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SURROGATE BASED DESIGN OPTIMISATION OF COMBUSTOR TILE COOLING FEED HOLES

K. Nagabandi[1]
Rolls-Royce India Pvt. Ltd.
Bangalore, Karnataka, India

R. Ferguson
Rolls-Royce Plc
Derbyshire, United Kingdom

S. Mills
Rolls-Royce Plc
Derbyshire, United Kingdom

X. Zhang
Faculty of Engineering & the Environment
University of Southampton, UK

D.J.J. Toal
Faculty of Engineering & the Environment
University of Southampton, UK

A.J. Keane
Faculty of Engineering & the Environment
University of Southampton, UK

ABSTRACT

Gas turbine operating temperatures are projected to continue to increase and this leads to drawing more cooling air to keep the metals below their operational temperatures. This cooling air is chargeable as it has gone through several stages of compressor work. In this paper a surrogate based design optimization approach is used to reduce cooling mass flow on combustor tiles to attain pre-defined maximum metal surface temperatures dictated by different service life requirements.

A series of Kriging based surrogate models are constructed using an efficient GPU based particle swarm algorithm. Various mechanical and manufacturing constraints such as hole ligament size, encroachment of holes onto other features like side rails, pedestals, dilution ports and retention pins etc. are built into the models and these models are trained using a number of high fidelity simulations. Furthermore these simulations employ the proprietary Rolls-Royce Finite Element Analysis (FEA) package SCO3 to run thermal analysis predicting surface heat transfer coefficients, fluid temperatures and finally metal surface temperatures.

These temperature predictions are compared against the pre-defined surface temperature limits for a given service life and fed back to the surrogate model to run for new hole configuration. This way the loop continues until an optimized hole configuration is attained. Results demonstrate the potential of this optimization technique to improve the life of combustor tile by reducing tile temperature and also to reduce the amount of cooling air required.

INTRODUCTION

The main objective of the presented paper is to optimize the cooling flow required for a large civil engine gas turbine combustor. Typically in a civil engine, the gas turbine combustor is a dual wall structure where the outer walls are thin continuous sheets or multiple sheets welded/brazed together into continuous liners. These liners consist of a series of apertures for the cooling air to pass through and impinge onto the inner wall structure[1]. The inner wall structure can again be continuous or have discrete pieces connected to the outer wall mechanically via studs or welds. In the current study these inner walls are discrete pieces called tiles which are made up of a relatively high temperature capable material compared to the liner as they directly face the hot combustion gases. Furthermore these tiles also have thin coating of TBC to protect them from high temperatures. These tiles are held to the outer wall using studs and nuts at multiple locations. In addition to this the liner-tile assembly has a series of large holes for dumping the air into combustion zone for dilution and the cold side of each tile has a series of staggered pedestals to enhance the heat transfer. The compressed air from the diffuser passes

[1] Corresponding Author. Email : KiranKumar.Nagabandi@Rolls-Royce.com

through the cold side of the liner and impinges onto the cold side of the tile through the cooling apertures or feed holes present on the liner. This cooling air after impinging onto the tile surface can travel either downstream or upstream on the cold side of the tile cold. As the air travels through the rows of pedestals it becomes turbulent and very efficiently removes heat through convection. Figure 1, below, illustrates an example of the layout of a typical tile and liner.

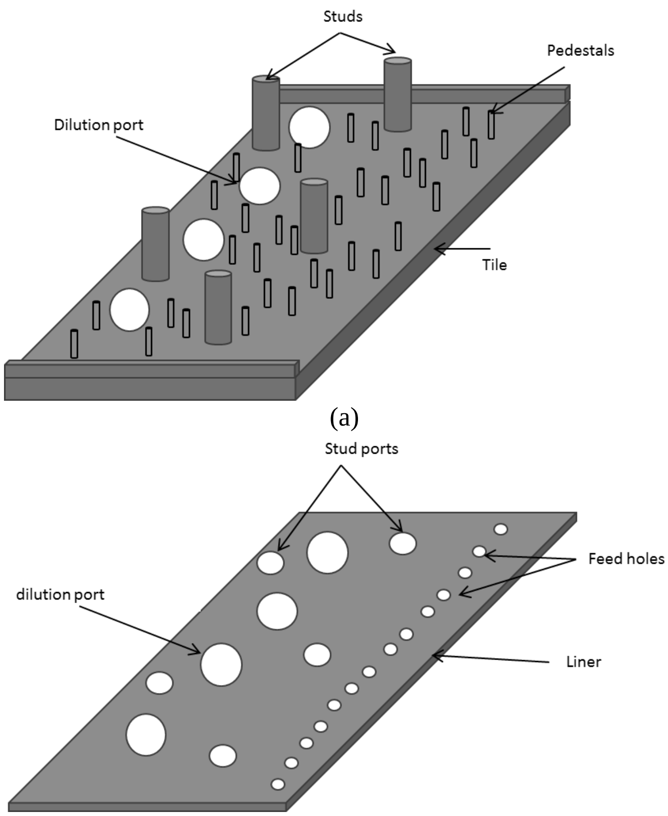


Figure 1: Representative picture of a tile (a) and liner (b)

Since the temperature generated within the combustion zone is very high, the tiles need to be cooled efficiently to ensure longer life. This leads to drawing more cooling air which in turn affects the performance of the engine. Thus it is very important to judiciously utilize the cooling flow.

There are a number of similar cases within the literature whereby the cooling arrangement of a combustor is optimized in some form.

Laraia et al.[1] employed a multi-objective design optimization of a combustion chamber cooling system to improve life. An artificial neural network employing results from 3D CFD and FEA analyses was utilized but this was restricted to a five dimensional design space and focused on optimizing the wall effusion characteristics by specifying zones of permeability rather than the high dimensional impingement cooled pedestal tile problem considered here.

Chi et al.[2] performed an optimization of the impingement cooling structure within a high pressure turbine vane. Their design parameterization enabled the diameters of 359 individual cooling holes to be varied independently with a conjugate gradient heat transfer analysis employed to predict cooling performance and a surrogate model used to reduce the number of CFD evaluations. By only considering the diameters of the holes within a limited range the complex geometry constraints considered within the current paper as holes are forced to maintain minimum distances from each other and other tile features were therefore missing. The following studies also employ a network model to predict changes in cooling air over the back of the tile and pedestals which is much cheaper to evaluate than the conjugate gradient model used by Chi et al.[2] which severely hampered the number of design evaluations they could make.

Stoakes and Ekkad[3] carried out an optimization study to improve the effectiveness of impingement cooling using a combination of conjugate gradient CFD simulations and validation experiments. The optimization only considered four parameters and the simulations involved a set of identical holes in a channel.

In another notable case from the literature Gordon and Levy[4] improved the combustor liner peak and average temperatures by modifying the cooling hole configuration and analyzing the effects using a conjugate heat transfer simulation of a complete combustor module.

In the following study an FE model representing the above tile and liner architecture is incorporated within a surrogate based design optimization workflow to reduce the cooling flow required for different service requirements where service requirements are represented by tile temperature constraints. Two example case studies are presented. The first considers a simple two variable optimization where the diameter and location of a group of holes is permitted to vary. This provides a graphical illustration of the chosen optimization approach. The second case study presents a 21 variable design optimization where the location and size of a series of feedholes are permitted to vary.

DESIGN ANALYSIS WORKFLOW

An initial FE model representing the architecture shown in figure 1 is built using commercially available meshing tool HYPERMESH. The convective surfaces of the model are applied with thermal boundary conditions which include the hot and cold side surface of the tile and liner. While doing so various heat transfer correlations are used appropriately based on flow behavior to calculate the heat transfer coefficients. The hot side of the tile is applied with a convective and radiative heat load generated using a Rolls-Royce bespoke CFD tool PRECISE [15]. Suitably calculated thermal contact conductance values are used at interfaces such as stud-nut, liner-tile mating surfaces etc. The creation and solution of the thermal model for metal or TBC temperatures is entirely done using Rolls-Royce bespoke FE tool SCO3 [5,6].

A cooling flow network is build using a Rolls-Royce bespoke flow network preprocessor CD13 and is solved using a flow solver FLOWNET [7] to get required cooling flow distribution.

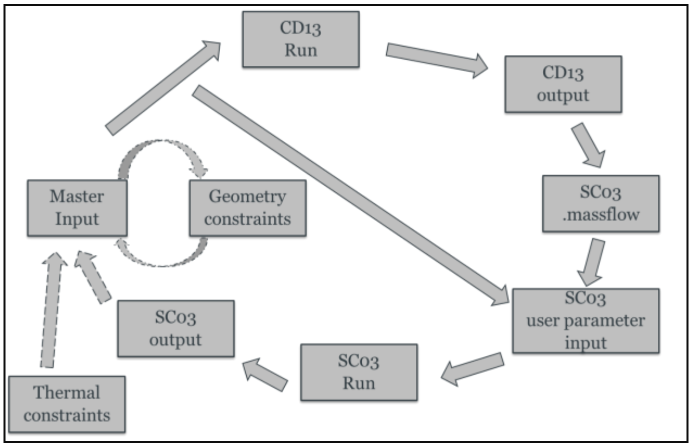


Figure 2: optimization workflow overview

The optimization workflow, illustrated graphically in Figure 2, is controlled via a master input file which defines a series of user parameters. This includes the number of holes, their position on the liner and their diameter as well as information on the tile temperature and geometric constraints. The dimensions of the tile and locations of other important geometric features, for example, dilution ports, studs etc. is also captured within this input file.

With the input file modified by the optimizer to change, for example, the position of a feedhole, the geometry constraints are then calculated. Essentially a collection of distance calculations these help determine the level of encroachment of a hole within a defined “keep out zone”, such as around a dilution port, or the ligament size between each of the feed holes. The acceptable level of encroachment can be specified as a constraint within the design optimization with the minimum ligament size, for example, being driven by known stress limitations.

While seemingly rather simple, the ligament size constraints can quickly become rather complex to model with a surrogate based optimization routine and care must be taken with the parameterization to ensure that these constraints are violated as little as possible.

With geometry constraints calculated the CD13 network model is constructed. Once solved this model calculates the total feedhole mass flow and gives an indication of the level of ingestion. This model also calculates the mass flow rate distribution over the cold side of the tile which is used within the SC03 thermal model to calculate HTCs.

The final step in the analysis chain is to load into the SC03 thermal model, the CD13 generated contour map of mass flow and a user parameter input file which accounts for the number, location and size of the feed holes defined within both the CD13 input and master input files.

Outputs from a successful SC03 analysis include the temperatures across both the surface of the TBC and metal which are then post-processed and compared to the target temperatures necessary to achieve a required service life. These temperature values will be different for different service requirements such as one or two shop visit etc. These temperatures are calculated for a given service life which means if that temperature is attained at that surface point, the tile will likely be serving the corresponding life cycles.

OPTIMISATION STRATEGY

A complete analysis of a single tile takes approximately 2 hours, depending, of course, on the mesh size and the number of compute cores the simulation is run on. The application of an optimization algorithm, such as a genetic algorithm, directly to the simulation therefore becomes relatively infeasible. Instead a surrogate based optimization process is followed here whereby models of the objective functions and constraints are constructed from a sampling plan of the original simulation. These models acts as surrogates for the true simulation and can be searched with very little cost. Assuming that the model is accurate it can drastically reduce the number of expensive simulations required and rapidly lead to an optimal solution.

Here an ordinary Kriging[8] based surrogate modelling technique is employed within the proprietary Rolls-Royce optimization suite OPTIMATv2. This suite includes a number of search algorithms and surrogate modelling approaches including, NSGA-II [9] and a hybridized particle swarm [10] for both surrogate searching and construction. In addition to this it contains a number of novel cutting edge surrogate modelling schemes capable, for example, of constructing gradient enhanced and non-stationary surrogate models [11]. An adjoint of the maximum likelihood function accelerates surrogate model construction [12] while both the construction and search routines are accelerated via the use of graphical processing units [13]. Further information on the precise formulation of the Kriging models can be found within the work of Jones [8] and Forrester et al. [14] and are excluded here for brevity.

Typical surrogate based optimization processes include some form of model updating procedure whereby the true objective functions and constraints are evaluated at regions of interest and these values are then used to update, or correct, the surrogate model. As well as being relatively accurate compared to other techniques Kriging models also offer a useful prediction of the standard error [8] in the model throughout the design space which can be used to provide a number of different update criterion. This prediction can be used to calculate a probability of improvement or an expected improvement value which can be used to locate optimal designs. The error prediction itself can be used to improve the global accuracy of the model. In the following case studies a variety of different model update criterion are employed.

CASE STUDY 1

As a simple illustration of the optimization process consider the geometry presented in Figure 3. Here the bounds of the tile, including the retention studs are illustrated along with the feedholes on the liner corresponding to this tile. The tile and liner hole configuration is symmetrical so only one half is presented here. In this instance the geometry constraint on hole position is also somewhat simplified by the lack of dilution port holes.

The seven feedholes within the indicated region are parameterized so that the axial position of the group of holes is permitted to move as well as the diameter of the holes.

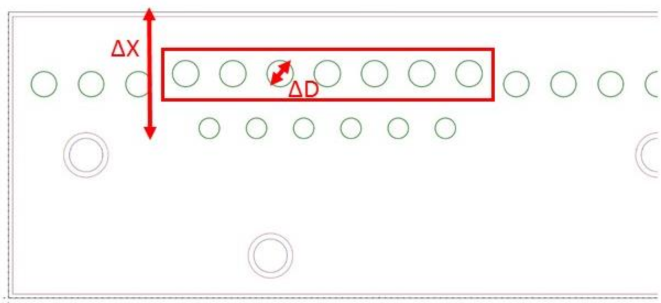
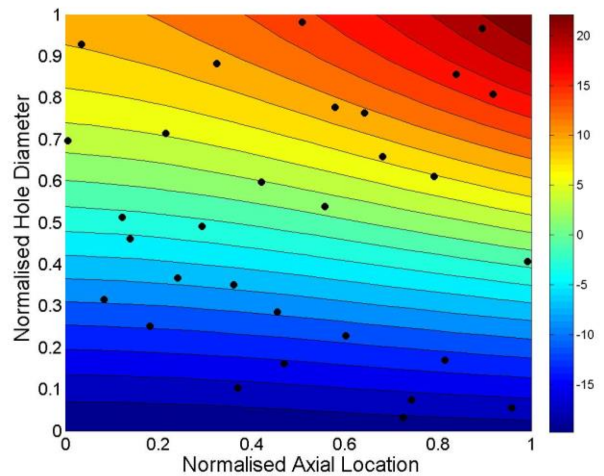


Figure 3: case study 1 impingement hole parameterisation

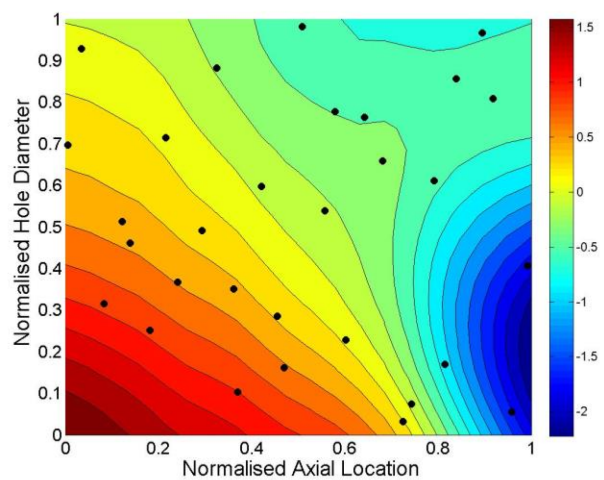
The above optimization workflow with automated geometry, aerothermal network and thermal analysis is run for a 30 point random Latin hypercube sampling plan from which surrogate models of mass flow, maximum tile metal temperature and hole ligament size are constructed. Surrogate models of both mass flow and tile temperature are presented in Figure 4 along with the locations of the initial sampling plan. Here the contours represent percentage change in both quantities with feedhole positions and diameters normalized relative to the baseline solution. Both surrogate models are relatively accurate with Pearson's r^2 correlation values based on leave one out cross-validation of over 0.98 in both cases. The maximum absolute errors are 2.98% and 7.64% for the mass flow and temperature respectively.

The surrogate model of ligament size is similarly well predicted with a correlation coefficient of 0.99 and a maximum error of 5.5% but is not illustrated here due to the inactivity of the constraint in the region of interest in the bottom right-hand corner of the design space. In this region the top row of holes have moved away from the bottom row and the hole diameters have reduced in size so there is little risk of the ligament size between holes being of concern. The nominal design in this instance is at [0.5,0.5].

With the surrogate models constructed they are searched using a multi-objective evolutionary search algorithm for minimum mass flow and tile temperature with designs along the resulting Pareto front then evaluated using the true thermal simulation. In this case a total of 15 Pareto optimal points are found with Figure 5 presenting the resulting Pareto front.



(a)



(b)

Figure 4: kriging predictions of percentage change in impingment massflow (a) & maximum tile temperature (b) with varying hole diameter and axial location

The Pareto front presented in Figure 5 illustrates a clear trade-off, in this case between the reducing the maximum tile temperature and the cooling air mass flow which can be used by an engineer to select an appropriately performing design. A 2% reduction in maximum tile temperature, for example, can be achieved for a 9.6% reduction in cooling air over the baseline design, while a 19.6% reduction in cooling air comes at the cost of a 1.46% increase in maximum tile temperature.

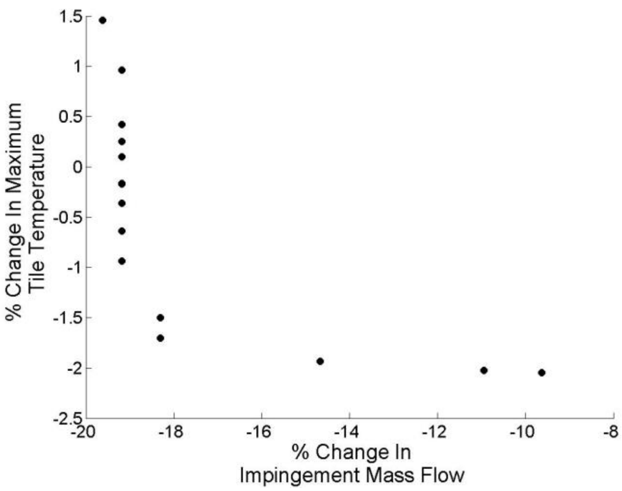
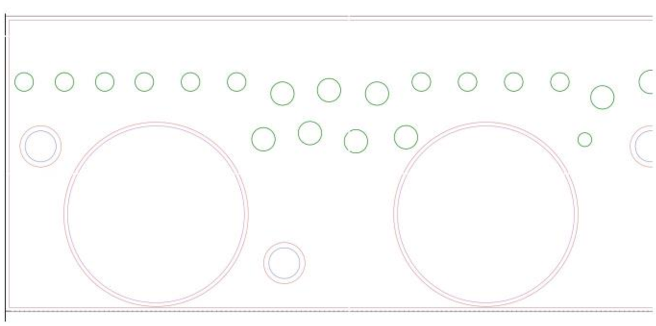


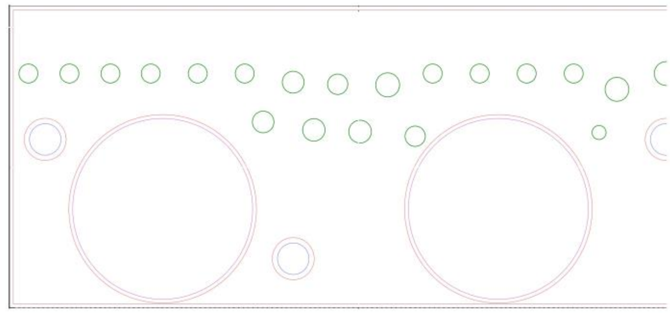
Figure 5: pareto front of maximum tile temperature and impingement mass flow

CASE STUDY 2

Case study 2 concerns a more complex tile configuration in a number of different respects. Firstly the tile itself is more complicated, there are more feedholes in the initial design and there are a total of four dilution ports present which adds complexity to the geometry constraints. The baseline design is illustrated below in Figure 6(a). Once again the tile is symmetrical and so only half the tile is presented.



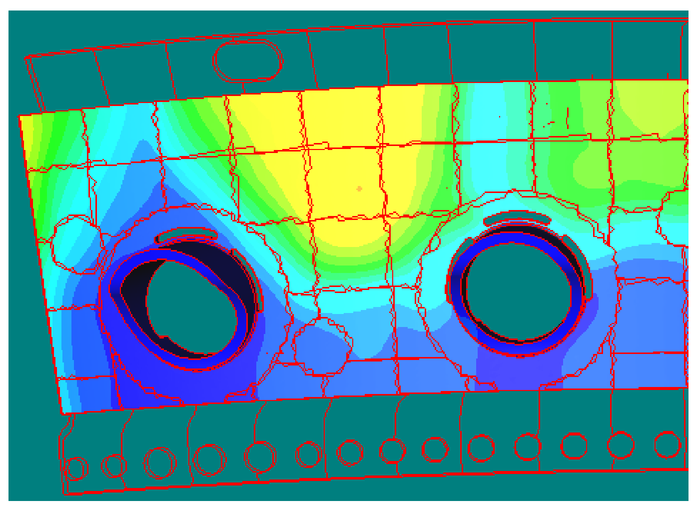
(a)



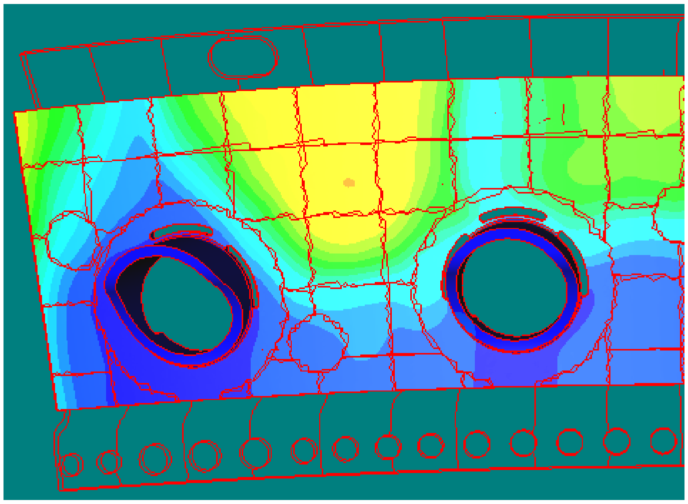
(b)

Figure 6: original (a) & optimized (b) impingement hole configuration

The geometry parameterization in this case consists of 21 design parameters. The seven holes located between the dilution ports in Figure 6(a) are each permitted to move axially and circumferentially. Each hole's diameter is also permitted to change independently. This introduces a considerable level of geometric freedom compared to case study 1. Here the optimization aims to minimize the feed hole cooling air mass flow subject to the temperature distribution over the tile being less than that specified for the required service life whilst respecting the assigned keep out zones and cooling hole ligament sizes.



(a)



(b)

Figure 7: tile surface temperature distributions for the baseline (a) and optimized (b) designs, Blue indicates cold regions & Yellow Hot

As per the previous case study a surrogate based design optimization approach is employed. In this case an initial random Latin hypercube sampling plan consisting of 361 design points is created and used to construct surrogate models of cooling air mass flow, maximum tile temperature at a number of locations on the tile surface, hole ligament size, keep out zone distance and ingestion mass flow rate.

Rather than constructing a single surrogate model of maximum tile temperature a series of separate surrogates are constructed for a 14 number of zones, or patches, over the tile surface. By only considering the maximum tile surface temperature it can be difficult for a surrogate model to accurately model the reduction in temperature in one region and corresponding increase in another region. This is essentially the combination of two responses and is better modelled by separating the temperature responses into different regions where possible. The complexity of the ligament size constraint when only the minimum ligament size is modelled across all seven holes leads to a similar issue. To resolve this further seven separate surrogate models are constructed one for the ligament size of each hole. In addition to this six further separate surrogate models constructed with constraints on keep out zone distance, ligament size of the non-parametric holes, upstream and downstream ingestion and the tile coating temperature. In total 27 surrogate models are constructed to model the constraints within this optimization problem.

To improve optimization performance the surrogate models are searched based on a variety of update criterion. These include two update points based on the surrogate model prediction, three update points based on the expected level of improvement over the current best design and five updates based on a maximization of the predicted error in the surrogate model. The first five updates aim to find an optimal design while the remaining five updates aim to improve the quality accuracy of the surrogate models to accelerate the design process. In total this process is repeated six times with the optimization therefore employing a total of 421 tile simulations. It should be noted that unlike the first case study this is a single objective optimization to reduce the cooling air mass flow subject to constraints on ligament size, keep out zones, ingestion and maximum permitted surface and coating temperatures.

As with case study 1, each of the surrogate models produced as part of this optimization have been accessed using a leave-one-out cross validation process. The final cooling air mass flow surrogate model exhibits an r2 correlation value of 0.84, a root mean square error (RMSE) of 7.3% and a maximum absolute error (MAE) of 35.6%. The six surrogate models of ligament size exhibit a mean r2 correlation of 0.64, a mean RMSE of 11.1% and a MAE of 51.9%. The patch temperature constraints exhibit a mean r2 correlation of 0.73, a mean RMSE of 9.6% and a MAE of 46.4% while the six remaining surrogates exhibit a mean r2 correlation of 0.82, a mean RMSE of 3.38% and a MAE of 19.1%. It should be observed that while the accuracy of these models is less than ideal in some cases, they never-the-less serve to effectively guide the optimizer into the correct location of an optimal solution and it is the results of the actual FEA simulation that are ultimately trusted and not those of the surrogate prediction.

The final design, illustrated in Figure 6(b) offers a 2.13% reduction in cooling air whilst not exceeding the target temperature for service life. The original seven holes are all of equal diameter while the optimized configuration has six holes with reduced diameters and the only hole to the top right remains the same. The positions of all of the holes have altered with the top middle hole moving down towards the hot spot. This forces the bottom middle two holes downwards to ensure the ligament size constraint is maintained. The bottom right most hole has reduced considerably in size which permits it to move much closer to the dilution port than the baseline configuration. In summary the holes have been reconfigured so that the impingement from the top-middle hole is more directly over the hot spot on the tile surface. The cooling is therefore more effective so less air is needed to maintain the same overall temperature. Figure 7 illustrates the contours of metal surface temperature between the two designs and the consistency between the peak temperature distributions can be clearly observed.

CONCLUSIONS

The following paper presents a novel design optimization workflow to optimize the cooling configuration of an impingement cooled pedestal tile-liner assembly. The presented workflow enables complex geometric constraints to be rapidly calculated and an aerothermal network analysis to be automatically performed for the specified tile configuration. The mass flow rate distribution from which is used to populate a thermal simulation of the assembly.

The workflow has been successfully demonstrated within two surrogate model based design optimizations. The first successfully performs a multi-objective design optimization to simultaneously reduce maximum tile temperature and cooling mass flow thereby allowing a design engineer to perform a trade-off between these parameters. The second case study successfully demonstrated the workflow within a much more complex 21 variable single objective optimization where the locations and sizes of seven feedholes are permitted to vary. Once again this optimization demonstrated a reduction in the required amount of cooling air while constraining the temperature to be under that required for a specified service life.

Going forward the presented workflow could be easily expanded to add or remove additional holes on the liner to further explore reductions in both tile temperature and cooling air requirements. The second case study in particular highlighted the need for a careful consideration of the cooling hole parameterization scheme to improve performance. The additional complexity introduced by the ligament size constraint reduces the number of feasible designs considered during the optimization. A parametric model which, by its formulation, does not produce designs which break this constraint would simultaneously reduce the number of constraints and simplify the optimization.

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