International Journal of Heat and Fluid Flow 54 (2015) 167–182

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Aero-thermal optimization of in-flight electro-thermal ice protection systems in transient de-icing mode

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ARTICLE INFO

Article history:
Received 25 November 2014
Received in revised form 10 April 2015
Accepted 20 May 2015
Available online 10 June 2015

Keywords:
In-flight icing
Optimization
Aircraft de-icing system
Conjugate heat transfer

ABSTRACT

Even if electro-thermal ice protection systems (IPS) consume less energy when operating in de-icing mode than in anti-icing mode, they still need to be optimized for energy usage. The optimization, however, should also take into account the effect of the de-icing system on the aerodynamic performance. The present work offers an optimization framework in which both thermal and aerodynamic viewpoints are taken into account in formulating various objective and constraint functions by considering the energy consumption, the thickness, the volume, the shape and the location of the accreted ice on the surface as the key parameters affecting the energy usage and the aerodynamic performance. The design variables include the power density and the activation time of the electric heating blankets. A derivative-free technique, called the mesh adaptive direct search (MADS) method, is used to carry out the optimization process, which would normally need a large number of unsteady conjugate heat transfer (CHT) calculations for the IPS simulation. To avoid such prohibitive computations, reduced-order modeling (ROM) is used to construct simplified low-dimensional CHT models. The approach is illustrated through several test cases, in which different combinations of objective and constraint functions, design variables and cycling sequence patterns are examined. In these test cases, the energy consumption is significantly reduced compared to the experiments by improving the spatial and temporal distribution of the thermal energy usage. The results show the benefits of the approach in bringing energy, safety and aerodynamic considerations together in designing de-icing systems.

1. Introduction

Ice protection systems (IPS), as essential equipment of all transport category aircraft, are used to ensure compliance with airworthiness requirements in icing conditions. These conditions occur when an aircraft flies through a cloud of supercooled water droplets with temperatures below the freezing point. As a result, the aircraft components may be contaminated by ice, increasing the drag by adding surface roughness and decreasing maximum lift and stall angle of attack possibly by inducing earlier boundary layer separation (Anderson, 2001). In-flight icing poses a major threat to flight safety through loss of maneuverability and controllability of the aircraft. To avoid such unfavorable consequences, ice detectors, such as piezoelectric transducers, pulse echo and microwave controllers, are used to detect any ice formation on critical surfaces. The ice then may be prevented or removed by an IPS. While most parts of the aircraft are potentially subject to ice contamination and its negative effects, it is only practical to protect the most critical parts, such as wings and lifting components, to minimize power requirements.

In-flight ice protection can be carried out in either anti-icing or de-icing modes. Anti-icing refers to prevention of ice accretion on the surface and de-icing denotes removal of accreted ice on the surface. A wide variety of ice protection systems exist and can be classified into three categories in order of common use: thermal-based, mechanical-based and chemical-based methods. Among thermal-based systems, hot air IPS and electro-thermal IPS are the most common. Hot-air systems consist of the piccolo tubes that transfer high-temperature bleed-air from the engine compressor, and impinging it on the inner skin of protected surfaces, such as the wing's leading edge. The bleed air then exits through holes on the lower side of the wing.

Hot-air systems have been the most widely used technology for commercial turbofan aircraft. The high amount of hot engine-core air required, may, however, not be available from the ever-larger bypass ratio turbofans of modern aircraft, causing a move toward no-bleed systems. In more electric aircraft, the need for bleed air and on-engine hydraulic power generation is significantly reduced and the use of electric power in the starter system of the main

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2015.05.012
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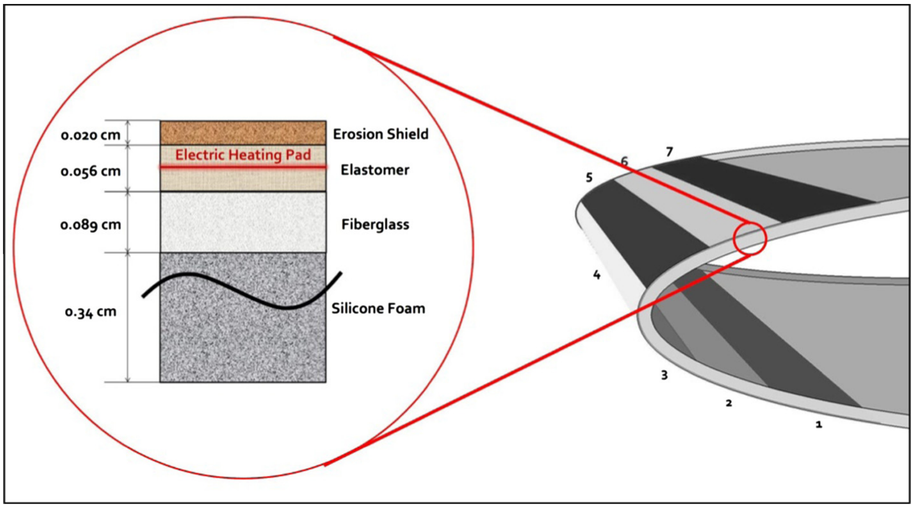

Fig. 1. The electro-thermal IPS.

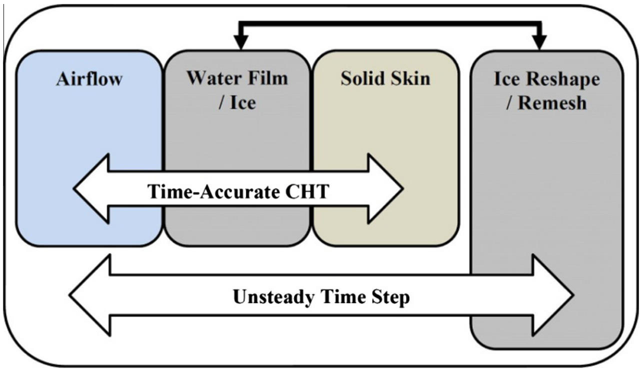

Fig. 2. Transient de-icing simulation procedure.

engine is increased (Rosero et al., 2007). The benefits of the no-bleed systems include (Sinnett, 2007):

- Fuel consumption is improved because the extraction, transfer and usage of the secondary power are more efficient.
- Reliability is improved because modern electronic devices are used and the engine has fewer components.
- Maintenance cost is reduced because of elimination of bleed systems, which are maintenance-intensive.
- Controlling and monitoring of the system is easier.
- An electro-thermal IPS can be fully integrated into composite structures.

Electro-thermal systems essentially include several electric heating blankets embedded inside the skin of the leading edges. The heaters may then be activated simultaneously for anti-icing or sequentially for de-icing. When operating in de-icing mode, an IPS consumes less energy, but provides less protection. A proper trade-off between energy consumption and protection should be reached in order to achieve optimal IPS operation. In spite of continuous improvements in the design of IPS, and rigorous certification rules, pilots continue to face unanticipated events due to ice forming on critical parts of the airframe. In addition, a non-optimal IPS can require high amounts of energy that may not be available at crucial moments and also result in increased fuel consumption, pollution and carbon footprint from a bigger engine carried by the aircraft through its lifetime, for the few moments it will be needed to anti-ice the aircraft.

The present work aims at filling some of the gaps in the area of optimization of electro-thermal systems in de-icing mode. For this purpose, various thermal and aerodynamic considerations are taken into account to ensure low energy consumption, high protection and minimum aerodynamic penalties. To the best of the authors' knowledge, this area has not been fully numerically studied. There are some experimental works attempting to improve current electro-thermal systems. Among them are: a wind tunnel studies of electro-thermal de-icing of wind turbine blades (Mayer et al., 2007), development of a recent technology in electro-thermal IPS enabling increased power densities on the leading edge of aircraft wings (Strehlow and Moser, 2009), testing the application of conductive polymer nanocomposites in making highly efficient electro-thermal IPS (Buschhorn et al., 2013). Numerical approaches to performance degradation analysis were performed in Reid et al. (2013a, 2013b) to provide guidelines for the design of wind turbine electro-thermal anti-icing systems. *Clean Sky*, an aeronautical research program in Europe, has recently launched a project on the combination of smart coatings with electro-thermal systems to minimize the runback ice over natural laminar flow wing surfaces (New aircraft de-icing concept based on functional coatings coupled with electro-thermal system, 2013). There are also a number of studies focused on the parametric analysis (Pourbagian and Habashi, 2012) and the optimization of electro-thermal systems in anti-icing mode (Pourbagian and Habashi, 2013a, 2013b).

This article is organized through the following sections. In Section 2, the method used for de-icing simulation is presented and the numerical results are compared with an experimental test case. Section 3 proposes two modifications that should be applied to the de-icing model prior to the main optimization in order to improve the final optimization output. The optimization methodology is presented in Section 4, which introduces the optimization algorithm, the objective and constraint functions, and reduced order modeling. The proposed methodology is also numerically investigated and applied to a number of test cases. Finally, conclusions are presented in Section 5.

2. De-icing simulation

To perform the de-icing simulation, an electro-thermal IPS model is selected from the very few experiments available in the open literature. This model was used in the experimental tests performed in the NASA Lewis Icing Research Tunnel (IRT) Al-Khalil