Comparison of Correlations and Experiments for Prediction of Vane Film Cooling in Gas Turbines

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1 Nomenclature

M	=	Blowing ratio
U	=	Velocity ratio
I	=	Momentum ratio
η	=	Film effectiveness
P	=	Hole spacing
D	=	Hole diameter
x	=	Downstream distance
AR	=	Area ratio
Tu	=	Turbulence intensity
DR	=	Density ratio
u	=	Velocity
L	=	Hole length
ρ	=	Density
α	=	Hole angle
Subscripts		
∞	=	Freestream
c	=	Coolant
aw	=	Adiabatic wall

Table 1: Nomenclature

2 Introduction

In an earlier report by Bradley[1], a number of correlations from the open literature were presented and evaluated. All these correlations manage to accurately describe the film cooling effectiveness for the experiments they are based on, but there is doubts regarding the general predictive value of these correlations, especially for engine-like conditions. The correlations have now been analysed to investigate their predictive capabilities - especially the general applicability of correlations is in focus, for example for geometries or flow conditions slightly different than those for which the correlations were originally designed.

2.1 Correlations

The correlations that have been included in the analysis is those by Brown and Saluja [2] ; LEcuyer and Soechting [3]; Baldauf et al. [4]; Bunker [5]; Baldauf and Scheurlen [6] and Colban et al. [7]. It should be noted that there are differences in the cases the correlations are developed for regarding e.g. Reynolds number, and turbulence intensity as pointed out in [1]. All correlations are for cylindrical holes, except the correlation by Colban et al. [7] which is for shaped holes.

The laterally averaged film effectiveness versus downstream distance for these correlations are plotted in Figures 1a and 1b for low and high blowing ratios, respectively. The correlation from L'Ecuyer appears twice in the figures since this correlation requires the maximum value as input, resulting in one curve for each of the experiments. As an experimental reference, the extensive experiments conducted by Yuen [8] were chosen. The correlations in the graphs are sorted after what kind of holes they are derived for. The black lines are for correlation derived for cylindrical holes, while the red and blue curves show correlations used for shaped holes. The four correlations presented by Bunker were originally derived for slots, but were modified by Colban et al. [7] to be valid for shaped holes.

The comparisons clearly show that there is a very large deviation between the correlations, and that no correlation manages to give an acceptable prediction of the film effectiveness of the reference data set over the whole investigated span of parameters. Also, no correlation could be determined to be "the best", since they are all developed for slightly different conditions. However, since the main objective of this investigation is the general applicability of correlations, this is a minor drawback. Some correlations appeared to be obviously erroneous, for example Baldauf 1997 and Brown 1979 for the high blowing ratio as can be seen in Figure 1b. Others gave reasonable agreement with experiments, but only for specific parameter cases.

A specific aim of this study was to see how the correlations perform on a flow with pressure gradient. This was also one of the reasons that the thesis by Yuen was chosen since this study contained experiments both with and without a pressure gradient. In the first step of this study, the intention was not to alter the correlations to take the pressure gradient into account, but to test them "as-is". Figure 1 includes experimental data for cylindrical holes both with and without pressure gradient. The result showed that the correlations did not work for the case with pressure gradient. This was expected, since the correlations did not even yield appropriate results without pressure gradient.

The figure show the spread between different correlations and that no correlation gives an acceptable prediction of the reference experimental film effectiveness. For low blowing ratios, all correlations

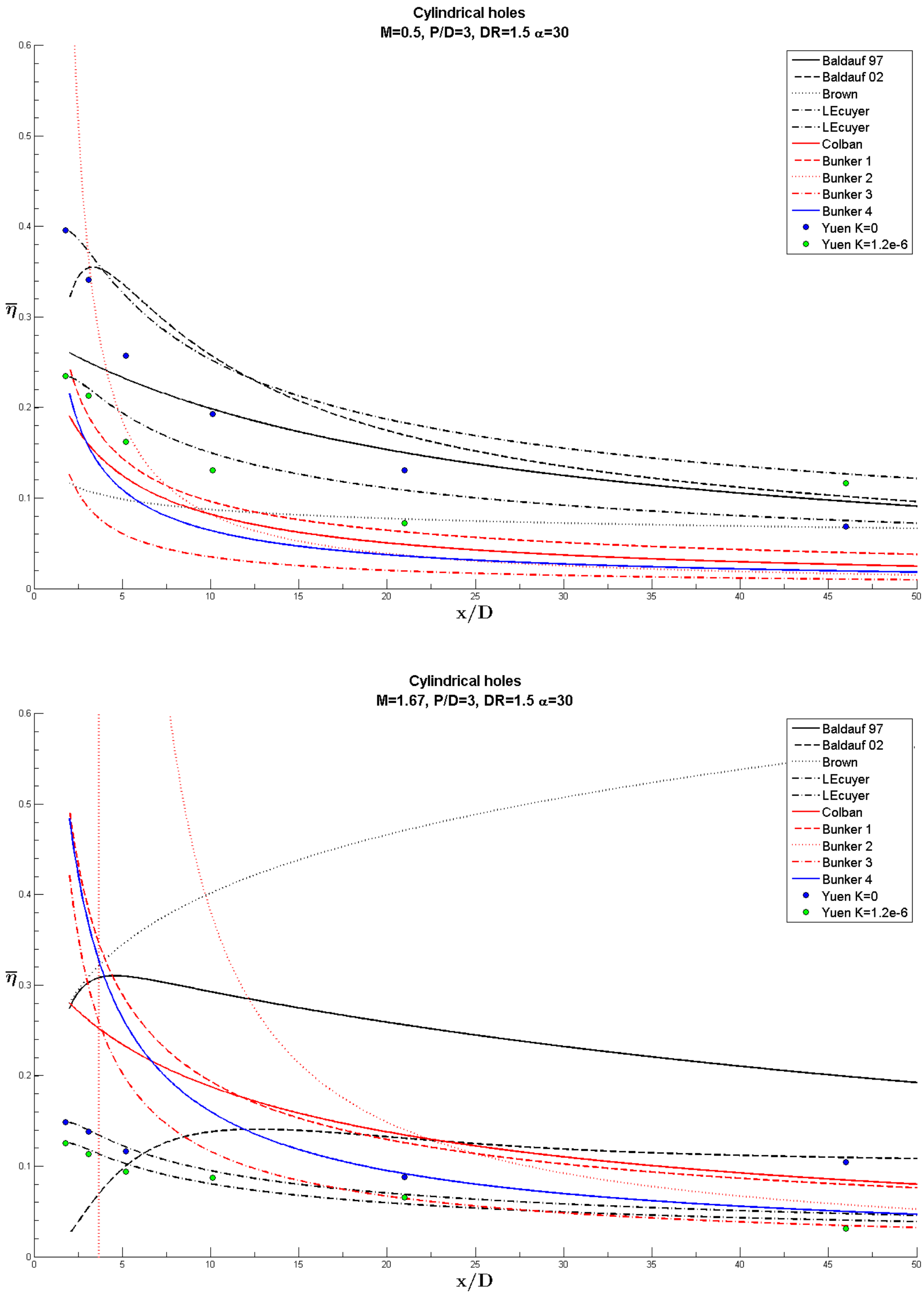


Figure 1: Spanwise averaged film effectiveness for cylindrical holes as a function of dimensionless downstream distance for the investigated correlations together with experimental results with and without pressure gradient. Low (top) and high (bottom) blowing ratios (M). Note the large differences between the correlations, especially for the high blowing ratio where some correlations deviated very much.

have the correct shape, with high effectiveness for x/D close to zero. The exception might be Baldauf 02 that peaks at around x/D=3. At higher blowing, the spread between the correlations is even greater. This visualizes the differences in flow behaviour between the high and the low blowing ratios. Even more clear is the difficulties to create a correlation that captures these differences in flow between high and low blowing ratios.

Figure 2 show a comparison of correlations and experiments for fan-shaped holes, both with and without pressure gradient. One conclusion from the figure is that most correlations consistently under-predict the film effectiveness given by the experiments. The correlations derived for shaped holes gives a similar result for the low blowing ratio, although much lower than the experimental values. The big difference between the experimental values and the correlations are probably due to the correlations not being valid for the parameter range used in these experiments. Specifically, the coverage ratio t/P (Hole breakout length over hole spacing), in the experiments are almost equal to 1, i.e. the hole breakout is covering the whole plate, while the correlations are only valid for lower values of t/P [7].

The correlations for cylindrical holes do not include this parameter and therefore predicts a higher film effectiveness than the shaped hole correlations. This prediction is still lower than the experimental values since the correlations don't take into consideration the effect from the shaped holes. For higher blowing ratios the deviations between different correlations are larger than for lower blowing ratios. The correlations for shaped holes still under predict the film effectiveness.

2.2 Experiments

After comparing the correlations to each other, it became obvious that they did not perform as expected as the difference between them was considered very large. Still, most of the correlations had been shown to give good results in the papers in which they were presented, so they had the predicting capability of the film effectiveness at least for that case. One reason for the large deviations might be that the correlations were used slightly outside the parameter span in which they were derived. The very large deviations, however, cannot likely be solely due to this aspect. In this light, the study was expanded to include also a comparison of experiments.

When it came to comparison of experiments, it was possible to find experiments conducted for similar conditions. The experiments compared was those by Baldauf et al. [4]; Baldauf and Scheurlen [6]; Lutum and Johnson [9] Schmidt and Bogard [10]; Sinha et al. [11] and Yuen [8]. Based on the effect of important parameters as investigated by e.g. Bogard [12], it was here concluded that the similarity of the experiments was so large that the resulting film effectiveness should be within the order of about $\pm 15\%$ from their average.

In Figure 3, the span averaged film effectiveness is plotted as a function of downstream distance for low and high blowing ratios. A large difference of above $\pm 25\%$ from their average value was obtained for a low blowing ratio, and an even larger difference at high blowing ratios.

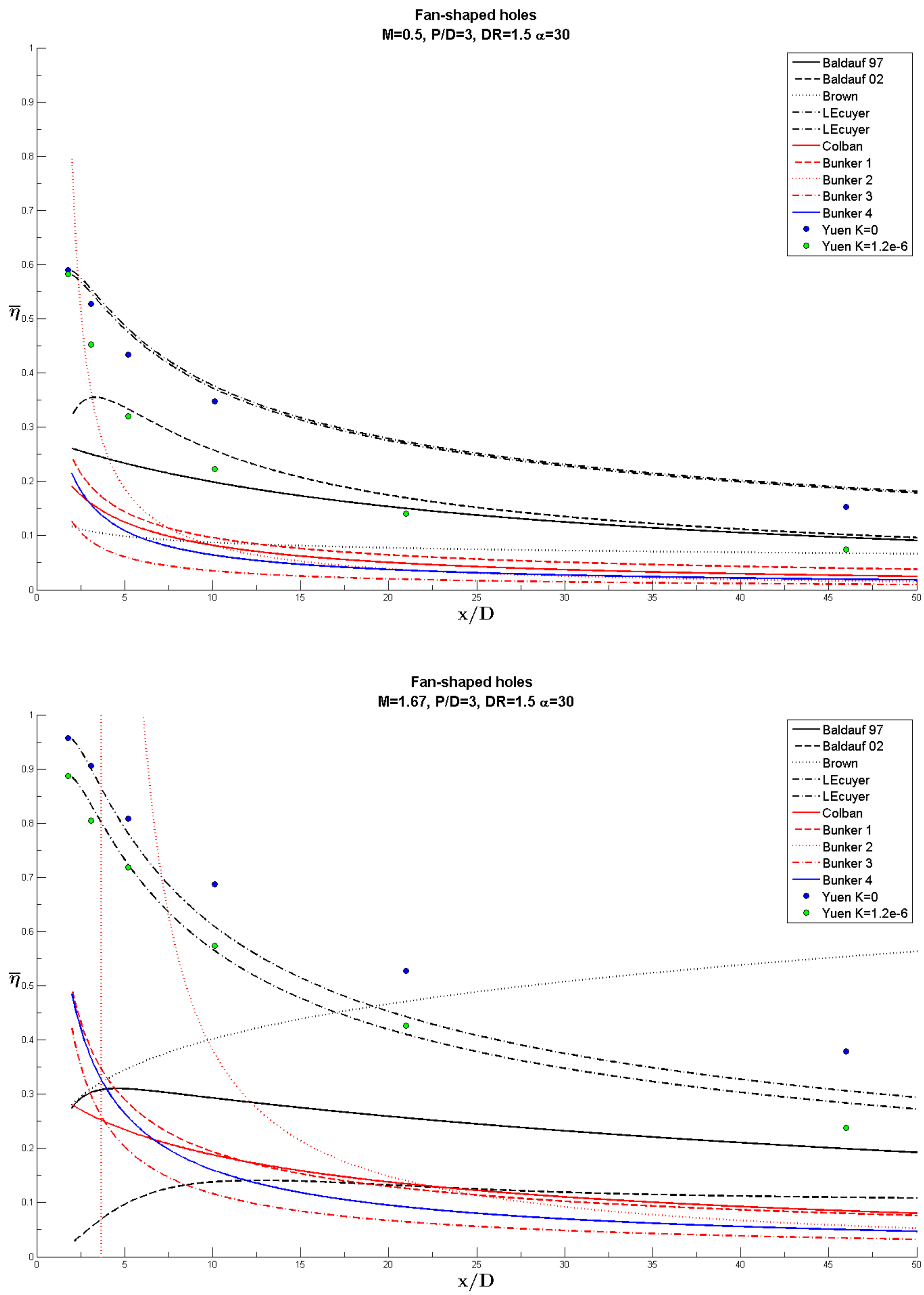
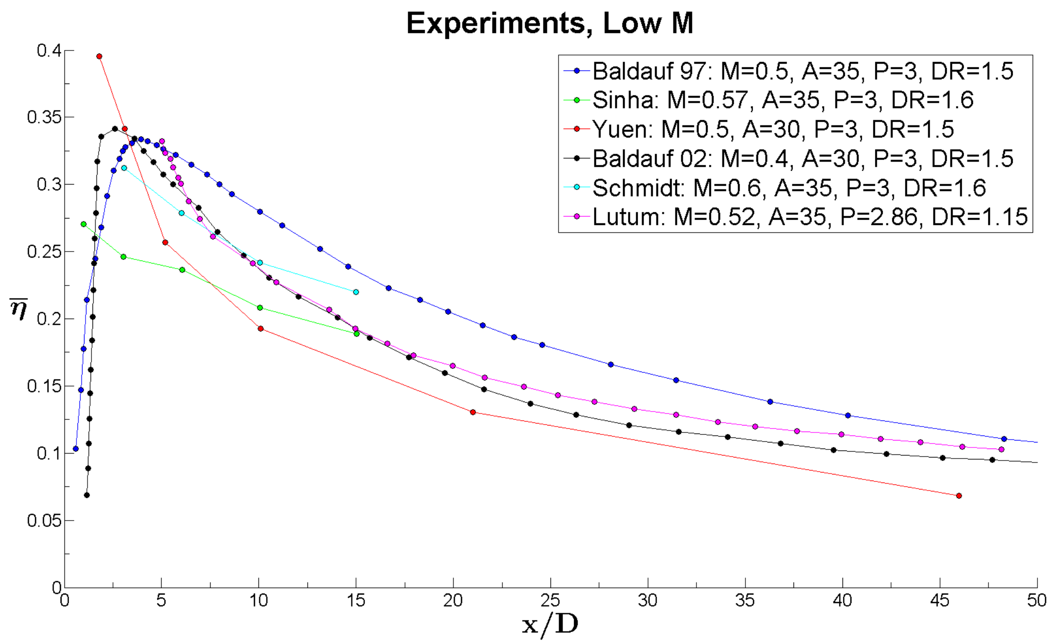


Figure 2: Spanwise averaged film effectiveness for fan-shapes holes as a function of dimensionless downstream distance for the investigated correlations together with experimental results with and without pressure gradient. low (top) and high (bottom) blowing ratios (M).



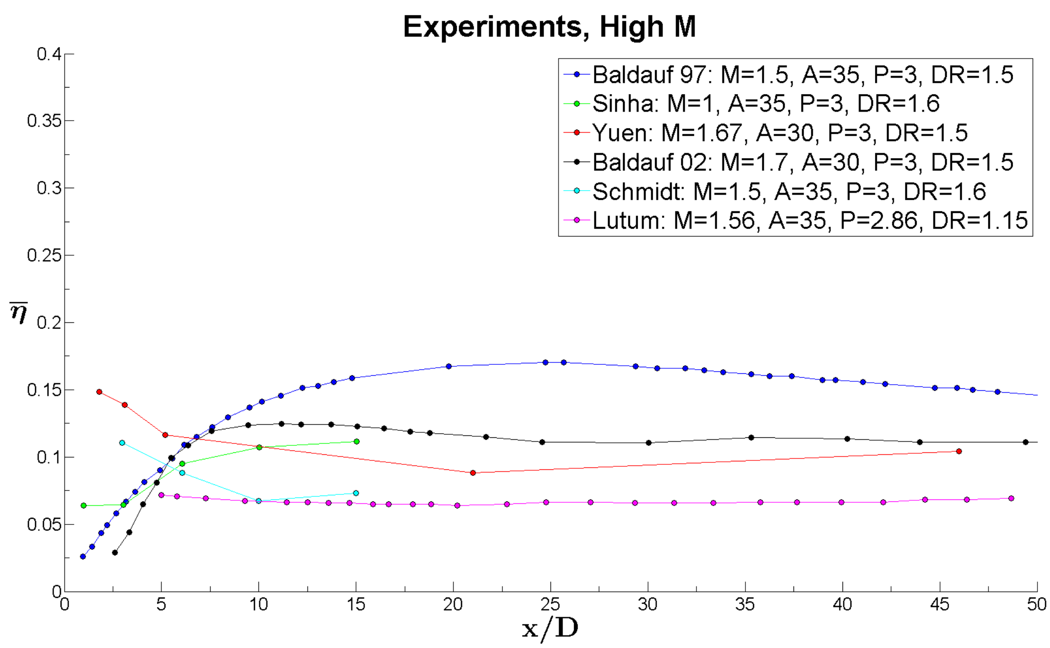


Figure 3: Experimental spanwise averaged film effectiveness for cylindrical holes as a function of dimensionless hole distance for low (top) and high (bottom) blowing ratios (M). Large differences exist for most of the distance, especially for the high blowing ratio.

2.3 Conclusions

It has been shown that there are very large differences between correlations designed to describe similar, although not identical, film cooling situations over flat plates. The general applicability of the correlations is low, which is further underlined by the fact that experiments carried out for very similar situations also show a large difference. No clear explanation for this have been found, although it is clear that effects other than the normal film cooling parameters can be of importance. The results implicate that differences in experimental and measurement equipment and their application play an important role as well. Correlations can still have a value, but only for relative comparisons using the same experimental conditions. This conclusion should be valid also for more engine-like conditions, e.g. surface curvature and pressure gradients, since such conditions are even more complex.

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