Experimental Simulation of Gas Turbine Film Cooling with a Thermal Barrier Coating and Active Deposition

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Motivation

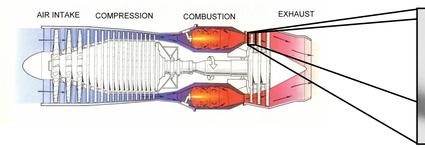
Gas turbine engines operate more efficiently at higher turbine inlet temperatures.

This study integrates **conjugate** effects:

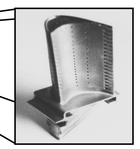
- **Internal Cooling**
- **Film Cooling**
- **Thermal Barrier Coatings**
- **Deposition**

→ Greater understanding of the coupled effects will lead to improved cooling designs and mitigate the effects of deposition.

Aircraft propulsion gas turbine engine:



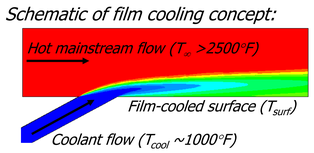
Cooled turbine blade:



Modeling Conjugate Effects

Film cooling is a key technology to enable higher gas turbine engine efficiency.

Schematic of film cooling concept:



Film cooling parameters:

- Density ratio: $DR = \rho_{cool}/\rho_\infty$
- Velocity ratio: $VR = U_{cool}/U_\infty$

Blowing ratio: $M = \dfrac{\rho_{cool} U_{cool}}{\rho_\infty U_\infty}$

- Adiabatic film effectiveness: $\phi = \dfrac{T_\infty - T_{surf}}{T_\infty - T_{cool}}$
- Heat transfer coefficient ratio: $\dfrac{h_f}{h_o} = \dfrac{\text{heat transfer with film cooling}}{\text{heat transfer without film cooling}}$

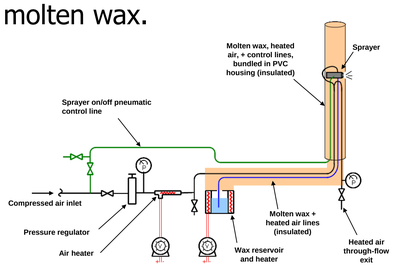
Thermal Scaling

$$\phi = \frac{1-\eta}{1 + Bi + h_e/h_i} + \eta$$

Parameter	Real Turbine	Model Turbine	Units
Vane Thickness	0.13 - 0.3	1.27	cm
TBC Thickness	0.014 - 0.072	0.51	cm
Vane Conductivity	20	1.02	W/m-K
TBC Conductivity	0.83 - 1.7	0.065	W/m-K
Heat Transfer Coeff.	1500 - 5000	25 - 90	W/m^2-K
Vane/TBC Thickness	2 - 20	2.49	-
Vane/TBC Conductivity	12 - 24	15.7	-
Vane Bi	0.3 - 0.6	0.3 - 1.1	-

Deposition

Engine contaminate is modeled with molten wax.

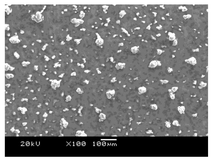


Depositing particles Stokes number is matched between the wind tunnel and engine.

$$Stk = \frac{\text{Particle relaxation time}}{\text{Characteristic time of flow field}} \qquad \text{for spherical particles: } Stk = \frac{\rho d_p^2 / 18\mu_\infty}{l_c / U_c}$$

Coal ash in engine: $d_{p,max}$ = 1-10 μm
Wax in wind tunnel: $d_{p,max}$ = 8-80 μm
Stk_d = 1-100

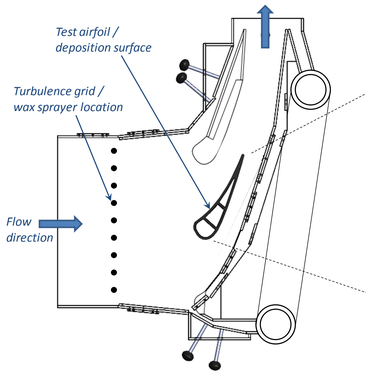
SEM image of sprayed wax particles:



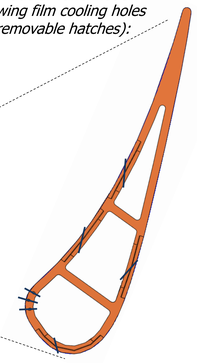
Film Cooling Designs

Test Section and Conjugate Vane

Schematic of vane model test section:

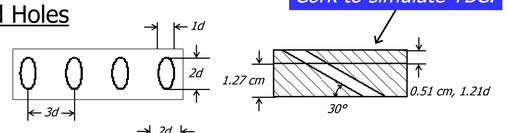


Schematic of vane model (showing film cooling holes and removable hatches):

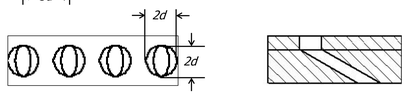


Vane is coated with Cork to simulate TBC.

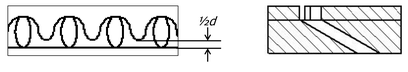
Pressure Side Round Holes



Craters



Modified Trench



Results

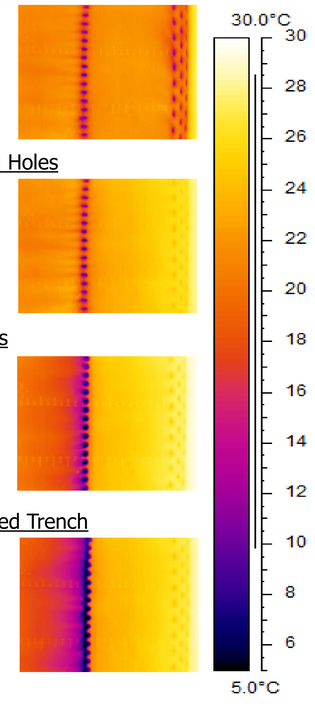
IR Images, M=2.0

Round Holes + Showerhead

Round Holes

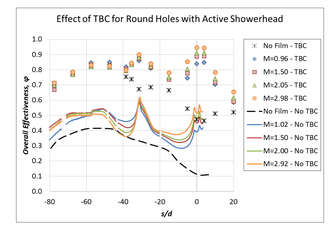
Craters

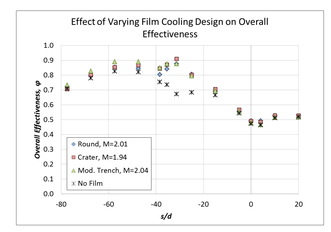
Modified Trench

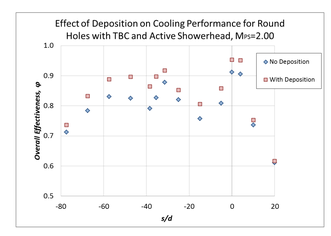


Post-Deposition Pictures

Thermocouple Measurements at TBC/Vane Interface







Conclusions

1.) The presence of TBC significantly reduces sensitivity to blowing ratio.

2.) Craters and modified trench showed better film cooling on surface of TBC but minimal improvement at the TBC/vane interface.

3.) Craters reduced deposition.

4.) Deposition led to an increase in cooling performance at the interface of the TBC and vane wall.