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Research Paper

Optimal design of tests for heat exchanger fouling identification

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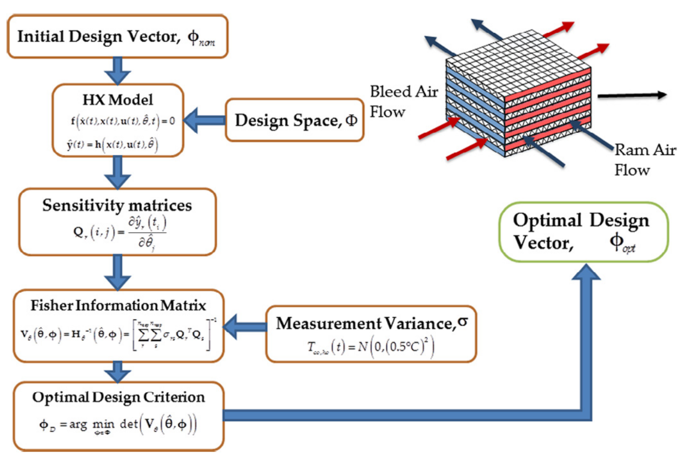
HIGHLIGHTS

- Built-in test design that optimizes the information extractable from the said test.
- Method minimizes the covariance of a fault with system uncertainty.
- Method applied for the identification and quantification of heat exchanger fouling.
- Heat exchanger fouling is identifiable despite the uncertainty in inputs and states.

GRAPHICAL ABSTRACT



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ABSTRACT

Particulate fouling in plate fin heat exchangers of aircraft environmental control systems is a recurring issue in environments rich in foreign object debris. Heat exchanger fouling detection, in terms of quantification of its severity, is critical for aircraft maintenance scheduling and safe operation. In this work, we focus on methods for offline fouling detection during aircraft ground handling, where the allowable variability range of admissible inputs is wider. We explore methods of optimal experimental design to estimate heat exchanger inputs and input trajectories that maximize the identifiability of fouling. In particular, we present a methodology in which D-optimality is used as a criterion for statistically significant inference of heat exchanger fouling in uncertain environments. The optimal tests are designed on the basis of a heat exchanger model of the inherent mass, energy and momentum balances, validated against literature data. The model is then used to infer sensitivities of the heat exchanger outputs with respect to fouling metrics and maximize them by manipulating input trajectories; thus enhancing the accuracy in quantifying the fouling extent. The proposed methodology is evaluated with statistical indices of the confidence in estimating thermal fouling resistance at uncertain operating conditions, explored in a series of case studies.

1. Introduction

The primary objective of an aircraft environmental control system (ECS) is to provide fresh air at appropriate conditions for the passengers and crew, while performing secondary heating and cooling to various aircraft components [1]. ECSs are required to control the temperature of hot "bleed" air stream after compression, using

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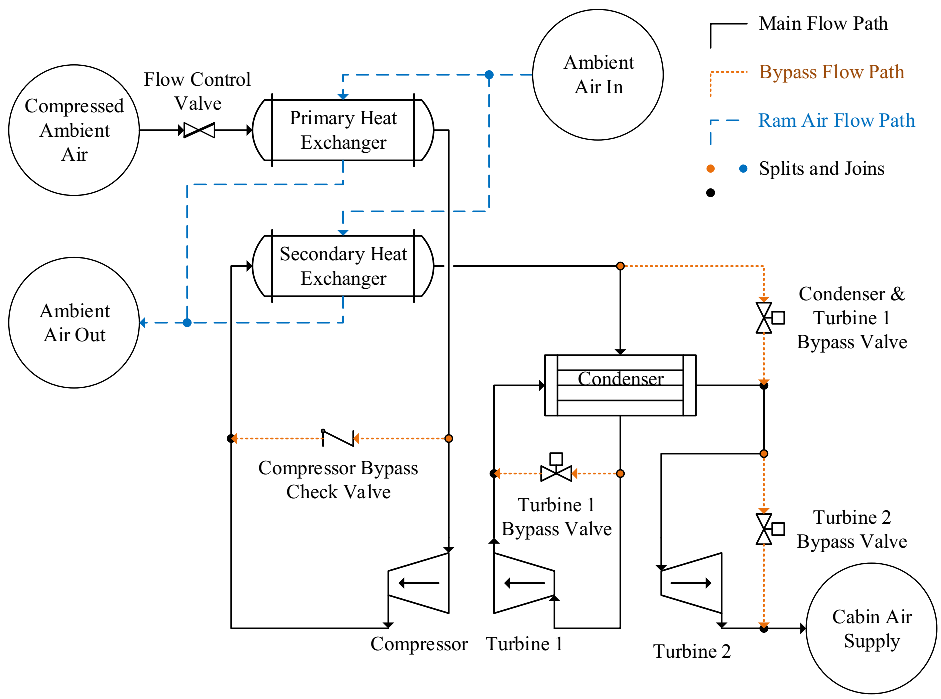

Fig. 1. Typical aircraft ECS piping and instrumentation diagram [3].

cross-flow plate-fin heat exchangers because of their small weight and volume relative to their heat transfer efficiency [2]. As shown in Fig. 1, the ECS primary heat exchanger uses ambient “ram” air as the cold fluid side to decrease the temperature of the compressed bleed stream. As a result, aircraft operations expose the ECS, and in particular its cold side, to fouling from contaminants such as sand, dust, and salt [4,5].

Fouling in aircraft ECSs is caused by deposition of dust particles suspended in the inlet airflow. Particulate accumulation is a function of air flow rate, concentration of contaminants, and system temperature and pressure [6,7]. The accumulation of contaminants on the ECS heat exchanger surface significantly reduces its heat transfer efficiency and performance over time while also increasing pressure drop, leading to significant costs from maintenance and component failures [5,8]. Therefore, the prediction, identification and isolation of ECS fouling have been the subject of several studies [9–11].

The physical phenomenon of particulate fouling is currently not well understood, making fouling behavior difficult to predict. Therefore, fouling detection methods are the primary means in monitoring fouling and its impact on aircraft operation [12]. Typically, online detection methods are applicable to estimate system states and predict deviations in heat transfer effectiveness [13]. Jonsson *et al.* [14] presented a fault detection method that uses an extended Kalman filter, designed for nonlinear state estimation and filtering of process and measurement noise. Kobayashi and Simon [15] employed a hybrid Kalman filter approach specifically for aircraft-related fouling detection that uses a continuous model combined with discrete-time measurements. Lalot and Palsson [16] presented an approach for fouling detection that uses artificial neural networks to update weighted biases into system networked layers. Delmotte *et al.* [17] implemented weighted uncertainty into a heat exchanger model using a fuzzy polynomial approach. A black-box method was developed by Lalot and Mercere [18] for performing model reduction using recursive subspace model identification. Ingimudardottir *et al.* [19] used wavelet functions for fault detection by applying wavelet transforms onto continuous or discrete measurements to reduce output noise. All these detection methods treat fouling as a state that increases gradually over time. They are less effective at lower accumulation rates, as it becomes increasingly difficult to discern between system deviation, noise and uncertainty. Moreover, classic methods such as the Kalman filter are difficult to use during offline analysis, as the duration is very small compared to most online applications.

In the particular case of aircraft ECS heat exchanger fouling detection, when aircraft operations are on the ground and prior to flight, a manually initiated built-in test, called iBIT, is used for fault detection [20]. iBIT generally lasts minutes, whereas fouling typically occurs over hundreds of hours, a significant difference in time scales between the fouling process and the time available for its offline detection. This separation of time scales allows fouling affected properties, such as deposit thickness and thermal fouling resistance, to be treated as parameters. Correspondingly, an alternative approach for fouling detection can be applied on the basis of parameter estimation. Here, we propose a method that calculates a set of system inputs that minimize fouling identification uncertainty in iBIT. This technique is based on Optimal Experimental Design (OED) methods [21].

OED is a model-based method that combines a system model with measurements and their variance to decrease the uncertainty of estimated model parameters [22,23]. The framework for OED is well known in the field of statistics of experiments and is commonly applied in precision-based estimation [24,25]. Generally, the objective of design of experiments (DOE) is to minimize uncertainty and maximize the information that can be extracted from a series of experiments [26,27]. Model-based DOE, or OED, relies on the explicit use of a mathematical model with uncertainty in its parameters, cast as an optimization problem that maximizes the information extractable from future experiments. Model equations reflect our current state of understanding of a system, whereas unknown parameters express our lack of fundamental knowledge. Model-based experimental design applications are abundant across all engineering disciplines and can be applied to any system (linear, non-linear, steady-state or dynamic). The requirement of this