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Experimental characterization of water droplet deformation and breakup in the vicinity of a moving airfoil

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ABSTRACT

An experimental study is presented on the deformation and breakup of water droplets in the vicinity of an incoming airfoil. The experimental campaign was carried out at the INTA rotating arm facility in the context of the INTA-NASA collaboration. In this experimental setup, the flow past the droplets accelerates (in the reference frame of the droplets) which is a situation similar to the one found in actual aircraft flight. This is in contrast to most of the previous more fundamental experimental studies in which the flow past the droplet has a constant velocity. During the tests, the velocity of the incoming airfoils ranged between 50 m/s and 90 m/s. Three different symmetric airfoil models were tested. They all had a spanwise length of 0.2 m. The chord lengths were 0.690 m, 0.468 m and 0.199 m respectively. The leading edge radii of curvature were 0.103 m, 0.070 m, and 0.030 m respectively. The undisturbed droplet diameters were in the range from 364 μm to 1075 μm. The base flow field was characterized using a Particle Image Velocimetry technique. The droplets were tracked using a high speed imaging system. The rate of deformation of the droplets was measured and the deformation and breakup processes were recorded and correlated to the parameters that defined the base flow. It was found that, within the range of tested experimental conditions, the favored breakup mechanism was of the so-called "bag and stamen" type. However, flow acceleration tended to anticipate significantly the onset of this breakup mechanism as compared to previous experimental studies in which flow velocity was constant. This is important, for instance, for researchers that develop theoretical and numerical models of droplet-gas interaction for aircraft simulation purposes.

1. Introduction

One relevant technical aspect that aircraft manufactures need to deal with when assessing aircraft operation is in-flight icing. A rather comprehensive review of the phenomenon, its relevance, and the methods for its detection and identification can be found in the article published by Caliskan and Hajiyev [1]. Additional detailed studies focused on the influence of icing on aircraft stability, performance degradation, dynamic parameters, and stall conditions have been reported by Lampton and Valasek [2], Han and Palacios [3], Dong and Ai [4] and Campbell et al. [5] respectively.

Regarding the methodology used to study this phenomenon, it could be observed that many studies dealing with this problem are of a numerical nature. This has been explicitly argued by Aliaga et al. [6] in the introduction section of their article where they write: "*The dearth of open literature experimental results for three-dimensional geometries, the closely guarded proprietary ones, and the almost complete absence of experimental results for rotating components in icing conditions, reverses the traditional relationship of computational fluid dynamics* (*CFD*) *vis-à-vis experiments, by curiously setting CFD algorithmic innovations of in-flight icing as the driver for experimentation*". In this context, a number of numerical (CFD) approaches have been recently published by Aliaga et al. [6], Ghenai and Lin [7], Hasanzadeh et al. [8], Honsek et al. [9], Iuliano et al. [10], Jung and Myong [11], Nakakita et al. [12], Rendall and Allen [13], and Zeppetelli and Habashi [14]. In practice, these numerical approaches involve an extremely high degree of modeling complexity since multiphase compressible turbulent flows with changing geometries (the ice accretion effect) are considered. Therefore, it is customary to relax some of the model hypothesis so as to generate a software package or an algorithm that can be used for practical prediction purposes. Among the large number of hypothesis that make up these ice accretion models, one of the most difficult to deal with is the one related to the motion, deformation, and eventual breakup

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of the water droplets before they impinge on the airfoil/wing. The effect caused by these hypothesis is even more important when super-cooled large droplets, up to 1.5 mm in diameter, are considered. For example, Aliaga et al. [6] modeled droplet behavior as a dilute gas–particle system in which droplets, considered to be of spherical shape, are not allowed to coalesce, deform, splash or break up. Ghenai and Lin [7] prescribed the number of particle trajectories, density, size and distribution of water droplets. Hasanzadeh et al. [8] solved the equation of motion of the (spherical) droplets using a Runge–Kutta type scheme after estimating their drag from the previously computed flow field solution. Iuliano et al. [10] followed a similar approach and neglect the interaction of the particle liquid phase on the gas phase (one way interaction). Honsek et al. [9] accounted for droplet deformation and breakup using the semi-empirical correlations of Clift et al. [15] and Pilch [16] respectively. Jung and Myong [11] proposed a second order finite volume upwind scheme that facilitates the computation of the problem using an Eulerian formulation only. Rendall and Allen [13] used a Lagrangian formulation for the droplets but developed a finite volume representation for the streamlines that speed up the global algorithm convergence procedure.

Then, in this context, it is of interest to keep developing methods that are able to provide reliable information on the droplet deformation and breakup processes that can be fed into general purpose aerospace related numerical codes so as to improve their predictive capabilities; and this can be done either numerically or experimentally. A very comprehensive review on the current status of the physics of aero-breakup can be found in the recent article published by Theofanous [17]. In this article, the author discussed at length (based, mostly, on experimental results) all physical aspects related to the deformation and breakup of droplets in a gas stream. Specifically, it covered his personal work and the work of many other researchers. It starts with drop deformation, which sets the stage for the first critically, and, then, it continues discussing the two main mechanisms leading to breakup: Rayleigh–Taylor piercing and shear-induced entrainment. Another article, this one from the early nineties, which also contains a good discussion on the physical aspects and on the work performed up to that date is the one by Wierzba [18]. In particular, this author discriminated between six basic types of breakdown mechanisms: vibrational, bag, bag and stamen, chaotic, stripping and catastrophic. This is in line with a previous extensive review work published by Pilch and Erdman [19] who identified five different breakdown sequences. Regarding numerical methods aiming to understand the physics of droplet deformation and breakup, it is relevant to reference, for instance, the studies published by Tan [20], Chen [21], Fakhari and Rahimian [22] and Yeom et al. [23].

This well know problem of liquid droplet breakup induced by a high speed gas flow is, still, an active area of research because of the need for additional experimental information regarding those situations that are more specific to aerospace applications. In this context, Vargas and Feo [24] have recently published an experimental study in which a rotating arm facility with an airfoil placed at the arm length and equipped with a high-speed imaging system was used to gather information on a series of water droplet global parameters as they intersected the airfoil path. This experiment, that involved extensive visualization, could be considered as a first approach providing experimental insight into the phenomenon. This article was followed by a NASA Technical Memorandum, Vargas et al. [25], in which a breakup mechanism was proposed. It is to be noted that most of the fundamental research studies carried out so far have made use of shock tube type experimental facilities. This is important in the sense that these facilities provide a constant velocity flow during a short time that, nevertheless, applies through the whole process of droplet deformation and breakup. Therefore, in this way, the physical phenomena, onset and development of instabilities and so on, can be related to the governing parameters of the problem, Reynolds, Weber and Bond numbers, in a natural way. However, the main difference when actual flight conditions are considered is that the flow past a droplet in the vicinity of the incoming airfoil/wing accelerates continuously. Then, in this context, the present article describes an experimental campaign in which a rotating arm facility is used to study how water droplets and the surrounding flow field behave as an incoming airfoil approaches. Compared to previous published results, the present study contains additional information on the characterization of the base flow field obtained via Particle Image Velocimetry (PIV). In this way, it is intended to establish a relation between the observed results of droplet behavior, the structure of the flow field, and the theory that may support the observations. In particular, this information could help to the calibration of more accurate models of droplet deformation and breakup that could benefit the research community that develops software for in-flight icing applications. Also, these results could be used for code validation purposes by those researchers that develop numerical methods aiming to study the process of aero-breakup. Regarding organization of the article, the experimental facility is described first; then, results are presented and discussed and, finally, conclusions are given.

2. Description of the experimental facility

Five modules integrate the experimental facility, namely: the rotating arm unit, the test airfoils, the droplet generator, the high speed imaging system and the PIV system.

2.1. The rotating arm unit

This rotating arm unit is made up of an electric motor, a support structure and a rotating arm, see Fig. 1.

The electric motor has a power of 5 kW and it is placed inside the support structure. The motor axle is vertical. The support structure is connected to the floor via four slip ring vibration dampers that contribute to stabilize the overall system. The rotating arm length measured from the rotation center to the center of the leading edge of the model is 2.2 m. A strut system is mounted opposite to the arm for balance and vibration control purposes. A LED optical system mounted on the support structure points a light beam towards the arm path in such a way that its reflection is collected by a detector, thereby allowing for the monitorization of the rotational velocity of the arm. The maximum rotational velocity that can be achieved is 400 rpm, which means that the maximum translational velocity at the rotating arm end is 90 m/s (Mach 0.26). The rotational velocity can be changed at discrete steps in such a way that the translational velocity can be varied at intervals of 1 m/s. An additional optical trigger is present that sends a signal when the model passes at certain locations.

2.2. The airfoil model

A blunt symmetric shape was selected so as to resemble the thick airfoils used for large aircraft. Three self-similar airfoils models, M1, M2 and M3, were manufactured out of Styrofoam. Their geometry was characterized by the chord length, c, the leading edge radius, r_{le}, and the thickness, e. These values for the three models were as follows:

- Model M1: $c = 0.690$ m, $r_{le} = 0.103$ m, $e = 0.276$ m.
- Model M2: $c = 0.468$ m, $r_{le} = 0.070$ m, $e = 0.187$ m.
- Model M3: $c = 0.199$ m, $r_{le} = 0.030$ m, $e = 0.080$ m.

Two photographs of model M1 and M3 together with its dimensionless profile are shown in Fig. 2.