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Film Cooling: Breaking the Limits of Diffusion Shaped Holes

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Film cooling in all of its various formats has become a mainstay of turbine cooling technology today. Over the past 40 years, investigations have been performed by a broad spectrum of researchers to understand the fundamental physics of film cooling, and to improve the state-of-the-art with respect to actual gas turbine performance. The primary focus of most research has been on the use of discrete film holes, or rows of film holes, on the hot gas path surfaces of the turbine as seen in the vane and blade photos of Figure 1. Virtually all aspects of film cooling have been explored, some in great depth and others to a lesser extent, both experimentally and computationally. One of the goals of film cooling in gas turbines has been the achievement of ideal cooling films, such as those from two-dimensional continuous slots with uniformly distributed cooling supply. This ideal is held to be the entitlement of practical film cooling, or at least the much sought after goal. Due to the many competing constraints of turbine design, it is generally impractical to place such slots into the high temperature surfaces of the turbine components. As a consequence, film cooling is performed almost exclusively through the use of discrete holes and rows of evenly spaced holes. In practical applications, both commercial and military, all film-cooling holes are either round or shaped. Furthermore, the use of the term "shaped", while allowing a potentially vast number of geometries, is actually limited again to a single class of geometry. Shaped holes are composed of round metering or throat sections with a uniform and symmetric expanded exit region on the hot gas surface. Most commonly, all shaped holes applied in practice have fan diffuser exits with divergence angles between 10 and 15 degrees on each lateral side as well as on the side into the surface.

Considering the extent and diversity of research into film cooling, it is somewhat surprising to realize that only a single primary advancement in this technology has been put into widespread practice over these many years. That single improvement has been the change from round film holes to fan-shaped, or diffuser, film holes. A recent review of diffuser shaped film cooling and its effects may be found in Bunker [1]. In this review, several concepts for alternative and improved discrete film cooling of the hot gas path are also presented. To fully characterize film cooling behavior one would need a multitude of parameters concerning the film injection, hot gas flow, geometry, and interaction effects. Manufacturing constraints influence and limit the geometry of the film holes and the part. These factors include the effective film hole diameter, film hole length-to-diameter ratio L/D, film hole axis angle to the external surface tangent, film hole orientation to the external and internal flow, film hole pitch-to-diameter ratio P/D, and the specification of the hole exit shaping. All of these factors primarily affect the adiabatic film cooling, or do so indirectly by affecting the film hole discharge coefficients. For more information, a fairly complete summary of film cooling as applied to gas turbines is contained in Bunker et al. [2].

Several alternate geometries of film cooling holes have been proposed within the last few years that have in some form demonstrated at least equivalent film effectiveness performance to the now common diffuser shaped holes noted above. In addition to published studies concerning discrete film holes of alternate geometries, patent literature contains many more examples of film hole geometries that were considered by their inventors to be either innovative or technically important advances to the state-of-the-art. These differing film holes may have specific form and function, either of limited or widespread potential, but each must also ultimately face the challenges of manufacturing, operability, and cost effectiveness. The present study looks at thirty examples of discrete hole film cooling geometries, including the standard bearer of diffuser shaped holes, to discern what is possible, what the typical detractors to implementation are, and how we might go forward to entitlement. Eight key factors are used to judge the potential performance for each film hole geometry including adiabatic effectiveness, manufacturing, cost, repair, geometry sensitivity, flow sensitivity, operational tolerance, and strength / durability. Figure 2 shows just a sample of the ranking matrix employed in this study. The study concludes with an example of very recent film cooling data for a geometry that climbs closer to ideal entitlement.

REFERENCES

[1] Bunker, R.S., 2005, “A Review of Turbine Shaped Film Cooling Technology,” *Journal of Heat Transfer*, Vol. 127, pp. 441-453.

[2] Bunker, R., Simon, T., Bogard, D., Schulz, A., Burdet, A., and Acharya, S., 2007, Film Cooling Science and Technology for Gas Turbines: State-of-the-Art Experimental and Computational Knowledge, *Von Karman Institute for Fluid Dynamics Lecture Series VKI-LS 2007-06*, ISBN-13 978-2-930389-76-1, Brussels, Belgium.

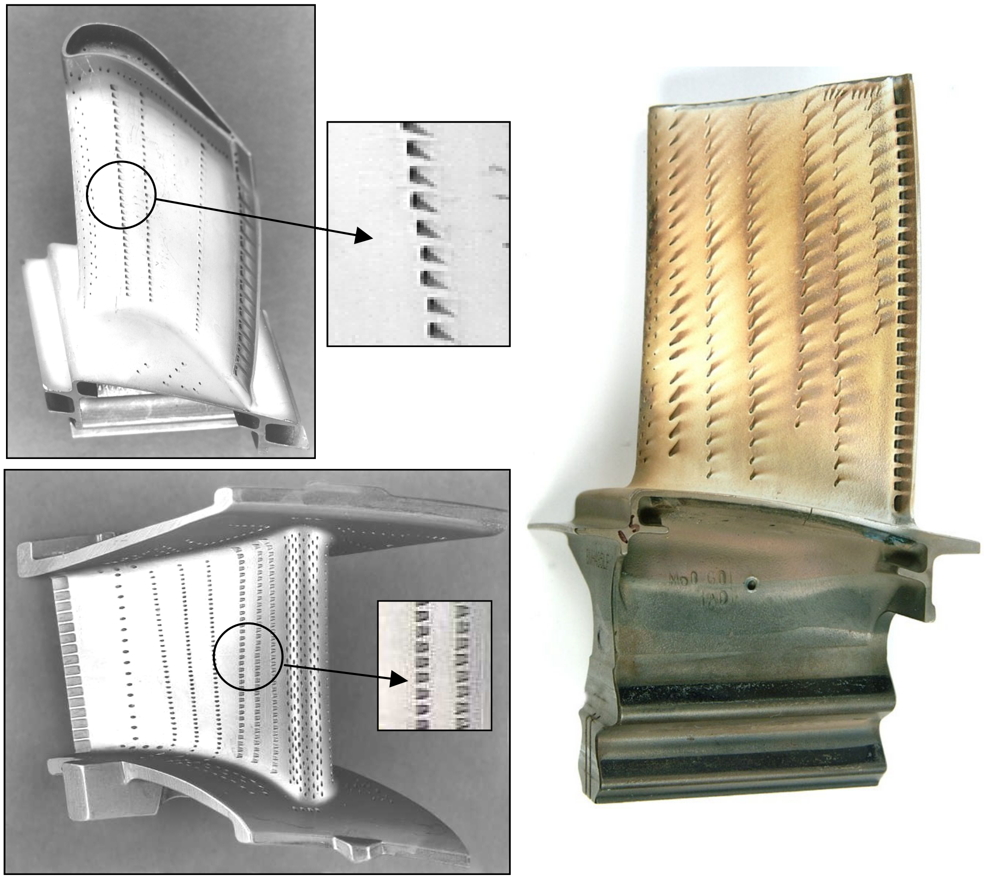
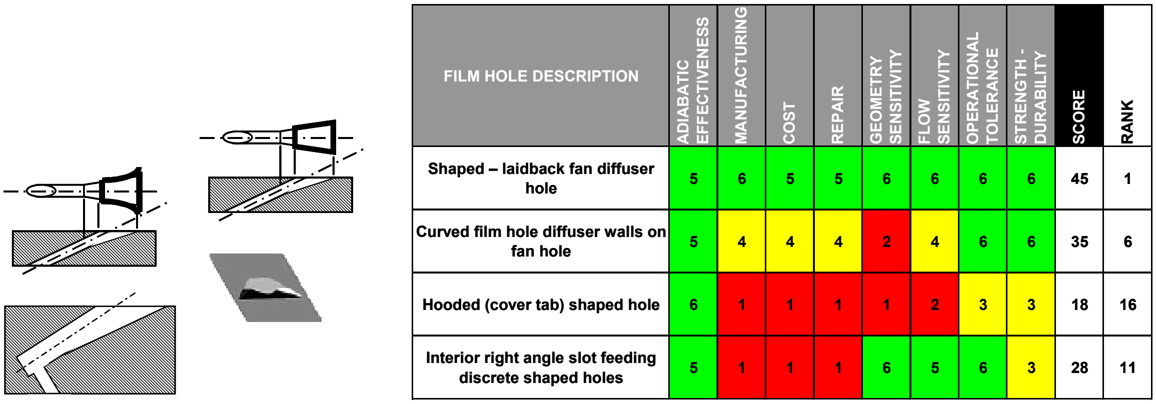


Figure 1. Examples of highly film cooled turbine airfoils.



FILM HOLE DESCRIPTION	ADIABATIC EFFECTIVENESS	MANUFACTURING	COST	REPAIR	GEOMETRY SENSITIVITY	FLOW SENSITIVITY	OPERATIONAL TOLERANCE	STRENGTH - DURABILITY	SCORE	RANK
Shaped – laidback fan diffuser hole	5	6	5	5	6	6	6	6	45	1
Curved film hole diffuser walls on fan hole	5	4	4	4	2	4	6	6	35	6
Hooded (cover tab) shaped hole	6	1	1	1	1	2	3	3	18	16
Interior right angle slot feeding discrete shaped holes	5	1	1	1	6	5	6	3	28	11

Figure 2. Excerpt from film geometry ranking matrix.