Atmospheric Ice Accretion Measurement Techniques

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ABSTRACT

Atmospheric icing on structures has proven to be an area of concern in many cold climate geographical regions like arctic and alpine. Difficulties encountered by the communication, construction and power industries in these areas are the subject of intense investigations for researchers from decades. Three main methods of investigation are generally employed by researchers to study atmospheric ice accretion on structures: a) continuous field measurements, b) lab based simulations using icing wind tunnel & c) numerical modelling. This paper presents a brief review study of various techniques to understand and measure the atmospheric ice accretion on structures, anti/de icing techniques and important parameters for numerical modelling of atmospheric ice accretion.

1. INTRODUCTION

Human activities are increasingly extending to the cold climate regions, where atmospheric icing will not only create human inconveniences, but will also affect human activities especially in the construction industry (communication towers and ski lifts), energy distribution (power network cables and towers), maritime activities, aviation conditions on the ground, meteorological observations and wind energy power production. Power network cables and radio masts have been damaged or destroyed on numerous occasions due to the added mass of ice or an increase in aerodynamic interaction leading to unacceptable movements [1]. The largest ice loads ever recorded on a power line is 305 Kg/m, which was recorded on a 22 kV overhead line in Voss, Norway on April 18, 1961[2]. Similarly; atmospheric icing on offshore structures such as ship masts, buoys, meteorological instruments and other structures causes many safety risks and inconveniences. During the past few decades, the need for better understanding of atmospheric icing in the marine environment has increased considerably due to human activities such as offshore oil drilling being intensified in Arctic and subarctic waters [3].

Atmospheric ice accretion takes place when a super cooled water droplet falls or moves with the wind and hits a structure and freezes. The complicated freezing phenomenon is affected by various properties such as air flow, the icing object and the impinging water droplets. When a super cooled water droplet hits a solid object, it spreads and turns into ice. The freezing process can be divided into two stages: first, part of the super cooled water in the droplet freezes rapidly, releasing the latent heat of fusion and thereby raising the temperature of the remaining water to 0 ^{o}C. In the second stage this remaining parts turns into ice, since the droplet gives up heat to its surroundings by convection, evaporation and conduction. The speeds of these processes determine the time required for this second stage [4] . Much progress has been achieved in understanding the physical process involved during

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atmospheric ice accretion on structures. Three main methods of investigation have been employed by researchers [5]:

1. Continuous field measurements of ice load and wind on ice load; allied with the simultaneous measurements of the meteorological variables.
2. Lab based simulations using an icing wind tunnel.
3. Construction of mathematical/numerical icing models.

Generation of an ice load database, with the corresponding historical weather database is of major importance and is vital in the validation of the experimental and theoretical simulations of the atmospheric icing process, but this involves high operational cost. The approach of employing an icing wind tunnel has an advantage that the effect of changes in the flow and thermal conditions on the accretion process can be readily reassessed and analysed. The main disadvantage of this method is that due to the many physical and meteorological variables, flow and thermal parameters controlling the ice accretion process, it is difficult to achieve a one to one correspondence between the icing wind tunnel and the field measurements. The third method involving the theoretical models, based on the known physics of the accretion process has obvious advantages especially, when implemented in the form of a mathematical model. However, icing models require the input of meteorological variables associated with the icing incident and often these are difficult to measure [5].

2. ATMOSPHERIC ICING ON STRUCTURES

Atmospheric icing on structures is a key factor when planning infrastructures in cold regions due to its huge economic consequences. Structures are not passive during ice accretion, but can experience devastating forces to which they respond [5]. Detailed knowledge on frequency and duration of icing events as well as maximum ice loads are crucial parameters for the design of structures in cold regions. Therefore the availability of robust field measurements under cold climate conditions will help in the planning for these regions.

The ISO (International standard organization) issued a standard # 12494 in 2001 for the atmospheric ice accretion measurement on all kinds of structures except for electric overhead line conductors. In this recommendation, a standard ice-measuring device is described as: a smooth cylinder with a diameter of 30mm placed with the axis vertical and rotating around the axis. The cylinder length should be a minimum length of 0.5 m, but for severe icing conditions it can be up to 1 m. The cylinder should be placed 10m above the terrain to give the consideration to maximum depth of the snow during winter [6, 7]. The vertical cylinder is not fully appropriate for freezing rain in the wet growth stage, for this purpose it is preferred to use sets of horizontal collectors (rods) which are orthogonally oriented, like the Soviet Standard Ice Collector or the Canadian Passive Ice Meter (PIM) as described in the IEC 60826: Design Criteria of Overhead Transmission Lines, 2003 [8]. This International Standard is intended for use in determining ice mass and wind load on the iced structure for the different types of structure, such as masts, towers, antennas and antenna structures, cables, rope ways (cable railways), structures for ski-lifts, buildings or parts of them exposed to potential icing, towers for special types of construction such as transmission lines, wind turbines, etc.

Ice accretion on structures is not only a function of environmental parameters such as liquid water content (LWC), temperature, wind velocity, droplet size, but is also dependent on the properties of the accreting object itself, such as, size (diameter, width etc.), shape (flat, sharp edges, cylindrical, spherical etc.), flexibility (rigid/flexible member in bending/torsion etc.) and orientation relative to wind direction (angle of incidence). And to some extent, it also depends on the surface structure (paint, steel, concrete etc.) and material (wood, steel, plastics etc.). Therefore measurements of ice accretion have to be specified with respect to the device, procedures and arrangements on testing site. The set-up must be designed in a way that causes the lowest possible influence on the accretion process itself. A standard reference device should always be part of the measurements, giving the traceability to standard measurements of ice accretion. Other parts of the set-up may help to establish the connections between "standard accretions" and the most important structural parameters as described above (size, shape, etc.).

On sites where melting or shedding are likely to occur shortly after the accretion period, observations must be carried out before this happens; for example by making use of camera systems. When automatic recordings are performed, it is important to add also visual observations during and/or after the accretion period, because only these types of observations can give sufficient information on such complex load situations. These visual observations have to be logged, and documented with appropriate digital camera pictures [9]. Following are some example cases of ice accretion on onshore structures.

2.1. ICE ACCRETION ON OVERHEAD POWER TRANSMISSION LINES

For electric overhead power lines installed in the cold regions, atmospheric icing is the most significant design parameter in economic terms. In recent years, there has been considerable research to study ice and wet snow accretion on overhead power transmission lines. Many ice accretion incidents involving overhead transmission lines have been reported. Icing particles carried by the wind adhere to the power line conductor and ice grows out into the wind direction. This causes an eccentric ice load on the windward side of the conductor and causes the conductor to rotate during the accretion process. Rotation of the conductor depends on the conductor stiffness and on the aerodynamic torque exerted by the wind. The International Electro-technical commission issued their IEC 60826 standard, which gives rules for design of overhead lines in order to make them function reliably under icing conditions [10]. The only requirement used in the IEC 60826 is that the "reference ice load" should be related to a "horizontal, circular conductor of 30 mm in diameter" [11]. IEC has also issued a Technical Report (IEC 61744), which includes a description of historical Meteorological test spans in Europe as well as in countries outside Europe for assessing climatic loads for overhead lines [12].

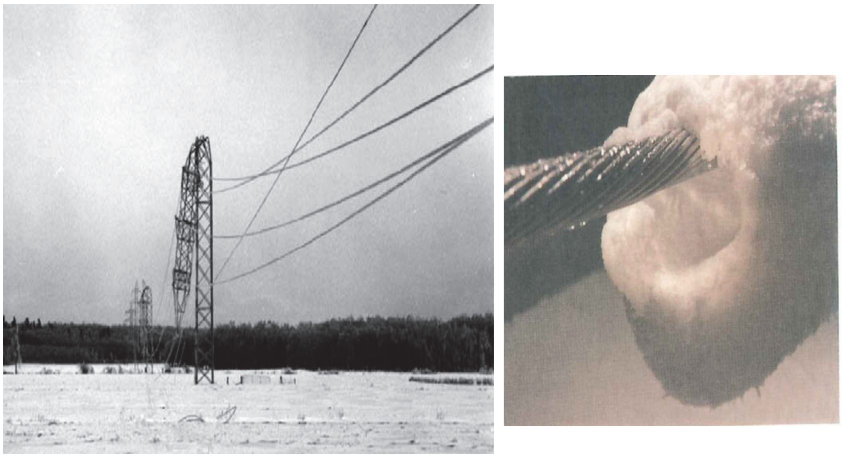

Figure 1: Example cases of ice accretion on overhead power network cables; source [13]

2.2. ICE ACCRETION ON COMMUNICATION DEVICES AND TOWERS

Atmospheric icing on communication transmission towers can cause problems ranging in severity from transmission pattern distortion to complete tower collapse. Ice accretion between antenna radiating elements can cause electrical shorting and equipment burnout. Also towers near populated areas are subjected to the added liability of falling ice chunks, which threatens lives and surrounding property. Many forms of ice can form on structures, depending on surface features such as shape, exposure and heat dissipation characteristics of the structure [14]. Many approaches have been used to prevent ice accretion on communication transmission towers to minimize its severity. Due to the large size of towers, many of the traditional anti icing and de icing methods are not cost effective when applied to whole towers. They are usually applied only to the sections immediately surrounding the antenna. Popular techniques used in this regard are shrouding, low adhesion coating and thermal heating.

Figure 2: Ice accretion on communication devices and towers on Fargnesfjellet near Narvik, Norway

2.3. ICE ACCRETION ON SUSPENDED BRIDGE CABLES

Blocks of ice falling from suspended bridge members in cold regions can cause traffic accidents, direct damages to vehicles and generally place human safety at risk. Denmark's great belt bridge, over the 3 years periods 2004-2007, has been closed for 12 hours per year on average, because of falling ice [15]. Similarly the Øresund Bridge has had to close 5 times during the last 12 years due to icing. A range of other Northern Europe bridges such as Uddevalla Bridge in Sweden and both the Severn bridges in UK have suffered from similar experiences. Anti icing and de icing systems are generally used to avoid icing on suspended bridges' cables [16].

2.4. ICE ACCRETION ON WIND TURBINES

Wind energy is a widely accepted source of power available everywhere in the world. Most northern regions of the world like arctic and alpine regions have good wind resources, but icing on wind turbines has been recognized as a hindrance to the development of wind power in these regions [17, 18]. A variety of problems due to icing on wind turbines have been documented including complete loss of power production, reduction of power due to the disrupted aerodynamics, overloading due to delayed stall, increased fatigue of components due to imbalance in the ice load [19] and damage or harm caused by the uncontrolled shedding of large ice chunks [20]. Annual power losses due to ice accretion on the wind turbine blades, at some sites subject to icing rate, are estimated to be about 20% [21].

3. ATMOSPHERIC ICE DETECTION AND MEASUREMENT

The main function of an ice measurement system is to detect and indicate the rate of an icing event. Every ice detection and measurement system has its own technique, they could be designed to measure the icing rate, the weight of ice and some are designed to indicate if an icing event is ongoing. There are two methods to measure the atmospheric icing on a structure, direct methods & indirect methods. The direct methods of ice detection are based on the principle of detecting property changes caused by ice accretion. The indirect methods of ice detection involve measuring weather conditions such as humidity, and temperature that lead to icing or detecting the effects of icing [6] . Empirical or deterministic models are then used to determine when icing is expected to occur [22]. One of the difficulties of ice detection is how to accurately represent the amount of ice accreting on a surface. Most ice detectors are point devices, that is, they measure icing rate, the presence of ice or its thickness at only one location. Yet, the interest of operators is often ice accretion over a large area, such as an antenna or wing. Users of ice detectors must recognize this problem when selecting detector technologies, when selecting detectors, and when interpreting signals from the detector [23, 24]. Following table below displays the mostly used prototype ice measuring instruments available on the market and reported by the COST-727 / WG2 participants in their 2006 report [9]:

Table 1: List of available and prototypes of atmospheric ice detectors in the market

Item	Instrument	Manufacturer
a	Rosemount 0872J / 0871LH1	Goodrich (USA)
	Rosemount 872C2 (ASOS-USA)	Goodrich (USA)
	SYGIVRE (Icing Rate Meter (IRM))	Hydro Quebec – Transénergie (CA)
	Vibrometer (Prototype)	Boschung (CH)
b	Infralytic IR detector (Prototype)	Infralytic (D), MeteoSwiss (CH)
c	T40 Series	HoloOptics (SE)
d	ICEmeter	IAP (CZ)
	METEO device	EGU (CZ)
	IceMonitor	Combitech (SE)
	ICECylinder (Prototype)	FMI (FI)
e	Rotating Multicylinder (Prototype)	VTT (FI), STATNETT (NO)
	Gerber	Gerber Scientific Inc. (USA)
f	Labko LID-3210C	Wavin-Labko (FIN)
g	Instrumar IM101 V2.4	Instrumar Inc. (CA)
h	Jokkmokk	Segerström (SE)

Table 2: Available techniques and devices of atmospheric ice detection

Year	Study/Company	Concept
2010	Owusu 2010 [25]	Capacitive Probe
2009	Labkotec Oy, 2009 (Company)	Ultrasonic principle
2008	Ryerson, 2008 [26]	Analysis of infrared red signal
2008	Goodrich, 2008 (Company)	Magnetostrictive principle
2005	Infrarlytic, 2005 (Company)	Differences in absorbing properties of materials
2005	Vibro-Meter, 2005 (Company)	Measurement of piezoelectric effects
2004	Maatuk, 2004 [27]	Effect of phase change on an icing surface
2003	Laakso et al., 2003 [28]	Monitoring of ice build on load cells
2003	Laakso et al., 2003 [28]	Impedance and temperature measurement
2003	Laakso et al., 2003 [28]	Infrared beam
2003	Seifert, 2003 [29]	Monitoring via camera
2002	Wallace et al., 2002 [30]	Measurement of electrical impedance
1999	DeAnna,1999 [31]	Movement or non-movement of a diaphragm due to water or ice covering it
1998	Lardiere and Wells, 1998 [32]	Monitoring the behaviour of a material with temperature
1996	Lee and Seegmiller, 1996 [33]	Measurement of electrical inductance
1996	Geraldi et al., 1996 [34]	Measurement of capacitance
1994	Federow and Silverman, 1994 [35]	Detection of refracted light along the surface of a plastic by a photo detector
1993	Goldberg and Lardiere, 1993 [36]	Strain and stress principles of an electro expulsive blanket
1993	Gerardi et al., 1993 [37]	Capacitance change (Piezoelectric sensor)
1990	Klainer and Milanovich, [38]	Variation in the optical properties of ice and water
1989	Khurgin, 1989 [39]	Covering an aperture by ice
1986	Hansman and Kirby, 1986 [40]	Ultrasonic principle
1984	Chamuel, 1984 [41]	Ultrasonic principle
1977	Magenheim, 1977 [8]	Transmission & monitoring of a low microwave signal into a layer of dielectric material

Existing atmospheric icing sensors are not robust enough and are mostly used mainly for detecting the presence of ice, but are not capable of measuring its distribution, thickness or composition. On the other hand, standard metrological sensors do not work properly during the icing conditions. In many cases it has been reported that even heating sensors, which were installed to detect icing for anti-icing or de-icing applications did not work properly under the icing conditions. A comprehensive literature review revealed that reliable and accurate measurements of ice accretion are scarce due to the fact that the available measurement techniques so far suffer problems in their accuracy and persistence under icing conditions. This fact makes it important to explore new methodologies in icing detection and measurement.

3.1. Atmospheric Ice Protection & Mitigation Techniques

Ice protection and mitigation technologies (Anti-icing and de-icing systems (ADIS)) are becoming more important since these reduce the huge losses caused by atmospheric icing on structures. The need for ice protection technologies is a function of the frequency and amount of ice accumulation on structures. The need for ice removal or its prevention may be urgently required so as to avoid the destructive effects of ice as the critical mass is reached. Practical means of removing ice and snow from structures prior to its critical mass accumulation can provide substantial benefits and savings to industry. Several ice protection techniques are being used by researchers to minimize the effects of ice accretion on structures and improve safety [42]. Icing mitigation systems result from two main strategies: anti-icing and de-icing systems (ADIS). Anti-icing prevents ice to accrete on the object, while de-icing removes the ice layer from the surface. Both strategies can also be further divided into two methods: Passive method and active method. Passive methods take advantage of the physical properties of the structure surface to eliminate or prevent ice, while active methods use external systems and require an energy supply that is either thermal, chemical or pneumatic [43]. Following are examples of anti/de icing techniques.

1. **Passive anti-icing and de-icing systems.**
    a. Passive anti-icing systems.
        i. Special coating.
        ii. Black paint.
        iii. Chemicals.
    b. Passive de-icing systems.
        i. Flexible turbine blades.
        ii. Active pitching (Semi-active).
2. **Active anti-icing and de-icing systems.**
    a. Active anti-icing systems.
        i. Thermal.
        ii. Air layer.
        iii. Microwave.
    b. Active de-icing systems.
        i. Heating resistance.
        ii. Warm air and radiator.
        iii. Flexible pneumatic boots.
        iv. Electro impulsive/expulsive.

Most icing prevention methods are active heating systems that need a control strategy. Simple and most common strategy for anti-icing system is to turn the heating on all the time, but this increases energy consumption [44]. Usually, the ADIS basic control includes an ice detection method that turn on the heating system when ice is detected. Anti-icing requires much more energy than de-icing because of the continuous heating. In theory, the surface temperature of the object must be kept above 0ºC whenever there is icing. Moreover, when ice melts on the heated elements, water can run back after the element and freeze again. To avoid this, the water must evaporate, which implies for the heated element temperature to be at least 100ºC. For de-icing systems, however, the power that is required to remove accretions already formed through rapid heating far exceeds the power required for anti-icing [45]. Icing identification must be fast to avoid power losses.

4. NUMERICAL MODELING OF ATMOSPHERIC ICING

Numerical modelling of atmospheric ice accretion is a complex coupled process and can be simulated by means of integrated thermo-fluid dynamic models. Progress has been made by researchers in the development of numerical models for predicting ice and snow loads on structures. Work continues in the construction of mathematical models and with the advent of more powerful computational resources, the availability of CFD based numerical codes for simulating airflow past structures and with the extension of field ice loads databases, great studies in the theoretical work are anticipated, especially in the modelling of more complex structures [5]. Several numerical codes for simulating the atmospheric ice accretion have been developed such as, LEWICE (USA), ONERA (France), DRA (UK), FENSAP-ICE (Canada) CIRAMIL (Italy) and TURBICE (Finland). Most of these numerical codes are based upon the potential flow theory base panel method and provide the results in a reasonable accuracy range. Numerical modelling of atmospheric ice accretion is based on four main steps, *1) Airflow field simulations 2) Droplet behaviour calculation 3) Boundary layer characteristic evaluation 4) Evaluation of rate and shape of ice accretion using a surface thermodynamic model.* These four fundamental modules deal with the various sub modules such as *a) evaluation of droplet trajectories b) Ice density calculation and c) Ice surface roughness calculation.* These sub-modules are connected with the main modules. The following sections briefly discuss the above mentioned sub sections.

4.1. AIR FLOW FIELD SIMULATIONS

To date, two types of numerical approaches are used by researchers to numerically model air flow behaviour. Euler's equation using the panel method or solving the complex non linear Navier-Stoke equation using the computationally expensive CFD solver. These equations are derived from three fundamental equations of conservation of mass, momentum and energy. A much simpler mean to obtain an approximate solution of the flow field is the panel method. This method assumes that the flow is incompressible, inviscid and irrotational. Potential flow theory is an approximate explanation of the flow externally of the viscous boundary layer and thus reasonable assumption for the high Reynolds number flows, where the boundary layer shows the schematic overview of the surface [46]. Potential flow theory based solution does not deal with the complex turbulence flows, whereas the Navier-Stoke's equation based numerical approach predicts the complex flow behaviours quite efficiently even at high angles of attack, where a large flow separation occurs.

4.2. DROPLET BEHAVIOUR

Calculation of droplet behaviour is connected with the air flow field calculations. In the Panel method approach; droplet behaviour can be calculated using the steady state equation of motion, while for CFD based simulations, droplet behaviour is calculated using the Lagrangian or the Eulerian approach. The Lagrangian method calculates the droplet behaviour by solving the motion equation of the droplets to track the trajectory of each droplet in the flow field, whereas the Eulerian two phase flow method treats the droplet as a continuum fluid, separate from, but interacting with, air. The Lagrangian approach can only be used for the case when the volume fraction of water droplet in the air is < 12% [47]. The Eulerian method has an advantage over the Lagrangian method as the same mesh can be used for the air flow and the droplets and the collection efficiency can be obtained on the solution of the droplets flow field directly meaning that particles do not have to be tracked. This also reduces the high computational power requirements.

4.3. BOUNDARY LAYER CHARACTERISTICS & ICED SURFACE ROUGHNESS

Calculation of the convective heat transfer coefficient is vital for the reliable numerical modelling of the atmospheric ice accretion. It depends upon the boundary layer properties such as, momentum, thickness and skin friction coefficient. Iced surface roughness has a huge impact on the numerical model, since roughness effects the boundary layer development and heat transfer, determining the final ice shape [48]. Surface roughness of accreted ice determines the location where the transition from laminar to turbulent takes place. Estimation of the boundary layer and surface roughness depend upon the Median Volume Droplet Diameter (MVD), droplet impact speed at stagnation line (V_o), Liquid Water Content (LWC) and ice surface temperature (T_s).

4.4. SURFACE THERMODYNAMICS

Ice accretion is a thermodynamic problem involving heat balance. The main thermodynamic contribution to the heat balance in this process consists of:

- **Latent heat**, Q_{latent}, is the heat released during freezing of the liquid water droplet. In simple terms; it is the amount of energy released or absorbed by a chemical substance during its phase change.
- **Aerodynamic heat,** Q_{aero}, is the heat caused by the viscous friction of the air flow.
- **Kinetic heat,** Q_{kin}, is the heat due to the collision of water droplets with the surface.
- **Convective heat,** Q_{con}, is the heat loss caused by the convection of air.
- **Evaporative heat,** Q_{evap}, is the heat loss due to the evaporation of air.
- **Sensible heat,** $Q_{sens,}$ is the heat loss caused by the temperature difference between the water droplet and object surface.
- **Radiative heat:** Q_{rad} is the heat loss due to radiation

$$Q_{lat} + Q_{aero} + Q_{kin} = Q_{con} + Q_{evap} + Q_{sens} + Q_{rad} \tag{1}$$

$$Q_{lat} = (1-\lambda)\alpha_3 F L_f \tag{2}$$

Where λ is the liquid fraction of accretion (normally set to a constant value of 0.3), α_1 is the droplet collision efficiency, α_2 is the droplet collection efficiency, α_3 is the droplet accretion efficiency and L_f is the latent heat of freezing that can be calculated by;

$$\begin{aligned} F &= \alpha_1 \alpha_2 w V A \\ Q_{aero} &= \frac{hRv^2}{2C_{p-a}} \end{aligned} \tag{3}$$

Where h is the convective heat transfer coefficient, R is the surface recovery factor (0.79 for cylindrical object), V is the incoming velocity and C_{p-a} is the specific heat of air [49].

$$Q_{kin} = \frac{FV^2}{2}$$
$$Q_{con} = h(T_s - T_a) \tag{4}$$

Where T_s is the surface temperature and T_a is the ambient air temperature.

$$Q_{evap} = \frac{h\,\varepsilon L_{vap}(e_s - e_a)}{c_p p} \tag{5}$$

Where k is the constant equal to 0.622, L_{vap} is the latent heat of vaporization, e_s is the saturation water vapour pressure at the surface, e_a is the vapour pressure of the ambient air and p is air pressure [50].

$$Q_{sens} = FC_{p-w}(T_s - T_d)$$
$$Q_{rad} = \sigma a(T_s - T_d) \tag{6}$$

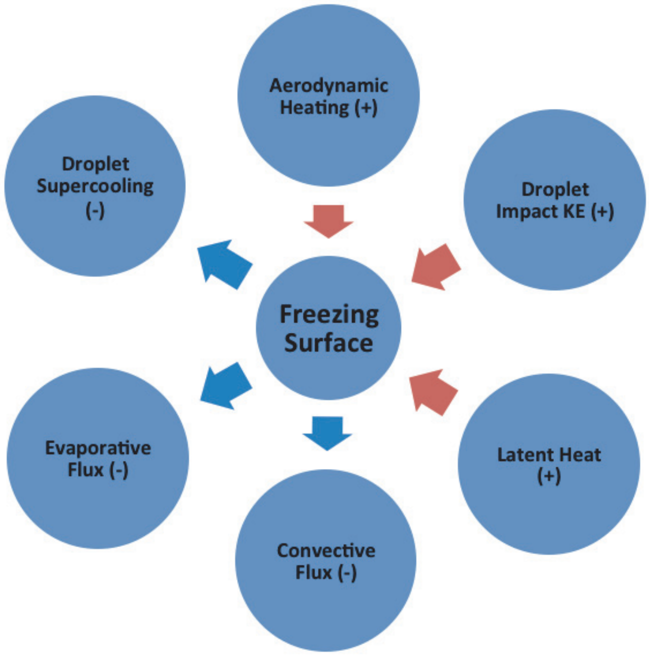

Figure 1: Heat Balance of the freezing surface

Where C_{p-w} is the specific heat of water and T_d is the droplet temperature. ? is the Stephan Boltzman constant (5.67e-10 w/m^2K^4). And 'a' is the radiation linearization constant (8.1e7 K^3). Analyses show that evaporation and convection on the cooling side and aerodynamic heating are the most important contributions to the thermal balance along the surface, while the kinetic heating and the sensible cooling contributions are almost negligible.

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