635.6	-	-
FF-pos-1	103	312	198.2	2901.1	638.25	-2.91	-0.5
FF-pos-2	84	383	178.6	2604.62	573.02	62.32	9.8
FF-pos-3	70	460	163.4	2383.24	524.09	111.24	19.4
RF-pos-2	58	555	155.9	2274.22	500.33	135.01	25.8

Two AHU's with a ventilation flow rate of 3400 m^3/hr have been installed side by side on the rooftop of TCDs Simon Perry building, one designated for AER technology and the other a control AHU with a commercial rainhood as shown in Figure 4. Various environmental and design conditions were monitored during the testing phase. Instrumentation was installed to monitor the pressure drop across both the panel and bag filters during particle loading. The sensors collected pressure data over 30-minute intervals with a Keithley 7700 Bench Digital Multimeter. The AHUs were monitored until either AHUs ePM1 70% fabric bag filter, or coarse 60% efficiency panel filter shown in Figure 70c, becomes fully saturated or exceeds the manufacturers recommended filter change limits of 100 Pa for the former and 50 Pa for the latter. The HOBO U30-NRC Weather Station was mounted on the building roof at a height of 0.5 m to capture the local wind speed and direction at 15-minute intervals.

- *Innovation 9: The results from the field experiments are in agreement with the findings from the numerical models. AER Case 3 results in a lower pressure drop and increased energy savings. The pressure data comparison between AER Case 1 and the commercial rainhood for the coarse panel filter resulted in similar trends and performances as predicted by the numerical models. AER Case 3 had a lower filter loading rate and was attributed to the extremely low AE for large diameter particles.*

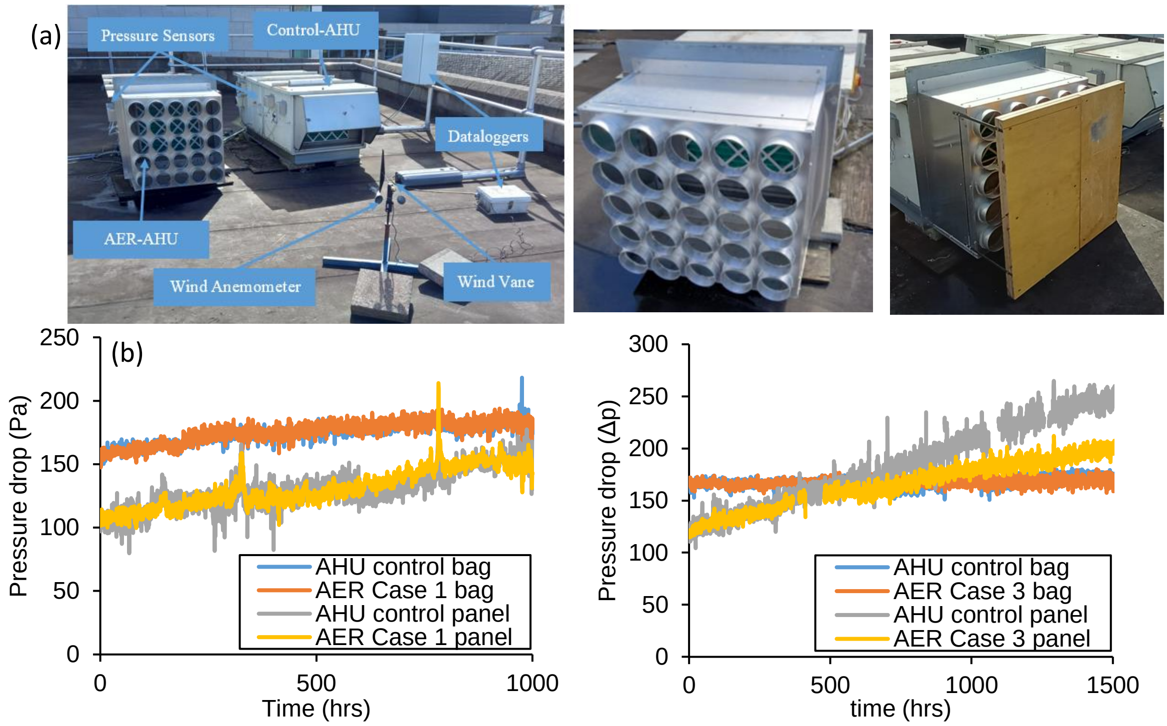

Figure 4 Filter pressure drop comparison between AER-AHU and a commercial AHU rainhood (Inlet 1).

2.5 Project Impact ---------

The RECAFS project has made important contributions to the Irish energy sector as the project successfully demonstrated a means to achieve major improvements in the energy efficiency of HVAC systems in buildings. According to the SEAI's Energy in Ireland Report (2021), 44% of primary energy supply was associated with energy in buildings in the residential and services sectors. The Climate Action Plan 2021 has identified the built environment as a key sector for reducing emissions in order to positively mitigate against climate change. Improving energy efficiency is central to our transition to a low carbon economy and net zero across all sectors of the economy as stipulated in the Climate Action and Low Carbon Development (Amendment) Bill (2021) by 2050. The National Mitigation Plan (2017) has also outlined potential improvements in the energy efficiency of the national building stock could reduce emissions from 7.5 Mt CO_2 in 2020 to 4.4 MtCO_2 in 2030 and significantly contribute to a 51% reduction in emissions by 2030. RECAFS aimed to contribute to the Irish energy sector by developing novel technology and practices that could reduce the energy consumption associated with a building HVAC system.

The EU directive on the energy performance of buildings identified building energy consumption as accounting for 40% of the total energy consumption within the EU and globally. HVAC systems in particular have been identified as a vital target area where significant reductions in energy consumption can be achieved. The 2020 climate and energy package legislated its member states towards three key targets of 20% reduction in greenhouse gas emissions, 20% of EU energy from renewables and 20% improvement in energy efficiency but has been now increased to 32.5 % for the latter by 2030 compared to projections of the expected energy use in 2030.

As the building sector currently accounts for 40% of the worlds energy demand and 30% of greenhouse gas emissions; the drive towards zero energy buildings and retrofitting of new innovative energy efficient technology [4] is key to the vision of sustainable cities, environmental stability and economic growth. Although significant challenges remain in identifying the key areas of energy consumption in not just a single building but with developing a holistic approach for every commercial and industrial building. A study on the disaggregation of a buildings energy consumers, demonstrates that HVAC systems are shown to account for between 40-50% of the energy consumption among non-domestic buildings [5]. Moreover the electricity usage associated with various motorised equipment is a significant contributor to HVAC energy consumption.

The creation of AER technology as a PM control mechanism for a building ventilation system and demonstration of lower filter loading was achieved throughout this project using numerical and experimental methods. Development of an AER, which is essentially a prefilter, will increase the filter lifespan and ensure a lower system resistance over an equivalent period of time compared to using only a rainhood. This technology will effectively contribute to the EU and national targets outlined above with regards to energy efficiency by lowering a ventilation fans energy consumption and a building carbon footprint. As there is a large HVAC market in Ireland, the technology could be retrofitted to existing HVAC infrastructure or installed in new buildings, in addition to incorporating best practices for AHU rooftop installation which could reduce energy consumption by upwards of 25%. In the Energy White Paper (2015), energy innovation is highlighted for its importance in helping to achieve Ireland's energy policy and RECAFS is strongly aligned with this national research policy.

The overarching objectives of the SEAI Research, Development and Demonstration (RD&D) Funding Programme include acceleration of the development and deployment in the Irish marketplace of competitive energy-related products, processes and systems. The knowledge and technology generated in RECAFS is clearly an innovative energy related product and the findings demonstrated an energy-related product/system and guidelines for improving Ireland energy sector. The use of AE as an energy efficient air pollution control for HVAC systems was successfully shown, supporting the SEAI remit in support of energy related research and development programmes. The SEAI RD&D programme also aims to grow Ireland's national capacity to access, develop and apply international class energy RD&D. The project results have been widely disseminated nationally and internationally showcasing Irelands ability to produce world-class cutting-edge energy research in the built environment. The completion of the RECAFS project has produced Irish researchers that are at the forefront of their field in the energy-efficient control of the quality of indoor air.

Economic Impact

The development of disruptive PM control technology for building ventilation systems will open a new sector in the HVAC market. A survey on the number of commercial buildings in Ireland with mechanical ventilation, analysis of HVAC sales reports and interviews with prominent manufacturers operating in Ireland revealed a potential retrofit market of 110,000 units and approximately 3500 AHUs sold annually for new builds. While significant progress was made, further field testing is required to confirm the effectiveness of AERs as reducing PM filter loading and pursuit of full commercialisation. The realisation of a fully commercial prototype will lead to the creation of manufacturing jobs upon successful IP licencing to a prominent Irish company operating in the HVAC sector. Furthermore, the roll out of AER technology will lead to increased work in the construction industry generated by AER installs until market saturation has occurred. The reduction in energy consumption will also directly benefit the operating cost of Irish businesses and industry, resulting in improved competitiveness.

Societal Impact

A reduction in HVAC system energy consumption as demonstrated will by association result in lower CO_2 emissions emitted into the atmosphere. Moreover, as HVAC systems are one of largest consumers of electricity in the operation of a building, lowering the energy costs incurred by the ventilation fans motor will also be of benefit to the owner/occupier. The sheer number of aforementioned AHU units in Ireland and by extension the world, means improvements in a ventilation systems energy efficiency will results in large scale energy savings. Expanding this concept further to maintenance activities and the number of filters inside a single AHU will translate to further savings. Finally, society in Ireland will benefit from the reduction of electricity consumption in HVAC systems, providing an improvement in energy security and efficiency nationally. Considering the current energy crisis and very large increases in energy costs, any technology that lowers a building energy consumption such as AERs is of vital importance to achieving a carbon neutral society.

Policy Impacts

RECAFS was originally targeted at contributing to the 20% improvement in the 2020 energy efficiency goals and now towards the 32.5% target for 2030. The results from RECAFS shows that AER technology and new building planning guidelines can be incorporated into mitigation strategies developed by policymakers. Both methods can act as additional mechanisms for the reduction of energy consumption and CO_2 emissions in buildings and could be included in future Climate Action Plans and National Energy Efficiency Action Plans. It is our policy recommendation that stricter guidance should be imposed on the design of the layout and location of HVAC systems on roof-tops, via the building regulations, to help achieve the potential savings shown in RECAFS.

Scientific Impact

The project outcomes resulted in several conference and journal publications that have expanded the literature on novel PM control technology and contributed to the newly created field of adapting AE for sustainable air pollution control in ventilation systems. The large orifice designs used in ventilation fresh air intakes and engineering of prototypes that restrict the entry of PM through the fresh air intake were poorly understood before RECAFS. The project has now detailed novels methods and technology that will reduce an AHUs filter loading and was disseminated through academic resources to the scientific community. The project also found a large scope to apply AE theory in reverse for other sectors of society including computers, urban topology consideration, vehicles ventilation inlets, passive ventilation and in residential buildings. Finally the project also increased the knowledge and human capital in Ireland as a result of the work conducted by producing a PhD level expert in this field.

2.6 Recommendations

A working prototype was successfully demonstrated using numerical methods and through a field test, albeit over a short monitoring period*. Therefore, additional field tests repeated with a longer monitoring period and conducted by the research community are required in order to fully gauge the AER device effectiveness in Ireland and beyond. An opportunity exists to expand the project further by analysing the performance of both the fabric bag filter and the coarse panel filters loading rates in different regions and/or environments (i.e. urban vs rural) throughout Ireland and the world. The deployment of the AER prototype should be enacted for real world projects undertaken by the HVAC industry on a trial basis. The long monitoring campaign and lack of data could be offset by a trial campaign in multiple occupied commercial buildings and the pressure across the filters monitored and compared to the pressure change rates pre AER install. Policy makers could recommend changes to the building regulations and ensure that every ventilation system fresh air intake has PM control technology installed and mandate AER usage over rainhood technology. This could provide a significant contribution to the aforementioned energy efficiency targets set out in the European green deal, with a very low capital cost. Similar practices are in place for various aspects of building construction and operation in order to improve the indoor environment for the building occupants and impact on the environment. AER technology will require successful commercialisation and licensing before full deployment and post field tests. The research community will have to enlist prominent Irish HVAC manufacturers to produce and sell this energy product on the EU and international markets.

*Field testing of filters requires 3-6 months per test due their typical lifespan, as such many tests were not feasible within the RECAFS project lifetime.

2.7 Conclusions and Next Steps

The research investigations within RECAFS were pursued systemically and have provided a significant contribution to the current literature on AE. The potential for development of a new form of PM control technology for large aspirating systems was successfully demonstrated. In order to expand this area of research and identify gaps in the knowledge, an extensive literature review was undertaken to achieve this outcome. The authors assessed the current state of building energy consumption and found HVAC systems were categorised as the largest consumer of energy in the built environment sector. Filtration systems, in particular were identified for potential improvement by incorporating AE concepts into the operation of a building AHU. This would consist of designing an inlet capable of restricting the entry of a significant portion of ambient PM concentration into the ventilation system. Additionally, the literature review found that considering urban building planning considerations when installing an AHU and mapping the local environmental characteristics to reduce AE could also be a viable control mechanism.

To achieve this, variables that could be influential in the transfer process of PM from the ambient environment to the indoor were identified. As there were no studies on how the existing HVAC infrastructure performed with regards to PM control, the first investigation sought to develop AE knowledge on rainhoods that would be typically installed on the Irish market. The study assessed a louvre and a single orifice rainhood with changing building and environmental conditions using numerical models. A building ventilation demands will vary throughout the day and the impact on AE as an AHUs flow rate fluctuates were examined. Moreover the size of a particles diameter had a significant impact on the trajectory and ingress into the AHU intake. St was used to evaluate each particles AE across a range of wind speeds in order to capture the various environmental conditions an AHU may be subjected to. Results showed that there was not a large difference in AE trends between both rainhood attachments. The investigation led to the creation of baseline AE trends that could be used for future evaluations against subsequently designed AERs. The findings from this study also outlined the variables that should be considered when designing next generation AER prototypes, particularly the wind direction.

Following the creation of baseline AE by examining existing HVAC infrastructure, this led to the development of AERs based on the dominant variable, wind direction, and incorporated an array of cylindrical orifices. Previous studies investigated the viability of cylindrical orifices with scaled AER models, and oversized AER field experiments and tested with inlets facing in different directions. RECAFS sought to examine the impact of cylindrical orifice arrays with similar total surface area as the commercial rainhoods as no studies had been conducted on an AER with equivalent dimensions to the AHU body which is important for practical implementation. The study was further expanded by orientating the inlets facing the rooftop surface and another prototype where a barrier was placed in front of the orifice array. In addition to the aforementioned passive control AER prototypes, an active concept was modelled on the assumption of a wind monitoring system where the AHU would respond to wind direction changes and prevent particle laden wind flowing directly onto the filter. There were clear differences in both flow patterns and AE trends when comparing each of the AERs together. Performance metrics were similar to the commercial lourve rainhoods. Results showed that there was scope for controlling the PM concentrations entering the AHU intake and new technology is required to address a buildings energy consumption. The study also quantified the energy consumption of each AER and the more commonly used lourve attachment under predefined conditions using their respective AE values. The investigation found a wide range of energy and monetary savings depending on the attachment where certain AER prototypes resulted in energy savings. The passive AERs Case 2 and 3 energy consumption over the period until saturation of 321 days incurred energy savings of 111.6 kWh and 89.7 kWh respectively amounting to monetary savings per filter based energy consumption of 3.5-4.4 %. Examining the active system, AER Case 4, the energy savings were as high as 234.5 kwh, more than the double the passive AER savings and a 9.3 % reduction in monetary costs associated with energy usage.

The literature review found additional gaps in knowledge with regards to urban and building planning considerations and AHU deployments on building rooftops. Careful consideration of a buildings surrounding environment could be used as a form of PM control for a ventilation system. Evaluating an AHUs proximity to local pollution sources and designing a system where the AHU is positioned at the maximum distance allowable by the rooftop dimensions would be advantageous. Additionally, the impact of the AHUs inlets rooftop orientation relative to the prevailing wind direction was also examined. The previous inlet design investigations findings on AERs and commercial rainhoods demonstrated the importance of the wind direction and suggested further analysis was required in a full urban environment. The numerical models quantified the effect on AE as the distance between the AHU inlet and heavily polluted street canyon increased and results showed AE was significantly reduced for a FF AHU by increasing the distance between the PM source and AHU. Although the rate of change from the windward face of the building to the leeward for a FF AHU was less and the RF AHU resulted in AE values that were approximately similar irrespective of the AHU rooftop position. Using the same methodology for calculating the energy consumption as the AERs previously, considering an AHUs position and orientation generated significant energy and monetary savings. A RF AHU regardless of its position AE of 58% incurs energy savings of 614.68 kWh compared to the filters performance at 100% AE and results in a 25.8% savings on the energy costs. Whereas a FF AHU located next to the PM source exceeded the filter AE by 3% generating a negative outcome on energy cost savings by -0.5%. Although this becomes savings of 19.4 % at the furthest deployment position from the PM source on the rooftop.

The previous investigations were all concerned with parametric numerical analysis in order to provide a clearer picture into a large ventilation systems AE. In reality, the real-world conditions are more dynamic and require field experimentation to determine the success of AER technology as a form of PM control in comparison to commercial rainhoods. The field study used AHUs situated side by side and fitted with AER attachments designed through numerical methods and the other with a rainhood. The results showed there is scope for improvement based on AER technology and inlet design and a lower pressure drop was successfully demonstrated. Placing a barrier in front of the AER inlet led to a cleaner panel filter over the testing period when compared to a commercial rainhood as the latter resulted in an extra 60 Pa increase in the system pressure compared to the latter.

Future research
The use of AE as a PM control mechanism for large ventilation systems is still in its infancy and relatively few studies have been conducted. Significant gaps in the literature were identified that were not addressed within this RECAFS and will form the basis for future research projects. These include (a) further improvements in AER design (b) urban environment investigations and development of building planning guidelines (c) conducting experimental wind tunnel tests and expanding field investigations (d) other real-world AE applications. Additional AER designs were identified for testing based on the manipulation of the wind flow around the AHU rather than through alterations to the orifice geometry or size. For example, the optimisation of strategically placed deflectors plates around the AHU body and/or inlet could further reduce AE. The application of green infrastructure could also lower AE and incur additional benefits to the urban environments. The active systems was only trialled with numerical models but a successful demonstration in the field would require linking a weather monitoring system to the active AER damper controls and should be pursued.

The full urban environment investigation of the impact of an AHUs proximity and orientation relative to a $PM_{2.5}$ traffic emission source was confined to an urban street canyon where the building height is equal to the street canyon width. While the literature in this field is well established for urban wind flows, there is a dearth of knowledge on the AE of a ventilation system in different urban building configurations under varying aspect ratios. Differing building heights creating asymmetric street canyons, building arrays and real-world case studies should be examined. Furthermore, the single and inline building is also of interest due to the effects of boundary layer separation at the rooftop impacting PM dispersion around the AHU body. The AE of passive ventilation in buildings has not been explored, in particular, the operation of the windows and their design characteristics. Assessing these parameters with the goal of reducing AE would also improve the IAQ by lowering PM concentrations entering the indoor microenvironments.

The field study demonstrated the success of the AER prototype with a barrier (Case 3) in front of the inlets and a similar performance between AER Case 1 and a rainhood but could only be compared to the numerical studies through a qualitative analysis. An experimental wind tunnel study is required for a full quantitative comparison where the AE is determined experimentally for a full-scale AHU which could be used for future validation and calibration of CFD models. The field studies should also be expanded to environments with a higher level of PM pollution (i.e. China, India, Bangladesh etc.). This will provide a better comparison between a rainhood and an AER as the panel and bag filter will load faster overcoming the issues experienced by testing in Dublin, Ireland and discern if AER technology is effective for smaller diameter particles in the PM_{10} range. Field studies should be conducted in multiple environment types such as near deserts where large sandstorms effect urban cities (Cairo), areas prone to wildfires (Australia, California) and other large scale natural events occur.

Finally, AE theory could be applied to other real-world applications for PM control not related to the built environment such as ventilation system intakes for vehicles, heavy machinery air intakes and grille design for computer ventilation. Analogous to building ventilation, both transport vehicles and heavy machinery could use less energy by ensuring lower filter loading rates. Numerous studies have been conducted on dissipating heat for better energy performance through increased airflow or fin surface area. None have been conducted on designing new orifices with low AE preventing dust being drawn into the system by the fan and covering the heat sink. Using AE to restrict the passage of large particles into a computer system could result in substantial energy savings considering their widespread usage worldwide.

References

[1] McNabola, A., O'Luanaigh, N., Gallagher, J., and Gill, L., 2013, "The Development and Assessment of an Aspiration Efficiency Reducing System of Air Pollution Control for Particulate Matter in Building Ventilation Systems," Energy and Buildings, **61**, pp. 177–184.
[2] Considine, B., Gallagher, J., Kumar, P., and McNabola, A., 2021, "Numerical Investigation on the Ingress of Particulate Matter from Ambient Air into the Inlet of a Building Air Handling Unit," Indoor Air, **31**(6), pp. 1940–1951.
[3] Considine, B., McNabola, A., Kumar, P., and Gallagher, J., 2022, "A Numerical Analysis of Particulate Matter Control Technology Integrated with HVAC System Inlet Design and Implications on Energy Consumption," Building and Environment, **211**, p. 108726.

[4] Liu, Z., Li, W., Chen, Y., Luo, Y., and Zhang, L., 2019, "Review of Energy Conservation Technologies for Fresh Air Supply in Zero Energy Buildings," Applied Thermal Engineering, **148**, pp. 544–556.
[5] Pérez-Lombard, L., Ortiz, J., and Pout, C., 2008, "A Review on Buildings Energy Consumption Information," Energy and Buildings, **40**(3), pp. 394–398.

SECTION 3: COMMUNICATION & DISSEMINATION (max 3 pages)

3.1 Communication, Dissemination and Exploitation

Acknowledgement of the SEAI RD&D Funding programme was included in the all the dissemination activity listed below for conference presentations and journal publications.

The project commenced March 2019 and initially targeted the identification of the gaps in knowledge associated with AE and HVAC systems through a literature review and a market assessment. As part of the market assessment, interviews and surveys were conducted with national HVAC manufactures and a project presentation was delivered to Mark Eire BV, the largest HVAC manufacturing company in Europe.

The first numerical study examined 2D models of AHU rainhood designs acquired from industry and their results presented at IMC36 in Trinity College Dublin. The scope of the IMC conference is generally associated with manufacturing and energy where the project falls under the latter theme. The scope provided a synergy due to the conference energy themes and projects objectives of reducing energy consumption in the built environment and reaching a new audience in the process for promoting AE as a control mechanism.

https://www.tcd.ie/mecheng/news/assets/IMC36-agenda-final.pdf
https://www.tcd.ie/mecheng/news/assets/IMC36_meet_TCD_public.pdf

The project team also attended the National Energy Research and Policy Conference 2019 in Dublin which was co-hosted by SEAI and the Department of Communications, Climate Action and Environment (DCCAE). This provided an excellent opportunity to network with other researchers and companies concerned with the reduction of energy consumption in society.

https://www.seai.ie/events/research-conference/

The global centre for clean air research (GCARE) through the University of Surrey is collaborator on the RECAFS project. A visit was conducted to the Clean Air Engineering for Cities (CArE-Cities) workshop pre Covid in September 2019, for networking opportunities. Subsequently The project results were disseminated via GCARE during a visit in Jan 2020 to deliver a presentation on the findings from the first journal paper and to detail the next step on the RECAFS project. A presentation on RECAFS was also given at a follow up event at GCARE in March 2022 under the Global Indoor Air Quality and Respiratory Infection webinar series titled "Passive indoor air pollution control in ventilation systems".

https://www.surrey.ac.uk/events/20190410-clean-air-engineering-cities-workshop

A second 2D numerical study was undertaken to model AER technology and deflectors and compared with the results from the rainhood 2D models presented at IMC36. The results were disseminated at International Conference on Urban Air Quality Management, Environment and Technology (ICUAQMET) 2020 in Amsterdam, Holland. Details of the conference can be seen below. Acknowledge of the SEAI RD&D Funding programme was included in the dissemination activity at this conference and all dissemination activity listed below. Subsequently, the paper entitled "*A study on the Effectiveness of Alternative Commercial Ventilation Inlets that Improve Energy Efficiency of Building Ventilation Systems*". was awarded the International Research Conference Certificate of Best Presentation award. This prestigious award is conferred annually upon an awardee based on a research paper and presentation that is adjudicated by an expert panel drawn from industry and academia.

https://www.tcd.ie/Engineering/about/news/ICUAQMETAward2020.php

The paper can be viewed with the following link:

https://publications.waset.org/energy-and-environmental-engineering

The conference Breathing City was attended online multiple times as this was related to current research in ventilation, urban environments, air pollution and the coupled interaction between indoor and outdoor flows. The event is hosted regularly by the University of Leeds and provides excellent networking opportunities.
http://breathingcity.org/

The first paper was published with *Indoor Air* in May 2021 and entitled "*Numerical investigation on the ingress of particulate matter from ambient air into the inlet of a building air handling unit*". This paper was published with open access and can be viewed at the following link:

https://doi.org/10.1111/ina.12856

The second paper "*A numerical analysis of particulate matter control technology integrated with HVAC system inlet design and implications on energy consumption*" was published in the Journal *Building and Environment* in March 2022 and was primarily concerned with the development of novel AER technology using numerical methods described above and can be viewed at:

https://www.sciencedirect.com/science/article/pii/S0360132321011161

Finally a third paper has also been submitted for publication at *Wind Engineering and Industrial Aerodynamics* and is under peer review since Aug 2nd 2022 and has a preliminary title of "*The impact of street level particulate emissions on the energy performance of roof level building ventilation systems".* A fourth paper is being prepared in the results from the AER and rainhood field experiments.

The final dissemination activity of this project at this point was a presentation of the entire RECAFS project at Environ 2022 'unlocking sustainability' in June 21st 2022 at Ulster University, Belfast, Northern Ireland. The presentation was titled after the aforementioned project name "reducing energy consumption in air filtration systems" in order to link the SEAI funding project to the presentation.

https://www.esaiweb.org/environ/

Finally, the website that was developed in the year 1 of the project has been updated to reflect the published material to date from the aforementioned conference paper and two journal papers. This will provide further insight into the progression of the AER and potential benefits for company's interested in the final product. As before, this enables them to analyse the findings and see the advantages of using an AER device instead of traditional rainhoods currently used on AHU's. The website is currently under subscription until Apr 2023 and will be updated with the third papers results and the outcomes from the field experimentation upon publication.

https://www.recafs.com/

Table 3.1 – List of Scientific Publications

Title	Main Author	Journal Title	Number, Date or Frequency	Publisher	Year of Publication	Is/Will open access be provided? If you marked "will", provide an estimate of the date	Peer-reviewed (Y/N)?
Investigating the effectiveness of alternative HVAC inlets in reducing the intake of particulate matter in building ventilation systems	Brian Considine	*International Conference on Urban Air Quality Management, Environment and Technology (ICUAQMET)*	Volume 15, No.1	WASET	2020	Yes	Y
A numerical analysis of particulate matter control technology integrated with HVAC system inlet design and implications on energy consumption	Brian Considine	Indoor Air	Volume 31, issue 6, Pages 1940-1951	Wiley	2021	Yes (Published as open access)	Y
A numerical analysis of particulate matter control technology integrated with HVAC system inlet design and implications on energy consumption	Brian Considine	Building and Environment	Volume 211, Pages 108726	Elsevier	2022	No	Y
The impact of street level particulate emissions on the energy performance of roof level building ventilation systems	Brian Considine	Wind Engineering and Industrial Aerodynamics	Under Review	Elsevier	T.B.C	Yes	Y

Table 3.2 – List of Dissemination Activities

Type of Activity	Main Leader	Title	Date/Period	Location	Type of Audience*	Size of Audience
Interviews	*Mark Eire BV, Systemair*	*Interview with prominent Irish HVAC manufacturers*	*8th May 2019*	*Systemair Dublin and Mark Eire BV, Cork, Ireland*	*Managing Director and Project Sales Engineer*	*4*
Project Presentation	*Mark Eire BV*	*Project presentation on the AE of existing rainhoods and the future of RECAFS*	*8th May 2019*	*Mark Eire BV, Cork*	*HVAC Manufacturing Company, Managing Director*	*4*
Conference (networking)	*GCARE*	*Clean Air Engineering for Cities (CArE-Cities) workshop*	*10th April 2019*	*University of Surrey*	*Industry, scientific community*	*40*
Conference (presenting)	*Trinity College Dublin*	*IMC 36*	*29th August 2019*	*Dublin, Ireland*	*Industry, scientific community*	*50*
Conference (Presenting)	*GCARE*	*Project workshop on PM control and AER technology*	*13th January 2020*	*University of Surrey*	*Industry, scientific community*	*20*
Conference (networking)	*SEAI & DCCAE*	*National Energy Research and Policy Conference 2019*	*20th November 2019*	*The Alex Hotel Dublin*	*Industry, scientific community, medias civil society, policy makers*	*200*
Conference (Presenting)	*GCARE*	*Global Indoor Air Quality and Respiratory Infection*	*25th March 2022*	*University of Surrey*	*Industry, scientific community*	*30*
Conference (presenting)	*Environ 2022*	Unlocking Sustainability	*21st June 2022*	*Belfast, Northern Ireland*	*Industry, scientific community, medias civil society, policy makers*	*25*
Website	*Trinity College Dublin*	*RECAFS.com*	*6th June 2019*	*N/A*	*Industry, scientific community, medias civil society, policy makers*	*1104*

**Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).*

SECTION 4: PROJECT STATUS & WORK PLAN

4.1 Work Plan

Table 4.1 – List of Work Packages

No.	Title	Status Update and Completion Status (%)
1	Desk Study of Existing HVAC Systems in Ireland	*100%*
2	Review of Aspiration Efficiency Literature	100%
3	Assessment of the AE of Existing HVAC Systems	100%
4	Development of Numerical Models of AE in HVAC Systems	100%
5	Lab-scale testing of AE as a particulate matter control mechanism	100%
6	A real-world demonstration of energy savings	100%
7	Communication, exploitation & Impacts	100%

In Table 4.2, please include details for each work package (copy and replicate the Table for each work package as required). Please provide an update on the progress, the specific milestones and deliverables achieved, and clearly identify any deviations from the original proposed work packages.

Table 4.2 – Summary of Work Packages

WP No. & Title	1. Desk Study of Existing HVAC Systems in Ireland		
Start Month No.	1	**Finish Month No.**	3
WP Lead	Aonghus McNabola		
WP Contributors	PhD student & John Gallagher		
Objective(s)	WP1-O1: To compile an assessment of the primary forms of HVAC systems in Ireland and industry analysis.	Completion Update:100%	
Description (max 200 words)	HVAC systems can comprise relatively small air handling units with ventilation flow rates in the region of 1700 m^3/h to relatively large units with ventilation flow rates up to 90,000 m^3/h. This very large range of flow rates and physical size presents different challenges to the use of AE as an energy efficiency measure. Therefore it is important to map out the existing market for HVAC systems in Ireland to quantify the typical operating conditions, layout and dimensions of air handling units in commercial buildings, hotels, hospitals, manufacturing industry, food processing, public buildings, etc. The results of this desk study will help to guide the direction of the development of the AER technology and also to quantify the scope for energy savings in different building types. Data will be collected from a combination of sources including the building energy rating database, interviews with prominent irish HVAC manufacturers (RMI Ltd; Mark Eire BV; EDPac Ltd; etc); product catalogues from HVAC manufacturers; and interviews with filter suppliers (e.g. Camfill farr, SIRUS, etc). The project team has already received letters of support from three of the aforementioned Irish companies.		
Milestones	WP1-M1: Target Market identified for lab scale and real-world research & development (Month 3)	Completion Status (%):100	
Deliverables	WP1-D1: Report on assessment of the distribution of air handling units across differing building types/sectors and industry analysis	Completion Status (%):100	

Deviations from planned WP (if applicable)	None		
Key Outcomes	The potential market size for AER deployment was estimated to be approximately 110,000 based on HVAC sales reports, SEAI housing stock and ventilation surveys and interviews with prominent Irish HVAC manufacturers. Additionally, around 3,500 new AHUs units are sold in Ireland every year ensuring a sustainable market for AER technology in Ireland alone.		

WP No. & Title	2. Review of Aspiration Efficiency Literature		
Start Month No.	2	**Finish Month No.**	4
WP Lead	Aonghus McNabola		
WP Contributors	PhD student & John Gallagher & Prashant Kumar		
Objective(s)	WP2-O1: To compile an up to date review of the relevant literature in aspiration efficiency		Completion Update:100%
Description (max 200 words)	In the preliminary phase of the project, the PhD student will compile a comprehensive review of the literature on aspiration efficiency from academic journals, scientific conferences and other sources. This up to date literature review will inform the basis for the design of prototypes and selection of influencing factors to examine for reverse engineering in later work packages. This literature review will also inform the design of laboratory and field experiments taking into consideration the measurement methodologies of the most salient articles. The literature review will also inform the design of methodologies in WP4 on the development of numerical models for the prediction of AE in different environments and under different boundary conditions.		
Milestones	WP2-M1: Gaps in knowledge confirmed/identified; AE factors for experimentation assessed; measurement and prediction methodologies informed.		Completion Status (%):100
Deliverables	WP2-D1: Literature review report WP2-D2: Experiment design methodologies report		Completion Status (%):100
Deviations from planned WP (if applicable)	None		
Key Outcomes	An up-to-date literature review report was generated and identified a number of gaps on AE and its use as a PM control mechanism for building ventilation systems. The literature on AE has been primarily focused on aerosol samplers and human nose and mouth study. Certain variables were identified as important including wind speed, direction, orifice size and particle diameter which were captured using the relationship between AE and St. As to the design report, CFD modelling was identified as the most efficient method for a large-scale study with multiple variables and designs. The turbulence model, validation using existing literature and definition of the boundary conditions that could impact the transport of PM from the ambient to the indoor environment were also procured from academic sources.		

WP No. & Title	3. Assessment of the AE of Existing HVAC Inlets		
Start Month No.	5	**Finish Month No.**	12
WP Lead	Aonghus McNabola		
WP Contributors	PhD student & John Gallagher & Prashant Kumar		
Objective(s)	WP3-O1: To establish a baseline of the typical aspiration efficiency of common HVAC ventilation inlets under the varying ambient weather and building operating conditions.		Completion Update:100%
Description (max 200 words)	In order to design a device which reduces the aspiration efficiency of HVAC inlets, we must first understand the AE of the existing situation to establish the baseline situation. As shown below there are many embodiments of a typical HVAC inlet. Each variation in their geometrical design would result in differing AE. There are also a variety of conditions under which they operate (1,700-90,000 m^3/h), as well as varying ambient weather conditions and particle sizes and compositions. All of		

these variables influence the AE of existing inlets which must be quantified for improvements to be made via reverse engineering of the concept.

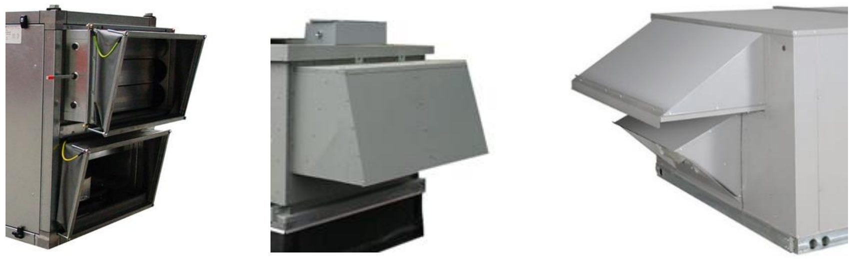

Figure 2: Example of 3 typical HVAC system inlet designs

These experiments will be conducted through a series of field measurements at real-world HVAC systems in Dublin. Ambient upstream concentrations of PM will be recorded for various size ranges across differing weather conditions. Simultaneously PM will also be measured inside the inlet allowing AE to be determined. Real-time measurements will be conducted in high resolution together with gravimetric samples for quality control purposes. Sampling will be conducted using two sidepak aerosol monitors (TSI-AM520) as well as using gravimetric sampling according to the methodology described in Adams et al [21].

Milestones	WP3-M1: Establishment of an AE baseline for HVAC inlets to measure improvements in subsequent WPs.	Completion Status (%):100
Deliverables	WP3-D1: Scientific publication on the aspiration efficiency of existing HVAC inlets, its impact of particle loading in HVAC filters, and its impact on energy consumption in the building sector. Target Journal: Building & Environment.	Completion Status (%):100
Deviations from planned WP (if applicable)	Nonne	
Key Outcomes	The numerical models used in this work package resulted in a publication in the journal Indoor Air and advanced the state of the art on AE for a building ventilation system. The results showed that when facing an AHU into the particle laden wind leads to high AE compared to facing the AHU away regardless of the rainhood used. Increasing the wind speed and particle diameter through St creates AE larger than 100% for a FF AHU. Conversely AE decreases for the RF AHU as St increases. Therefore, the design of novel AERs must account for the wind direction in order to lower the filter loading rate. A fluid flow analysis was also successfully conducted for the AHU in particle laden wind and provides a clearer picture into the transport process of PM between the indoor and outdoor environment, especially with varying particle diameters.	

WP No. & Title	4. Development of Numerical Models of AE in HVAC Systems		
Start Month No.	5	**Finish Month No.**	30
WP Lead	Aonghus McNabola		
WP Contributors	PhD student & John Gallagher & Prashant Kumar		
Objective(s)	WP4-O1: Advancing our understanding on the use of AE as an energy efficient PM control mechanism. WP4-O2: Reducing particulate matter concentrations in HVAC inlets by 70%.	Completion Update:100%	
Description (max 200 words)	Numerical models of both generic and specific HVAC inlets will be developed in the computational fluid dynamics platform ANSYS. Generic models will be developed in order to conduct factorial experiments of each of the factors influencing the AE of inlets. We will examine the effects of: • Ambient wind speed & direction • Ventilation Velocity • Particle composition & distribution • Particle losses in transmission zone • Stokes numbers • Orifice geometry • Gravitational impacts • Particle concentration		

	• Interference between multiple inlets These factorial experiments will enable the precision engineering of the AE concept to achieve: specific PM or energy efficiency targets; understand the trade-off between PM control and energy savings, and identify the limits of the AE approach to control PM and save energy. The trade-off between energy saving and PM control arises in balancing the initial pressure drop of the AER inlet design (reducing energy consumption) with its AE. Some measures to improve AE could increase initial pressure drop. Specific HVAC inlets will be modelled for the purposes of assessing the performance of lab and real-world demonstrations of the concept in WP5/6. Numerical models will be calibrated and validated against physically measured AE data from WP5/6 and previous AE experimental datasets available in the literature.	
Milestones	WP4-M1: The ability to precision engineer HVAC inlets to be energy efficient PM control devices using AE is acquired.	Completion Status (%):100
Deliverables	WP4-D1: Scientific publication on the fundamental science behind the energy efficient control of PM air pollution in HVAC inlets using aspiration efficiency. Target Journal: Energy & Buildings.	Completion Status (%):100
Deviations from planned WP (if applicable)	None	
Key Outcomes	The AER designs were based on the outcomes from the previous work package by considering the wind direction and preventing the particle laden wind flowing directly at the AHU inlet. This results in lower energy consumption for an AHU fabric bag filter due to a lower PM filter loading rate. AER technology resulted in energy and monetary savings of approximately 10% compared to rainhood technology. The AE for particles greater than 10 micron for AER technology on average was also typically much less than the commercial AHU rainhood, thus preserving the filter life of the coarse panel filter for a longer period. Finally, by considering an AHUs rooftop position and orientation, significant savings in energy ban also be incurred. A holistic approach that accounts for inlet design and impact of the surrounding environment ensures the greatest gains can be achieved and both represent a low carbon solution for sustainable buildings.	

WP No. & Title	5. Lab-scale testing of AE as a particulate matter control mechanism		
Start Month No.	8	**Finish Month No.**	18
WP Lead	Prashant Kumar		
WP Contributors	PhD student & John Gallagher & Aonghus McNabola		
Objective(s)	WP5-O1: Facilitation of the calibration and validation of numerical modelling and informing the design of prototypes for real-world testing		Completion Update:100%
Description (max 200 words)	1:25 physical models will be tested under controlled conditions in an experimental setup. An AE test chamber will be constructed to allow the assessment of the impacts of individual factors on the AE of a number of HVAC inlet designs. The purpose this activity will be to verify the modelled results from WP4 and to optimise the design of full scale demonstrations. A test protocol will be developed based on relevant standards: ISO-23045:2008 energy efficiency of new buildings, and ISO-16890-1:2016 air filter testing. The Air Quality Laboratory at the University of Surrey will be used for this purpose. A best practice methodology inspired by testing aerosol samplers will be adopted [22, 23] Particle concentration in the test chamber will be measured using a fast particle analyser, measuring concentration and particle-size distribution in the free air stream (C0) and the air passing through the AER inlet (C). Measuring C and C0 under different operating conditions, will quantify the AE of the inlet. Different testing conditions will be obtained by varying the following parameters: (i) the angle of wind		

	α (0–180°), (ii) ambient wind speed (0.1–10 m/s), (iii) vent velocity (0.5–2 m/s), and (iv) particle size (0.1–10 µm).	
Milestones	WP5-M1: Numerical models validated in laboratory conditions	Completion Status (%):100
Deliverables	WP5-D1: Report on calibration & validation of numerical models.	Completion Status (%):100
Deviations from planned WP (if applicable)	Again COVID restrictions made travel access to the UK impossible. The numerical models were validated against published wind tunnel literature on experiments analogous to particle laden flow around an AHU such as a PM sampler, as approved by SEAI.	
Key Outcomes	The turbulence and DPM model were calibrated and validated against experimental data from a PM sampler across a range of particle diameters. A scaled AHU model would essentially be of a similar magnitude as the sampler. The numerical and experimental results were in good agreement. Moreover, the turbulence model for wind flow were also validated for a full-sized urban canyon. A $PM_{2.5}$ source defined through a particle diameter distribution curve representing emissions from a vehicular source was also used in a full urban environment and validated. Therefore validation of the numerical models was achieved at a design scale for the AHU inlet attachment and of an AHU situated on a building rooftop in a full scale urban environment.	

WP No. & Title	6. Real-world demonstration of energy savings		
Start Month No.	17	**Finish Month No.**	33
WP Lead	John Gallagher		
WP Contributors	PhD student & Aonghus McNabola & Prashant Kumar		
Objective(s)	WP6-O1: Full-scale demonstration of energy efficient control of air pollution under real-world conditions WP6-O2: Reduction in energy consumption of 40%		Completion Update:100%
Description (max 200 words)	Full-scale real-world demonstration of the energy efficient control of particulate air pollution will be demonstrated at a commercial building in Dublin City Centre. The demonstration will use the results of previous work packages to achieve the project objectives of a 40% reduction in energy consumption for the ventilation fan. The demonstrations will comprise assessment of the AE and energy consumption of two identical HVAC units previously assembled for the purpose of our preliminary assessments outlined earlier in [15]. Particle concentration upstream and downstream of the two HVAC units will be recorded to compare the AE of both units. Pressure drop in each HVAC unit will also be monitored to determine energy consumption over time. Ambient wind speed and direction will also be recorded. One of the HVAC units will be fitted with an AER inlet design from WP4/5 while the other will remain unchanged as a comparison. A variety of common HVAC filters will be assessed to demonstrate differing levels of energy saving achievable for coarse and fine filters. Particle size distribution and composition will also be monitored during this work to demonstrate the effectiveness of the AER for differing particle sizes and types.		
Milestones	WP6-M1: 40% energy saving demonstrated in the field		Completion Status (%):100
Deliverables	WP6-D1: Scientific publication of real-world demonstration of energy efficient air pollution control in HVAC systems under differing filter types and weather conditions. Target Journal: Applied Energy		Completion Status (%):100
Deviations from planned WP (if applicable)	None		
Key Outcomes	AER Case 1 and Case 3 prototypes were tested for 1000 and 1500 hours respectively. The results confirmed that an array of cylindrical inlets (i.e. AER Case 1) has a similar filter loading rate as a commercial rainhood. If a barrier is paced in front of the inlet (AER Case 3), AE is lowered, especially for larger particles. The coarse panel filter for the rainhood loaded at a faster rate than the AER with a		

	barrier, resulting in a lower pressure drop across the filter. Finally the bag filters in each experiment loaded very slowly which is indicative of the low concentration environment for PM_{10}/$PM_{2.5}$ and would require much longer monitoring periods for a full comparison between rainhoods and AERs.

WP No. & Title	7. Communication, exploitation & Impacts		
Start Month No.	12	**Finish Month No.**	36
WP Lead	Aonghus McNabola		
WP Contributors	PhD student & John Gallagher & Prashant Kumar		
Objective(s)	WP7-O1: Communication of project concept and results to relevant stakeholders WP7-O2: Facilitation of the exploitation of the project outputs by Irish Industry and ensuring achieving of project impacts		Completion Update:100%
Description (max 200 words)	The results will be disseminated widely at national and international scientific conferences and through the publication of peer-reviewed journal articles. The project will submit its work for publication to 3 international conferences in the fields of air pollution science, energy and buildings and HVAC systems. We will also attend national fora such as the SEAI energy show and the ENVIRON conference. The project will also maintain a website. WP7 will also include activity on the exploitation of research outputs. In line with the objectives of the SEAI research programme, in order to facilitate widespread deployment of the RECAFS findings, the project team will submit an invention disclosure to the technology transfer office of Trinity College Dublin, with a view to protecting the IP created in the project, and creating further opportunities to license or otherwise commercialise the AER inlet designs. WP7 will include activities to ensure the impacts of the project are achieved. We will compile a list of potential technology licensees and engage in 1-to-1 meetings with these companies with a view to encouraging the take-up of the technology in the market. We will meet with major Irish HVAC manufacturers and building services design companies to disseminate the project concept and generate market interest.		
Milestones	WP7-M1: List of potential technology licensees compiled WP7-M2: IP protection initiated		Completion Status (%):100
Deliverables	WP7-D1: Publication of project results in 3 international conferences and 2 national conferences WP7-D2: Publication of 3 peer-reviewed journal articles		Completion Status (%):100
Deviations from planned WP (if applicable)	None		
Key Outcomes	The RECAFS project website created at the project start had a substantial viewership over the course of the project. Two peer reviewed Journal articles have been published so far from the RECAFS project, a third currently under review, and a 4th is in preparation. An international conference paper was also published and was subsequently awarded best paper by the conference hosts. Networking was conducted at the SEAI roadshow, GCARE workshop in the University of Surrey and at the Breathing City event hosted regularly by the University of Leeds in order to promote the project. Finally, the project results were presented at the national conferences, IMC 36 in TCD, GCARE webinar and Environ 2022 in Ulster University.		