# HOT:
## Humidity Optimization Tool

## Final publishable summary report

### 1.- Publishable Project Executive Resume:

The energy consumption cost of Aircraft Environmental Control Systems (ECSs) reaches 1.000 million euro per year. These systems are responsible for the conditioning and quality of the air breathed by passengers. Besides this, their performance also has to take into account some primary safety issues. One example is the avoidance of condensation at landing windows in helicopters.

The technology used at ECSs is well known and mature, regarding machinery and humid air behaviour. On the contrary, for the processes that include condensation, the prediction of some key aspects is at the edge of scientific knowledge. These include: (i) the condensation droplet number and size, (ii) the fog evolution and visibility, as well as (iii) the fraction of liquid water laden on the flow in respect to the fraction wetting the walls. This is the reason why this Humidity Optimization project for Aircraft ECSs has been commissioned within the Clean Sky Joint Undertaking structure by the EU-Commission, DG Research.

The structure of the project is divided in three blocks that have achieved the following advancements in respect to the previous state of the art:

A) Fog visibility criteria and description of the fog plume generated by an axisymmetric nozzle:
   - Development of a "Fog entity" parameter criterion.
   - Capability and means to model the generation and evolution of an axisymmetric nozzle fog.
   - Capability and means to predict the visual impact of the fog plume.

B) Generation of a tool for prediction of flow downstream of selected ECS elements:
   - Module for two-phase flow prediction at the exit of a generic turbine.
   - Module for two-phase flow prediction at the exit of a mix-manifold.
   - Module for two-phase flow prediction at the exit of a post-turbine Heat exchanger.

C) Experimental validation of the tool:
   - Test campaign for validation of turbine outlet and post-turbine heat exchanger outlet.
   - Test campaign for validation of the axisymmetric nozzle fog model.
   - Test campaign for validation of generic mix-manifold outlet.

The main result of the project is an experimentally validated tool able to provide the commented relevant two-phase flow characteristics. This is a key element for improved detail-design of ECSs. In addition, a database with the valuable experimental data from the test campaigns has been compiled. These data is useful for studies or validation of any further issue related to these two-phase flows. Also the state of the art regarding numerical calculation of two-phase flow has been improved along this project. These techniques can be applied to a large deal of technological fields where these flows play a relevant role, including environmental and health related issues.

The impact potential of this project on the society surpasses its cost by orders of magnitude. Just a save of 1% in the energetic performance of aircraft ECSs would save 10 million euro per year (i.e. 36.000 tons/year of kerosene). This means a reduction of the emissions to the atmosphere of 100.000 tons/year of $CO_2$ and a saving of 400 TWh/year of energy. To this primary impact, additional benefices from the application of this knowledge to any other two-phase flow technological field should be taken into account.

# 2.- Summary description of project context and objectives

### 2.1.- Project context, state of the art and Background.

Earth atmosphere is composed of humid air. This composition is also the requirement for human comfort. It implies that a broad range of devices have to deal with humid air. These devices range from complex ECS (Environmental Control Systems) at aircrafts, to almost any air breathing machine, including engines.

Humid air behaviour and its interaction with usual machinery are well known. The modelling of this “humid air” is the limit of complexity for standard engineering. It provides the amount of liquid water produced in a device but does not solve important issues. Many of the key aspects of the processes that include condensation are at the edge of scientific knowledge. Some of these aspects are related to:

(i) The condensation droplet number and size: besides metastable states that blur the exact location of condensation, the final number of droplets and average size is often a complex to model issue.

(ii) The fog evolution and visibility: The interaction between light and droplets is known, but the evolution of a fog formed by a jet entering a stagnant atmosphere is a complex two-phase flow issue depending on a large number of variables of the jet and the ambient. As a consequence, the evolution of the visibility is also intricate.

(iii) The fraction of liquid water laden on the flow in respect to the fraction wetting the walls: even solving all of the previous issues, the fraction of droplets that hit the wall of the involved devices is not an easily closed question.

These issues are characteristics rarely solved in actual engineering. They are subjects to unveil in the research field. This project has focused on solving them for the ECSs processes.

### 2.2.- Project objectives.

The basic purpose of the project is to develop an engineering tool able to predict generation and evolution of water fogs in the ECSs. This tool should be able to provide the two-phase flow characteristics that allow for improved detail-design of ECSs and the consequent minimization of their energy consumption. Only regarding aircraft ECSs, the amount of kerosene directly consumed worldwide is in the order of 3 million tons per year. Just an improvement of 1% on their performance, based on a better process knowledge, would save every year 10 million Euro and a 100.000 tons of $CO_2$. Despite these are a small proportion of the possible target devices, it justifies the cost of this project in just 10 days.

To achieve this general purpose, the most relevant two-phase flow processes within the ECS functioning have to be studied in detail and their characteristics unveiled. Under this view, the particular objectives of the project are:

1) Determination of a fog visibility criterion. A “Fog entity” parameter that allows to stablish the visual impact of a given fog has to be developed.

2) Development of a tool able to predict the fog generated downstream of selected ECS elements. This means to indicate the size and number of the water droplets generated. The selected elements are: (i) Pack outlet turbine (ii) Post-turbine Heat exchanger, and (iii) Mix-manifold

3) The tool should also be able to predict the amount of liquid water content that has hit the walls and is no longer laden in the flow.

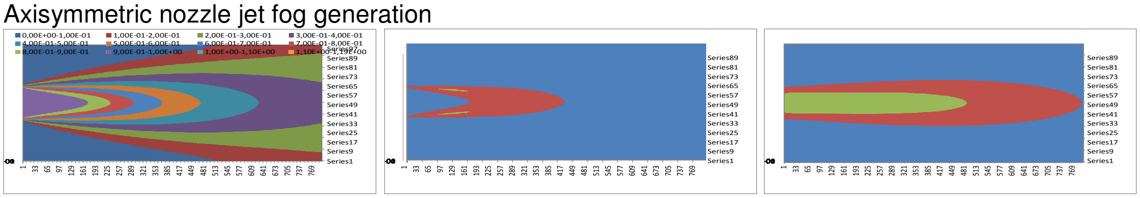
4) Development of numerical model able to provide the characteristics of the fog generated by an axisymmetric nozzle. This includes the evolution of such fog in a stagnant atmosphere and the visual impact of the fog plume.
5) Generation and compilation of experimental data that allows to validate the tool developed and the model for fog plumes. This implies design of the experimental test benches and associated test campaigns.

## 3.- Description of main Science & Technology results/foregrounds

The structure of the project is divided in three blocks that have achieved the following advancements in respect to the previous state of the art:

A) Fog visibility criteria and description of the fog plume generated by an axisymmetric nozzle. This block is focused on the characterization of the parameters which may have an impact on fog visibility and how they evolve along the plume as it mixes with the stagnant ambient. The main Science and Technology results in this block are:
   - A “Fog entity” parameter criterion has been developed. This criterion is independent of ambient conditions and easily related to visual impact of the fog plume.
   - A module with the capability to model the generation and evolution of a fog plume has been added to the originally planned fog prediction tool. This module considers the plume generated by an axisymmetric nozzle discharging in a stagnant atmosphere. Special numerical methods have been developed which allow for simple integration of the complex two-phase phenomena.
   - The combination of the previous two advances, have allowed predicting the global visual impact of the fog plume. This is a relevant issue, besides ECSs consumption, as these plumes could impair vision in the aircraft.

Axisymmetric nozzle jet fog generation



(dimensionless velocity at 0,01 steps) (supersaturation at 1% steps) (fog entity at 0,01 steps).

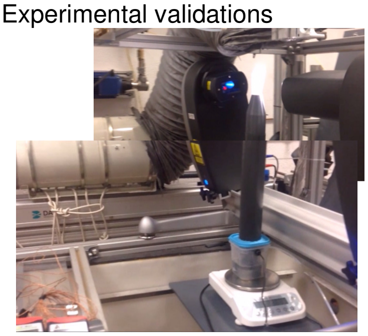
B) Generation of a tool for prediction of flow downstream of selected ECS elements. A detailed theoretical model has been made for each of these components. Based on these models, codes for numerical calculation have been developed on several computation environments, allowing to test and to improve the code. A final version has been programmed in Python with the possibility to run the software both manually and as integrated batch processing for other automatic applications. The different modules predict the amount of water laden in the flow, number and size of the droplets. The S&T results cover the following elements:
   - Module for two-phase flow prediction at the exit of a generic turbine. It is based on the geometry, the working conditions and the design specifications.
   - Module for two-phase flow prediction at the exit of a mix-manifold. The mixing of up to three inlets is calculated including wall interaction and heat exchange.
   - Module for two-phase flow prediction at the exit of a post-turbine Heat exchanger. It is based on the geometry and exchanged heat.

C) Experimental validation of the tools. The experimental validation covers both, fog plume model and the flow downstream of the selected ECS elements. Initially, part of the experimental data is used for fine tuning of the models. After this, the rest of the data is used for validation these models. For this purpose, three measurement campaigns have been accomplished:

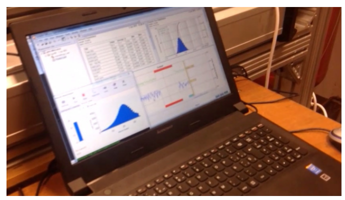
- Test campaign for validation of turbine outlet and post-turbine heat exchanger outlet.
- Test campaign for validation of the axisymmetric nozzle fog model.
- Test campaign for validation of generic mix-manifold outlet.

For all campaigns the instrumentation bench was developed in this work package. For the first and the third also the experimental test bench was developed.

Experimental validations

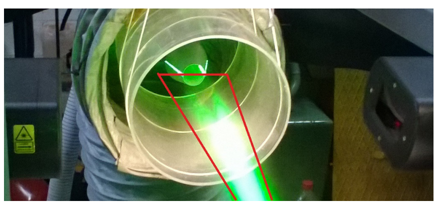


(Fog entity criterion)

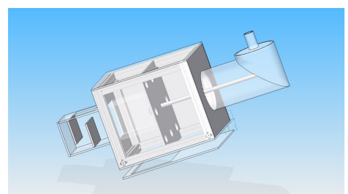


(fog droplet profile measurement)

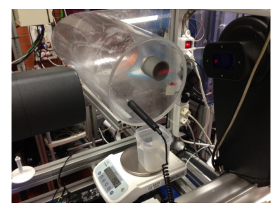
(jet validation test bench).



(Marginal fog visualization)



(generic mix-manifold design)



(Mix-manifold tests)

## 4.- Potential impact and main dissemination activities and exploitation results

### 4.1.- Environmental benefits

Due to the extensive use of air breathing devices, the operating improvements based on the application of this tool will generate benefits much larger than the cost of the project.

As commented above, 1% improvement in the energetic performance of aircraft ECSs would save 36.000 tons/year of kerosene (in the order of 10 million euro). This means a reduction of the emissions to the atmosphere of 100.000 tons/year of $CO_2$ and a saving of 400 TWh/year of energy. These benefits alone are orders of magnitude larger the cost of the project.

Extension to other devices like power plant cooling towers or steam turbines would increase these benefits by additional orders of magnitude.

In the long term, the increase of knowledge on fog generation and evolution can also be applied to many other fields related to the environment (e.g. pollutant dispersion prevention or aerosol cleaning procedures).

**4.2.- Maturity of works performed**

The computational tool and the axisymmetric nozzle jet model generated in the project are mature for industrial use.

The experimental data is fully compiled and provides information that is not usually available, given the difficulty to measure small fog particles.

In scientific terms, further research on these two-phase flows is of interest, given the large amount of know-how acquired along the project.

**4.3.- Dissemination plan**

Due to the difficulties during the project, although the dissemination plan is active, it will be carried out in full after the termination day of the project. This is assured by the interest of the academic institutions involved. As an example, in the previous European project, 9 journal publications were produced after the termination day. The dissemination plan includes:

- Project web page content:
  - Droplets laden nozzles experimental images without numerical data
  - Automotive turbo-compressor experimental facility
  - Malvern measuring laden jets
  - Turbulent jet mixing profiles and reference to stabilization of equations
  - Jet measurement test bench
  - Generic mixmanifold test bench

- Journals and Congresses projected contents:

(i) Generic numerical means developed that are not related to the project exploitation possibilities.

(ii) Depending on exclusivity contract, the previous contents would be expanded to include full publication of the project results.

**4.4.- Exploitation**

An exclusivity agreement will be attempted with the Topic Manager. In case this is not reached, there are no immediate plans to offer it to other companies but there is the intention of publishing the results in scientific journals as generic objective of the academic institutions involved.

**Project Summary**

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| Acronym: | HOT |
| Name of proposal: | Humidity Optimisation Tool |
| Technical domain: | Two phase flow visibility, thermodynamics and fluid-mechanics |
| Involved ITD | Systems for Green Operations |
| Grant Agreement: | 632508 |
| Instrument: | Clean Sky JU |
| Total Cost: | 275,000.00 Euro |
| Clean Sky contribution: | 206,250.00 Euro |
| Call: | CS-2013-2-SGO-02-080 |
| Starting date: | 1st December 2014 |
| Ending date: | 30th November 2016 |
| Duration: | 24 months |

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