18th Brazilian Congress of Thermal Sciences and Engineering
November 16–20, 2020 (Online)

ENC-2020-0522
IN-FIGHT ICING INSTRUMENTATION SYSTEM: A SYSTEMATIC LITERATURE REVIEW

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Abstract. Context: *The test data generated by the icing flight test instrumentation system is proof of the aircraft's capacity to operate safely in-flight icing conditions, continuous or intermittent.* ***Objective:*** *The objective of this systematic review is to analyze research about sensors for measuring in-flight ice particles and other types of equipment of an icing flight test instrumentation system aiming to develop a new system test.* ***Method:*** *The Systematic Literature Review (SLR) is the basis of the work.* ***Results:*** *51 studies have demonstrated relevant information to support the development of a new ice instrumentation system* ***Conclusions:*** *The synthesis of new technologies and sensors found it would be possible to start a project to develop a new ice instrumentation system, being necessary to evaluate the maturity of the solutions presented.*

Keywords: *Flight Test Instrumentation, Icing sensors*

1. INTRODUCTION

According to analyses of the causes for the aircraft accidents in recent years, aircraft icing is a major external cause (Cao *et al.*, 2018). This chapter describes some elements of the problem formulation. Green (2006) used the National Transportation Safety Board (NTSB) Accident Database and Synopses, the Federal Aviation Administration (FAA) Accidents/Incidents Data System (AIDS) and the National Aeronautics and Space Administration (NASA) - Aviation Safety Reporting System for a research about Inflight Icing accidents and Incidents from 1978 to 2002. The research (Green, 2006) shows that the event sequences were modeled of the aircraft stall followed by loss of control is the most common occurrence, followed by hard landings.

Appiah-kubi (2011) updated the research of Green (2006) with the US inflight icing accidents and incidents from 2006 to 2010. The databases revealed 228 icing related accidents and 30 inflight icing related incidents. The analysis showed that 40 of the accidents were related to inflight icing occurring on the wings, fuselage or control surfaces. This research (Appiah-kubi, 2011) was determined that icing events depended more upon the use and effectiveness of ice protection system (IPS) equipment as well as the management of ice accretion by the aircrew. Cao *et al.* (2018) show that aircraft icing influences the flight safety.

This paper is organized as follows. Section 2 presents background and related work. The research methodology adopted to conduct the SLR is presented in Section 3. The results and the analysis related to our research questions are presented in Section 4 . Our conclusions are presented in Section 5.

2. BACKGROUND AND RELATED WORK

Concerning other related works, a search was made to search for other systematic literature reviews or literature reviews of the development of any flight test instrumentation system. Some bases were searched with a probability of finding a job related to Flight Test Instrumentation. The bases surveyed were the American Institute of Aeronautics and Astronautics (AIAA) (https://arc.aiaa.org/), Institute of Electrical and Electronic Engineers (IEEE) (https://ieeexplore.ieee.org/ Xplore/home . jsp) and ProQuest - Aerospace Database (https://search.proquest.com/). In addition to these bases, it was also searched for systematic literature review works on Google Scholar. The search strings used were applied to the title of the articles. A search set for this: (flight AND test AND instrumentation AND systematic AND "literature review"). Another set of searches was: (flight AND test AND instrumentation AND literature AND review). For any of the search options and on any basis, no results from the previous study or work related to a systematic literature review or just a literature review for a Flight Test Instrumentation System were returned.

2.1 In-flight Ice Formation

According to the European General Aviation Safety Team (2015), In-Flight Airframe Icing will occur on an aircraft if liquid water hits a part of the airframe which has a temperature below freezing. European General Aviation Safety Team (2015) also shows these environment characteristics to in-flight icing formation:

*Ice tends to form close to leading edges.

*It does not mean that the water droplets are in the solid-state in a cloud with freezing temperature and they can remain supercooled in the liquid state until –40°C.

*The ice spreads back and is less visible below 0°C.

*Convective clouds have generally supercooled droplets.

2.2 Flight Test

According to Ward *et al.* (2006), flight testing piloted is an interdisciplinary process fundamental to the development of new systems and to the advancement of aeronautical knowledge. As described by Ward *et al.* (2006), a full-scale aircraft prototype for a flight test is required to demonstrate the requirement validation and all aircraft manufacturers fly prototypes to check their design assumptions before ramp-up of production. For Kimberlin (2003), the flight testing involves engineering disciplines and the purpose is to validate and refine the design, determine if aircraft can be operated safely by its crew, or have data compiled from the systems, quality, and performance of the aircraft.

Kimberlin (2003) mentions that the flight test results will be compared with established requirements for flight safety and those government organizations manage these regulations.The Federal Aviation Administration (FAA) is the government organization which manages flight test in the United States. Other countries have similar organizations and an aircraft manufacturer only can sell your product if its model completed your flight test with success (Kimberlin, 2003). The two major international governing bodies present the regions with the largest aircraft manufacturers are the FAA in the USA and the European Union Aviation Safety Agency (EASA) for Europe. The National Civil Aviation Agency (ANAC) is a federal regulatory agency whose responsibility is to regulate and supervise civil aviation activity in Brazil, both concerning its economic aspects and about the technical safety of the sector.

2.3 Certification

Airbus is one of the largest aircraft manufacturers of the World and according to them (AIRBUS, 2020), Certification is a regulatory obligation. A Type Certification is issued by a regulatory body and means that the operation and manufacture of a specific airplane model comply with design and airworthiness requirements. AIRBUS (2020) also shows that an aircraft operator can only operate his aircraft if the specific model has a Type Certification issued for the operation region and the certification process have the following phases: Design review, Test review and ground tests, Test review and flight tests, and Aircraft operators.

The Title 14 of the Code of Federal Regulations (14 CFR) Part 25 is the aircraft certification standard for the United States whose regulatory agency is the Federal Aviation Administration (FAA) and the CS-25 is the regulation for the European Union whose regulatory agency is the European Aviation Safety Agency (EASA) (AIRBUS, 2020). The RBAC (Regulamento Brasileiro da Aviação Civil) 21 regulations establish the requirements to obtain the Type Certification in Brazil by the Agência Nacional de Aviação Civil (ANAC, 2019). The Project Sense for Ice (Sense4Ice, 2020) mentions that for the flight icing conditions operation, the aircraft manufacturer must demonstrate to the respective regulatory agency that your aircraft model is compliant with the airworthiness requirements according to Appendix C of 14 CFR Part 25 and the CS-25. Supercooled Large Droplets (SLD) have caused aircraft accidents over the last three decades (Sense4Ice, 2020) and Appendix O of 14 CFR Part 25 is a new certification rule created by the regulatory agencies due to these accidents on this atmospheric conditions. Appendix C of the 14 CFR Part 25 (FAA, 2011) defines the Atmospheric Icing Conditions for the continuous maximum icing, intermittent maximum icing and Ice accretions parameters. Appendix O of 14 CFR Part 25 (FAA, 2016) describes the atmospheric conditions, flight qualities performance of the aircraft, volume diameter of supercooled large droplets, and other airworthiness requirements.

2.4 Flight Test Instrumentation (FTI)

Crounse (2005) describes that the purpose of a flight test instrumentation system is to register and recorder the data of the flight test campaign providing access for system engineers analysis the aircraft performance. According to Eshelby and Gregory (2000), the purpose of the flight test instrumentation system is to register the evidence of aircraft performances during flight tests. The Flight Test Engineer (FTE) and the System engineers define the aircraft parameters and requirements for the flight tests. Test specifications compose part of the requirements for the development of flight instrumentation systems. The Instrumentation engineer develops the Flight test Instrumentation design for the installation in the aircraft. During the flight tests, the FTE evaluates the aircraft performance through the solutions and parameters installed in the prototype aircraft according to Crounse (2005).

Airborne Instrumentation systems can be composed of some basic components showed by Crounse (2005): many transducers, signal conditioners, modulators, multiplexers, Test Recorders, Telemetry systems, and Special systems that are some systems associated with special tests like aircraft's flutter modes, icing tests, and other cases.

The Icing Instrumentation system is one of the special instrumentation systems of a prototype aircraft. The main function of this system is to record the parameters that demonstrate the test conditions according to Appendix C and O of CFR Part 25 / CS-25, complying with the minimum flight quality requirements. The test result is a proof of the aircraft can operate safely on in-flight icing conditions. In general, the aircraft manufacturing companies use the solutions of these suppliers for an Icing test campaign to certify their products: Science Engineering Associates Inc. (SEA) (SEA, 2020) and Droplet Measurement Technologies (DMT) (DMT, 2020).

3. RESEARCH METHODOLOGY

This section presents the design and the execution of the Systematic Literature Review (SLR). The research methodology to conduct the SLR was based on the guidelines proposed by Kitchenham *et al.* (2009), Unterkalmsteiner *et al.* (2012) and Mian *et al.* (2007). The SLR will identify gaps in the literature and provide a framework for new researches.

3.1 Review Protocol

The review protocol has a structure with the definition of research questions, search process, criteria for inclusion and exclusion of papers, quality assessment, data extraction, data analysis, and dissemination (Unterkalmsteiner *et al.*, 2012) according to Figure 1.

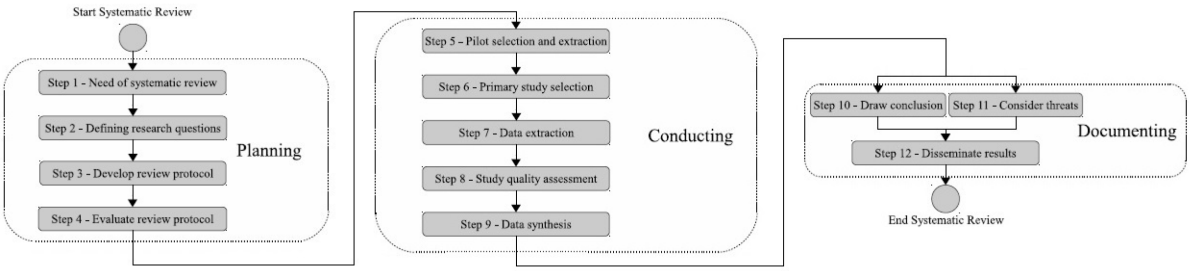


Figure 1. Protocol adapted from Unterkalmsteiner *et al.* (2012)

3.2 Research Questions

The research questions (RQ) are exactly what we want to answer with the SLR based on primary studies. There are 4 questions plus 2 as sub-questions.

*RQ1: What are the ice measurement technologies developed in the last 10 years?

*RQ1.1: What kind of new methods and technologies to measuring in-flight ice droplets were researched?

*RQ1.2: What are the new sensors developed for measuring in-flight ice droplets?

*RQ2: What kind of data acquisition system was used to test in this researches?

*RQ3: What is the technological maturity of the found solutions for measuring ice droplets?

*RQ4: What are the installation requirements of the new icing sensors?

The purpose of the RQ.1 is to identify all technologies used and developed in the last 10 years about icing conditions measurements. The purpose of the RQ1.1 is to identify the possibilities of new methods and technologies to measuring ice droplets regardless of the stage of sensor development. The purpose of the RQ1.2 is to identify some new icing sensors in the last 10 years. The purpose of the RQ2 is to identify the data acquisition systems used for the signal condition of icing sensors. The purpose of the RQ3 is to identify the research and development stage of any component of a data acquisition system. The purpose of the RQ4 is to identify requirements or ways of installing the sensors for the tests performed and assist in decision making for selection.

3.3 Search Strategy

The selected resources chosen were American Institute of Aeronautics and Astronautics (AIAA) (https://arc.aiaa.org/), American Meteorological Society (AMS) (https://journals.ametsoc.org/), Cranfied CERES (https://dspace.lib.cranfield.ac.uk/), Emerald Insight - Aircraft Engineering and Aerospace Technology (https://www.emerald.com/insight/publication/issn/0002-2667), International Council of Aeronautical Sciences (ICAS) (https://www.icas.org/Papers_previous_congresses.html), Institute of Electrical and Electronics Engineers (IEEE) (https://ieeexplore.ieee.org/Xplore/home.jsp), NASA Technical Reports Server (https://ntrs.nasa.gov/), ProQuest - Aerospace Database (https://search.proquest.com/),Science Direct (https://www.sciencedirect.com/journal/aerospace-science-and-technology), and Scopus ([http://www.scopus.com).

The search strings were refined and defined based on the elements of an ice instrumentation system. The following search string was used to search within title, abstract, and full text of the publications: ("aircraft icing" OR "droplet measurement" OR "droplet sensor" OR "MVD") AND ("ice droplet" OR "ice crystal" OR "ice particle" OR "water droplet" OR "Ice instrumentation" OR "Icing instrumentation" OR "Ice test" OR "Icing test" OR "LWC") AND ("Ice sensor" OR "Icing sensor"). The Liquid Water Content (LWC) and the Median Volume diameter (MVD) are parameters for characterizing ice condition measurements.

3.4 Inclusion and exclusion criteria

The study selection criteria were determined based on that papers should be scientific articles from journals, magazines, and conferences related to flight test instrumentation.

The inclusion criteria were defined as Primary articles from the last 10 years, articles about types of equipment and sensors for in-flight icing instrumentation, and articles related to measurement techniques of in-flight ice particles. The exclusion criteria were defined as Secondary studies, researches until 2009, studies not related to Icing Instrumentation, short papers (less than 4 pages), and articles related to instrumentation equipment from SEA and DMT suppliers.

3.5 Procedure for studies selection

The studies were obtained from electronic databases using the search string. AIAA returned 59 titles, AMS 9, Cranfield CERES 13, Emerald 16, ICAS 18, IEEE Xplore 134, Nasa Technical Reports Server 24, ProQuest 48, Science Direct 73, and Scopus 176 search results. On this Stage 1 (Table 1), the citations of this search results (570) were downloaded and organized with the Parsifal tool. Out of 570 search results, 488 were unique according to Parsifal duplicate analysis (Stage 2 - Table 1). After reading the title and the abstract of the papers, we excluded 427 studies, based on the exclusion criteria. After this criteria application, 61 papers remained in the selection process (Stage 3 - Table 1). After reading and analyzing 61 papers left for the full-text reading, and applied the Quality Assessment, it was obtained 51 relevant papers for data synthesis (Stage 4 - Table 1). The detailed result of the study selection is described in Table 1.

Table 1. Stages and number of selected studies

Source	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
AIAA	59	49	11	11
AMS	9	9	0	0
Cranfied CERES	13	13	2	2
Emerald Insight	16	15	4	4
ICAS	18	18	1	0
IEEE	134	111	17	11
NASA TRS	24	22	7	6
ProQuest	48	39	3	2
ScienceDirect	73	68	8	7
Scopus	173	144	8	8
Total	**570**	**488**	**61**	**51**

3.6 Data extraction and syntesis

The data were extracted according to Figure 5 from each of the 51 primary studies included in this SLR. During the synthesis process, data were collected from any component of an ice instrumentation system.

3.7 Quality assessment

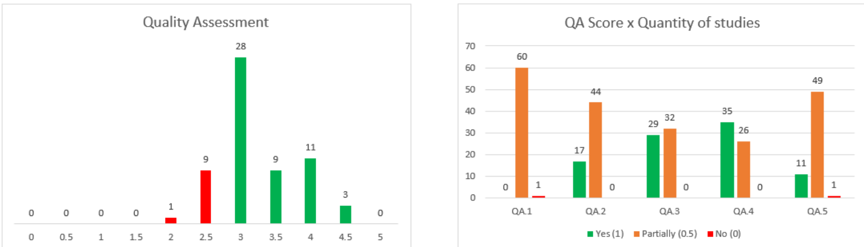
According to Kitchenham Kitchenham *et al.* (2009), the quality assessment is critical in a SLR to investigate and classify the quality differences of differences study results. The quality assessment (QA) of the studies in the SLR was achieved by a scoring technique to evaluate the completeness and relevance of the selected studies. All papers were evaluated against a set of 5 quality criteria. The quality assessment were defined as:

*QA1. Does the study answer the research questions?
*QA2. Is the research methodology explained clearly?
*QA3. Does the study explain the context in which the research was conducted and the concepts were applied?
*QA4. Is the research detail sufficient to understand all stages of development?
*QA5. Does the research demonstrate all the final results with the possibility of reproduction?

Each quality assessment question has 3 scoring options: “Yes” (score = 1), “Partially” (score = 0.5) or "No" (score = 0). The result of the quality assessment of each research is the sum of the five scores for the quality questions of the respective study.

3.8 Quality assessment results

The quality assessment helped in the validation of the studies. The maximum score for Quality Assessment per article was 5. Studies were chosen with a score equal to or greater than 3. The result was that 83.6% of the 61 studies reached a score equal to or greater than 3. As shown in the graph in Figure 2-a, the result the most repeated of the individual notes of the articles was 3, which is the amount of 28 articles. There were no articles reaching the maximum score of 5, but 4 studies reached a score of 4.5, 11 studies were rated 4 and 9 studies with a score of 3.5. The 9 studies with score 2.5 and 1 study with score 2 were discarded for the next stage of stratification of results due to quality criteria for not having a score equal to or higher than 3.



a) Quality Assessment b) QA Score x Quality of studies

Figure 2. Quality assessment results [The Author]

The Figure 2-b presents an analysis of the Quality Survey for each question. In an evaluation for each quality question, QA.1 was partially attended by 60 studies, 1 study that did not meet, and no article reached the highest grade in this question. For QA.2, 17 studies reached the maximum score and another 44 articles met partially. For QA.3, 29 studies answered completely and 32 studies answered partially. For QA.4, 35 articles answered completely and another 26 studies answered partially. QA.5 has been fully answered by 11 studies and partially by 49 studies. QA.1 was the only question where no article completely answered, demonstrating that there was no article that completely answered all the research questions. During the research of other systematic reviews of the literature on the ice test instrumentation system, no related studies were found in the researched databases.

3.9 Theats to validity

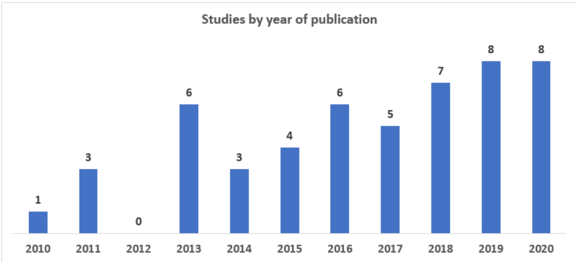
Information on specifications essential to the full functioning of the device may be lacking, compromising the reproduction of results. Due to not finding previous systematic literature reviews, the sources of research were expanded, but technical reports and patent searches were not included. They were also not compared if any of these studies were patented. Because it is a high-tech and strategic issue for companies, it may be that developed products have become patents.

4. RESULTS AND ANALYSIS

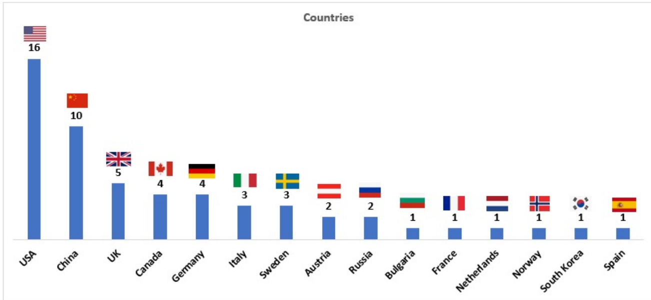
This section describes the results of the SLR. The answers to each research question will be discussed separately. The selection process resulted in 61 studies that met the inclusion criteria and we extracted the data following the extraction form described in the Table 1 of the 51 most relevant studies after the quality assessment had been applied. The results are presented by an overview of general findings and analysis for each research question.

4.1 Overview of the studies

The selected studies were published between 2010 and 2020. In Figure 3-a, it is present the number of studies by year of publication. According to the inclusion criterion, studies from the last 10 years were selected. Figure 3-a shows that

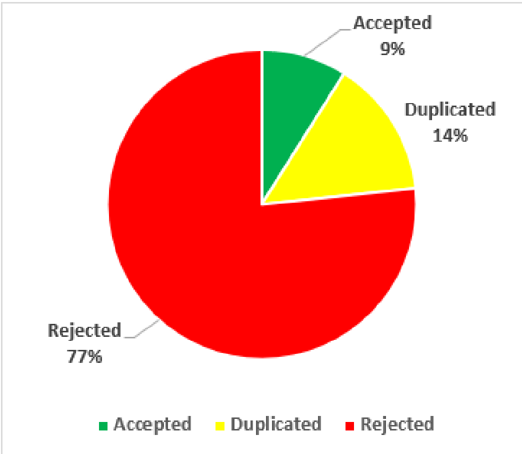


a) Studies by year of publication

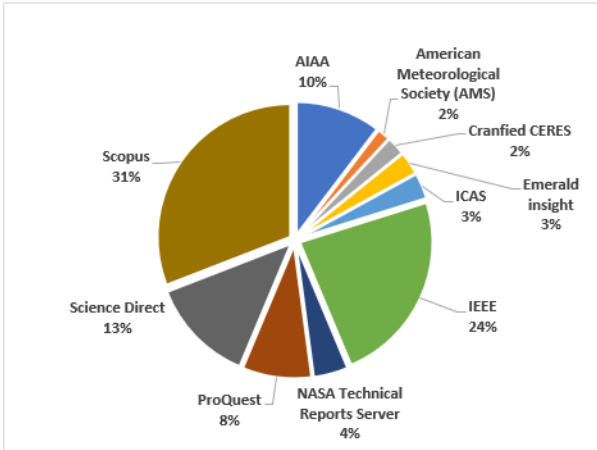


b) Countries of Author's studies

Figure 3. Studies analysis [The Author]



a) Selected studies



b) Research database analysis in the Stage 1

Figure 4. Database analysis [The Author]

there are no articles identified in 2012 and most studies are concentrated in the last 5 years. In 2010 there was 1 study, 3 studies in 2011, 6 studies in 2013, 3 studies in 2014, 4 studies in 2015, 6 studies in 2016, 5 studies in 2017, 7 studies in 2018, 8 studies in 2019, and 8 studies in 2020. The last 2 years have been with the largest number of studies per year.

The distribution of studies selected was analyzed according to the author's country. Figure 3-b shows that the studies are spread over several countries. Austria has 2 studies, Bulgaria has 1 study, Canada has 4 studies, China has 10 studies, France has 1 study, Germany has 4 studies, Italy has 3 articles, the Netherlands has 1 study, Norway has 1 study, Russia has 2 articles, South Korea has 1 article, Spain has 1 article, Sweden has 3 studies, the United Kingdom has 5 articles and the United States has 16 studies. According to this selection, the United States is the country with the largest number of studies on the instrumentation of flight icing tests.

There were 570 studies selected in the Stage 1 after applying the search strings in the research bases (Table 1). At the end of stage 4, 9% of the studies were accepted, 14% were duplicates and 77% were rejected. This analysis is shown in Figure 4-a. In search of Stage 1 selection, AIAA had 10% of studies, AMS 2%, Cranfield CERES 2%, Emerald Insight 3%, ICAS 3%, IEEE 24%, NSA TRS 4%, ProQuest 8%, Science Direct 13%, and Scopus 31%. Figure 4-b shows this analysis and the IEEE source return more studies than other research databases. In the Table 1 it is possible to observe that the AMS and the ICAS did not have any studies selected in Stage 4 for data extraction. After Stage 4, the IEEE and the AIAA were the research bases with the largest number of selected studies.

4.2 Research Questions analysis

The Research Questions analysis shows the correlation between the 51 selected studies and the research questions. The references cited in each analysis demonstrates some findings that it was extracted from the respective study even if it partially answered the question.

4.2.1 RQ1:What are the ice measurement technologies developed in the last 10 years? RQ.1.1: What kind of new methods and technologies to measuring in-flight ice droplets were researched? RQ1.2: What are the new sensors developed for measuring in-flight ice droplets?

An analysis of RQ.1 and its sub-questions (RQ1.1 and RQ1.2) were made together due to complementary information. All selected articles have some information related to these RQs. This research question can be summarized with the following topics about sensors or ways icing measurements: Item Icing quantification and mapping, Carbon Nanomaterial-Based material, Wind Tunnel sensors, Optical sensing, RadarDoppler Spectra, Aircraft Supercooled Icing Model, Capacitive ice sensor, Temperature sensors, Imaging detection imaging, Electromechanical Resonant Ice Protection Systems, Embedded Temperature anti-icing, Electrothermal and eletromechanical Component, Droplet Imaging Instrument, Icephobic mateiral, Temperarature measurment by Imaging, Ice accretion measurement by Imaging, Ultrasocinc guided waves, Ultrasonic Sensor, Icing scaling Method, Heaters by induction, IKP2 probe, Shadowgraph Measuring, Spectroscopy, Imaging equipments for Icing tests, and Fiber optics for icing accretion measurements (Strunin and Zhivoglotov, 2014; Thompson *et al.*, 2017; Chang *et al.*, 2016; Boudala *et al.*, 2019; Bakhoum *et al.*, 2014; Struk *et al.*, 2017; Boinovich *et al.*, 2013; Lamraoui *et al.*, 2013; Bartkus *et al.*, 2017; Ikiades *et al.*, 2013; Luke *et al.*, 2010; Kong and Liu, 2014; Cho *et al.*, 2015; Rieman *et al.*, 2020; Thornberg and Rydblom, 2016; Pommier-Budinger *et al.*, 2018; Knoll *et al.*, 2020; Iuliano *et al.*, 2011; Ding and Chang, 2020; Rydblom *et al.*, 2019; Esmeryan, 2020; Struk *et al.*, 2011; Waldman and Hu, 2016; Soltis *et al.*, 2015; Struk *et al.*, 2018; Mendig *et al.*, 2018; Shen *et al.*, 2019; Irajizad *et al.*, 2019; Liu *et al.*, 2011; Dong, 2019; Villar *et al.*, 2019; Strapp *et al.*, 2019; Rydblom and Thörnberg, 2016; Leitzke and Zangl, 2019; Zeng *et al.*, 2020; Bachelor *et al.*, 2020; Zou *et al.*, 2013; Davison *et al.*, 2020; Struk *et al.*, 2013; Dong and Ai, 2013; Liu *et al.*, 2017).

4.2.2 RQ.2: What kind of data acquisition system was used to test in this researches?

This research question can be summarized with the following topics about softwares, concepts and data acquisiton systems for an icing instrumentation system: Lewice, PSpice/Multisim, Deep Neural Network softwares (Caffe, Tensorflow, Theano, and Paddlepaddle), NUAA-ICE2D, PoliMIce, LEWICE3D, LabView, C++, VC software, MATLAB 2017, IBM Rhapdosdy, DS Simulia Dymola, Mtatworks Simulink, OpenModelica, Icing detection model, Eulerian method for new supercooled large droplet modeling, and Decision-making system (Strunin and Zhivoglotov, 2014; Thompson *et al.*, 2017; Chang *et al.*, 2016; Wang *et al.*, 2018; Boudala *et al.*, 2019; Bakhoum *et al.*, 2014; Dong, 2018; Guo *et al.*, 2016; Zocca *et al.*, 2017; Fujiwara *et al.*, 2020; Ikiades *et al.*, 2013; Kong and Liu, 2014; Thornberg and Rydblom, 2016; Iuliano *et al.*, 2011; Soltis *et al.*, 2015; Irajizad *et al.*, 2019; Liu *et al.*, 2011; Dong, 2019; Villar *et al.*, 2019; Strapp *et al.*, 2019; Rydblom and Thörnberg, 2016; Leitzke and Zangl, 2019; Zeng *et al.*, 2020; Bachelor *et al.*, 2020; Zou *et al.*, 2013; Davison *et al.*, 2020; Struk *et al.*, 2013; Dong and Ai, 2013; Liu *et al.*, 2017).

4.2.3 RQ.3: What is the technological maturity of the found solutions for measuring ice droplets?

This research question can be summarized with the following topics about test installation locations and maturity for installation on the aircraft: CYOD airport, Wind tunnels, Laboratories, NASA Glenn's Icing Research, NASA Glenn Research Center's Propulsion Systems Laboratory (PSL), Testing chamber, Fog Chamber, Icing Wind Tunnel, NRC cascade wind tunnel, Iowa State Icing Research Tunnel, NRC Research Altitude Test Facility, YBF-02 icing tunnel, NRC Convair 580, NASA DC-8, Convair, and A340 flight tests (Strunin and Zhivoglotov, 2014; Thompson *et al.*, 2017; Boudala *et al.*, 2019; Bakhoum *et al.*, 2014; Guo *et al.*, 2016; Struk *et al.*, 2017; Lamraoui *et al.*, 2013; Zocca *et al.*, 2017; Fujiwara *et al.*, 2020; Bartkus *et al.*, 2017; Cho *et al.*, 2015; Rieman *et al.*, 2020; Thornberg and Rydblom, 2016; Pommier-Budinger *et al.*, 2018; Norde *et al.*, 2018; Rydblom *et al.*, 2019; Struk *et al.*, 2011; Mendig *et al.*, 2018; Liu *et al.*, 2011; Strapp *et al.*, 2019; Rydblom and Thörnberg, 2016; Leitzke and Zangl, 2019; Zeng *et al.*, 2020; Bachelor *et al.*, 2020; Zou *et al.*, 2013; Davison *et al.*, 2020; Struk *et al.*, 2013).

4.2.4 RQ.4: What are the installation requirements of the new icing sensors?

This research question can be summarized with the following topics about shape of sensor or installation requirements: Probe and Camera (Strunin and Zhivoglotov, 2014; Thompson *et al.*, 2017; Boudala *et al.*, 2019; Bakhoum *et al.*, 2014; Guo *et al.*, 2016; Struk *et al.*, 2017; Lamraoui *et al.*, 2013; Sørensen *et al.*, 2015; Armanini *et al.*, 2016; Bansmer *et al.*, 2018; Ikiades *et al.*, 2013; Luke *et al.*, 2010; Cho *et al.*, 2015; Rieman *et al.*, 2020; Thornberg and Rydblom, 2016; Knoll *et al.*, 2020; Rydblom *et al.*, 2019; Waldman and Hu, 2016; Mendig *et al.*, 2018; Rydblom and Thörnberg, 2016; Leitzke and Zangl, 2019; Zeng *et al.*, 2020; Zou *et al.*, 2013; Davison *et al.*, 2020)

4.2.5 Findings about a New Icing Instrumentation architecture

Figure 5 shows a summary of the information found in the 51 selected studies. This information is structured according to the architecture of an ice instrumentation system and shows many possibilities of combined solutions to the integration and development of a new in-flight icing instrumentation system.

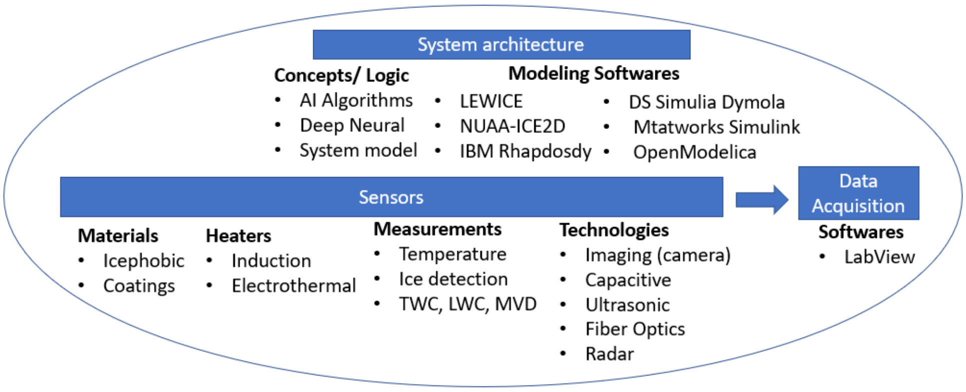


Figure 5. New FTI architecture according research findings [The author]

5. CONCLUSION

Through research questions, it was possible to conduct the efforts and work of this research. The fact of not finding a correlated previous work did not allow a comparison with the search results. Through RQ.1 it is also possible to verify that none of the studies selected in the last 10 years have demonstrated all the information and specifications of a new ice instrumentation system. There may be new technologies for measuring ice that is not mentioned in the bases surveyed or that hold patents, and this may be due to characteristics in the aeronautical market and their protection of information. The United States of America and China are the countries that most demonstrated studies related to ice instrumentation. The most difficult information to find is related to the maturity of the searches. For implementation on an airplane, the sensor will have to prove to be in a laboratory operation maturity. Few studies have demonstrated a new sensor installed on the plane or with information on the number of hours of testing in the laboratory.

Figure 5 summarizes all technologies and sensors developed or under development based on this review. It is possible to state that with the combination of some studies found, a proposal for a new ice instrumentation system can be developed. There are incremental innovations in parts of the systems studied. As a next step, a product development project needs to be structured, placing this synthesis of figure 5 as evaluation options for each component, logic, system architecture, software, or technology mentioned. An integrated product development process will be necessary to ensure the successful implementation of the new system.

6. ACKNOWLEDGEMENTS

The authors would like to thank all aviation professionals who supported this research.

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