THE DECOUPLING PROBLEM: ERRORS IN BOUNDARY CONDITION SEPARATION IN METAL EFFECTIVENESS MEASUREMENTS

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ABSTRACT

Overall cooling effectiveness measurements (or metal effectiveness measurements) are becoming increasingly used to understand complex coupled systems in gas turbine experimental research. Unlike traditional techniques in which individual boundary conditions are measured in isolation and superposed using a thermal model, overall cooling effectiveness measurements give the final result of a complex coupled system. In correctly scaled experiments this allows aerothermal performance at near-engine conditions to be evaluated directly, and is thus powerful both as a research technique and for de-risking engine development programmes. The technique is particularly useful for evaluating the thermal performance of heavily cooled (both internal and film) nozzle guide vanes, because of the complexity and degree of interaction of the underlying boundary conditions. An intrinsic limitation of metal effectiveness measurement data is that the individual boundary conditions (the internal and external heat transfer coefficients, and film cooling effectiveness, for example) cannot be directly obtained from the final measurement. *Decoupling* of these boundary conditions would allow deeper understanding of the systems which are the subject of experiments.

The objective of this paper is to present methods to extract the individual underlying boundary conditions from data available in typical overall cooling effectiveness experimental measurements, and to assess the uncertainty associated with decoupling techniques. Although we reference experimental data from advanced facilities for metal effectiveness research throughout, much of the analysis is performed using low-order heat transfer models to allow the impact of experiment design and measurement errors to be clearly separated at each stage of analysis.

INTRODUCTION

Research investment in overall cooling effectiveness measurement techniques has been driven by the desire to accurately assess the overall thermal performance of nozzle guide vanes or turbine blades at engine-realistic conditions [1, 2]. The traditional approach of predicting overall thermal performance of such parts from a thermal model with boundary conditions obtained from separate experiments has the disadvantage that errors in underlying measurements can accumulate in the final result. Additionally, certain coupling terms are inherently absent in the separated experiments, limiting the accuracy of the predicted performance even in the absence of experimental errors. Metal effectiveness techniques are arguably more suited to overall performance assessment than the traditional method. One limitation, however, is that underlying boundary conditions are not automatically determined from the metal effectiveness measurement. Doing so would prevent a number of advantages to both researchers and engine designers, but is not an entirely straightforward process, not least because of the relative complexity of establishing (and even describing) confidence limits on the decoupled variables. Consider, for example, that the relationship—ratios of values, for example—between a number of variables may be known with a considerably higher degree of confidence than the value of any single variable, and that this information in itself may be of considerable value in solving certain types of problem. We refer to these complexities in the most general form as *the decoupling problem*.

The paper is structured around various simplified elemental problems, designed to typify certain aspects of the overall problem in such a way that the behaviour of the system can be understood. These are:

1) *Impact of precision and bias errors in one-dimensional system without film cooling subject to a step change in the mainstream temperature*. We use this idealized system to understand the impact of precision and bias errors in measurements of mainstream temperature, coolant temperature, and external wall temperature on the accuracy with which the underlying (extracted) boundary condition values of h_1 and h_2 can be determined.

2) *Impact of time constant of the temperature step in one-dimensional system without film cooling subject to a step change in mainstream temperature.* We use this to understand the impact of experimental design (in terms of realistically achievable time constants) on the accuracy with which the underlying (extracted) boundary condition values of h_1 and h_2 can be determined.

3) *Three-variable versus two-variable problem in one-dimensional system with film cooling subject to a step change in external wall temperature.* We introduce η_f as an additional free variable, and examine the impact on the accuracy with which h_1, h_2 and η_f can be determined.

RESULTS AND DISCUSSION

To assess the impact of precision and bias errors in a one-dimensional system without film cooling, random bias and precision errors of a certain range are equally applied on the nominal mainstream, coolant and external wall temperature traces. Then, the values of h_1 and h_2 minimizing the average temperature difference between the modified nominal response and the simulated response using the modified mainstream and coolant temperature traces are extracted. This process is repeated many times in the form of a Monte Carlo simulation to determine the range of values h_1 and h_2 can take for a given error range.

Figure 1 presents the 95% confidence region for the best-fit (output) values of h_1 and h_2 (obtained from Monte Carlo simulations) as a function of the input error (bias and precision) on each of the three (input) temperature signals. Each error range was run for 10,000 simulations to build up the output error map. The test case was that of a perfect step change in time in mainstream temperature (time constant equal to zero) and constant coolant temperature.

The area covered by the 95% confidence region on the $h_1 - h_2$ map shows the level of uncertainty associated with the extracted values of h_1 and h_2. The area enclosed by the 95% confidence limit grows approximately quadratically with the magnitude of error on the input signals. We also see that h_1 is better constrained than h_2 for a given input signal error magnitude. This is explained by the fact that the external wall thermal response for this particular test case (step change in time in external temperature) under these conditions is more sensitive to a change in h_1 than a change in h_2. To understand this relative sensitivity, consider, for instance, an input bias error to the true external wall thermal response. The required change on h_2 to best-fit the true signal with a bias shift (for the same mainstream and coolant temperature traces) is greater than the required change in h_1. Thus, the 95% error band in h_1 is smaller than the corresponding error band in h_2.

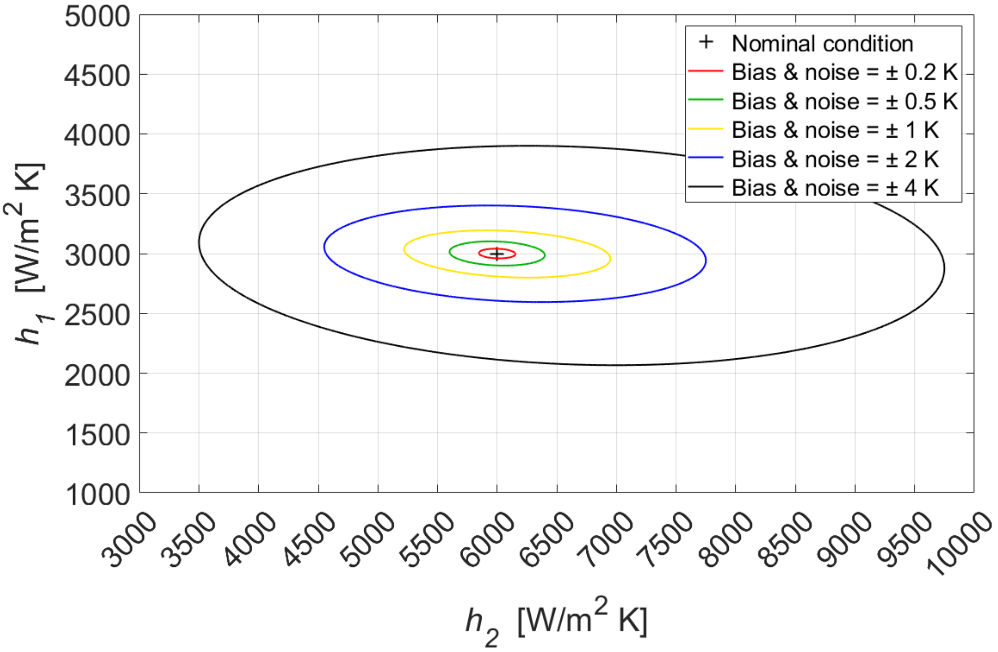

Figure 1. 95% confidence region for h_1 and h_2 as a function of the bias and precision errors range for a perfect step change of the mainstream temperature and constant coolant temperature without film cooling.

NOMENCLATURE

h_1 = external heat transfer coefficient
h_2 = internal heat transfer coefficient
η_f = film cooling effectiveness

REFERENCES

[1] Kirollos, B., Lubbock, R., Beard, P., Goenaga, F., Rawlinson, A., Janke, E., Povey, T., 2017 "ECAT: An Engine Component AeroThermal Facility at the University of Oxford," Proceedings of ASME Turbo-Expo 2017, Paper No. GT2017-64736.

[2] Luque, S., Aubry, J., and Povey, T., 2009, "A New Engine-Parts Annular Sector Cascade to Prove NGV Cooling Systems," 8th European Conference on Turbomachinery, Fluid Dynamics and Thermodynamics, Verlag der Technischen Universtat Graz, Graz, Austrai, March 23-27, pp.865-878