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AIRFOIL COOLING HOLE PLUGGING BY COMBUSTION GAS IMPURITIES OF THE TYPE FOUND IN COAL DERIVED FUELS

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16 Abstract
The plugging of airfoil cooling holes by typical coal-derived fuel impurities was evaluated using doped combustion gases in an atmospheric pressure burner rig Very high specific cooling air mass flow rates reduced or eliminated plugging The amount of flow needed was a function of the composition of the deposit It appears that plugging of film-cooling holes may be a problem for gas turbines burning coal-derived fuels

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SUMMARY

Film cooled airfoils were heated in the Mach 0.3 combustion gases of a burner rig. The flame temperature was varied but the initial leading edge temperature of the airfoil was cooled to 815° C by air whose pressure was then fixed for the duration of the run. The combustion gases were doped with a combination of Fe, Pb, Ca, Na, K, and P at ratios similar to those found in Solvent Refined Coal but at higher total concentrations. Cooling hole plugging was monitored by the observed increase in leading edge temperature. As the air mass flow ratio (coolant/hot gas) increased beyond a minimum, which was a function of the deposit chemistry, the tendency for plugging decreased. The flow rates needed to substantially reduce plugging were quite high, indicating a potential problem for gas turbines operating on coal-derived fuels.

INTRODUCTION

To operate gas turbines at higher temperatures for improved cycle efficiency, engine designers are increasingly relying on air cooling to reduce metal temperatures, thus providing adequate airfoil rupture life (ref. 1). Film cooling, one of the more advanced cooling techniques, relies on the flow of compressor air through cooling passages inside the airfoil and the discharge of that air through small holes located at areas of critical heat flux e.g., at the leading edge. Such schemes have been quite successful in aircraft engines burning clean fuel and have permitted substantial increases in turbine inlet temperature. However, the use of large amounts of compressor air results in a reduction in overall efficiency. Another drawback is that any substantial plugging of the cooling holes will result in an unacceptable rise in local metal temperature. Localized failure could then result from either excessive temperature/stress levels, or in extreme cases, melting.

In aircraft gas turbines such plugging is unlikely as the combustion products of the relatively clean jet fuels used contain only slight amounts of impurities that could deposit in the holes. However, plugging of film cooling holes has been noted in marine turbines (data obtained from G. B. Katz of the Naval Ship Engineering Center). He found thick (up to 0.8 mm) deposits rich in iron, covering the surface of first-stage blades and vanes. In many areas, but especially on the leading edge, the cooling holes were completely covered and, in extreme cases, leading edge melting was noted. The times required for these extreme buildups were in excess of 1000 hours although substantial deposits were noted after several hundred hours. The source of the deposits was not determined but is was noted that iron was present in the air and the fuel at levels of only several parts per million As a result of the observations of Katz, work was initiated by the authors to try to determine some of the factors affecting hole plugging in such tests using a burner rig and doped Jet-A fuel. The results of this work were reported in reference 2. In brief, the position, structure, and phase composition of the deposit formed in the Navy test was duplicated in the burner rig. The extent of the deposit was shown to be a function of the deposit composition, dopant concentration, the metal temperature, and the flame temperature. It was concluded that many types of deposits could plug the cooling holes, but that probably a low melting point deposit or a deposit containing a low melting point phase was the most effective The source of the impurities causing the deposit was assumed to be the fuel The rate and extent of this plugging was increased by small amounts of phosphorous.

If such harmful deposits could form from the combustion of relatively clean marine diesel fuel, it may be anticipated that problems will be at least as severe for industrial or utility turbines using heavy oils or minimally processed coal-derived fuels. The purpose of this paper was to determine whether or not a potential film cooling hole plugging problem exists for turbines burning such fuels The approach used was similar to that of reference 2. Actual airfoils, in this case, showerhead film-cooled blades, were cooled using a constant internal pressure as is suggested by the work of reference 3 The blades were heated by the doped combustion gases of a burner rig. As the holes became plugged, the leading edge temperature of the blade increased. This temperature rise was used to estimate the extent of cooling hole plugging. It must be noted that this type of experiment, i. e., atmospheric pressure rig testing, can only give qualitative information or point to a potential problem. For a quantitative assessment of this problem, high pressure rigs with close simulation of engine airflows are needed.

MATERIALS AND PROCEDURES

The experimental arrangement is shown schematically in figure 1. Dopants were added as aqueous salt solutions directly to the combustion chamber in which clean A-1 jet fuel was burned. Dopant concentrations were expressed as parts per million by weight of the combustion products (table I) The doped combustion products were exhausted through the nozzle, exiting at Mach 0.3 and striking the blade normal to the leading edge. The blades were cooled by ambient temperature air flowing through the internal cooling passages and out through the leading edge film-cooling holes. The cooling air pressure was fixed for the duration of the run. The blades were weighed before the start of the run and at intervals during the run. The leading edge temperature was monitored optically to ±10° C throughout. Typically, the temperature rose rapidly at the start of the run as cooling holes plugged and then leveled out after several hours. Once a constant leading edge temperature was established, the run was terminated. The severity of hole plugging was judged by the temperature rise (ΔT).

The ratios of dopants were chosen based upon typical analyses for Solvent Refined Coal (SRC) - light organic liquid. The levels were set to allow accelerated testing (~8 hr) and are approximately 30 times the levels expected in the combustion products of SRC. The acceleration was not expected to change the composition of the deposit, only its rate, as was demonstrated in the work of reference 2. The compositions of the two dopants used are shown in table I Dopant A is based, as discussed above, on typical SRC analyses, while Dopant B has some phosphorus, an element identified in reference 2 as one capable of greatly increasing hole plugging.

The initial metal temperature for these tests was fixed at 815° C (1500° F) while flame temperature, as measured by sonic probe, was varied from 1100° C to 1800° C, and the cooling air was then adjusted accordingly. The flame temperature changes were accomplished by changing the fuel-to-air ratio but resulted in little change in the mass flow. Table II shows the relationship of the specific mass flows of the combustion gases and the cooling air, the former being calculated for the throat of the nozzle and not corrected for divergence, a correction which would result in even higher ρV ratios. Even without that correction, which amounts to a mass flow ratio increase of ~ 25 percent, it can be seen that the ratio of cooling air to combustion gas mass flows is quite high. The mass flow ratios used in this test (table II) cover a greater range than could be expected on a gas turbine airfoil.

RESULTS AND DISCUSSION

A summary of test conditions and results is given in table III. Three tests were made with Dopant A and four with Dopant B. The metal temperature at the start of the test was 815° C in all cases and 815 $+\Delta T$ at the conclusion of the test. Flame temperature and cooling air mass flow were the major variables. However, they were not independent of each other as the higher flame temperatures required greater amounts of cooling air to bring the initial leading edge temperature to 815° C

Figure 2(a) is a photograph of a post-test blade which had very little leading edge temperature rise (11° C), a value close to the sensitivity of the temperature measurement. The holes show very little evidence of plugging, although there is a measurable deposit along the leading edge. The coolant: hot gas mass flow ratio of 2.3 is quite high. In contrast, figure 2(b), which had a measurable leading edge increase of 39° C shows complete closure of holes. The coolant: hot gas mass flow ratio of 0.4 for the latter is low for leading edge film cooling holes. These results are similar to the results of vane testing presented in reference 2.

In general, the amount of cooling hole plugging as determined by, metal temperature rise, ΔT caused by Dopant B was greater for similar test conditions than that caused by Dopant A. This confirms the earlier conclusions of the work of reference 2 that phosphorus in combination with iron and calcium greatly accelerates the tendency for hole plugging.

In attempting to evaluate the effects of flame temperature and cooling flow, several points must be considered. Not all of the holes are covered by the flame and therefore, even with maximum possible plugging, some internal cooling remains. The ΔT expected for maximum plugging is directly proportional to the flame temperature and the minimum, with no plugging, is zero. It appears that at low flame temperatures, which have also low cooling mass flow rates, the deposit easily plugs the holes. The coolant mass flow rates appears to be too low to keep them swept clean. In this regime, as the flame temperature increases so does ΔT (fig. 3). However, as the flame temperature was increased in these tests, the cooling air mass flow rates were also increased (fig. 4) to maintain the starting leading edge temperature at 815° C. As the cooling mass flow rate increases, the cleaning starts to be effective, perhaps aided by a reduced viscosity of the outer layers of the deposit, and ΔT begins to decrease again. The point at which this reversal takes place should be a function of, among other things, substrate temperature and deposit composition.

This seems to be the case for the present data for Dopant B as plotted in figure 3. ΔT seems to go through a maximum as flame temperatures (and thus total cooling flow) increase. This also may be true for the Dopant A data, but, in the absence of low flame temperature data, some uncertainty exists. ΔT first rises as both cooling air flow and flame temperature increase. At some critical value of cooling air flow rate and flame temperature, ΔT begins to decrease as a result of high cooling air velocities sweeping the cooling holes clean The critical threshold appears to be approximately

$$\frac{(\rho V)_{\text{cooling}}}{(\rho V)_{\text{heating}}} = 1.0$$

for the dopants selected in this study. However, small variations in the dopant composition could change this value substantially

It appears probable that any composition could be prevented from depositing by sufficient cooling mass flow. Whether an engine designer could afford to divert sufficient air flow to keep the holes clear and still retain sufficient efficiency and aerodynamic flow, would depend strongly on the nature of the deposit, and the cycle efficiency penalty associated with increased cooling air requirements and aerodynamic losses It is quite probable, however, that there are many fuels with impurity combinations which would lead to substantial cooling hole plugging problems. These problems would be aggrevated by higher turbine pressures and certain cooling designs where the specific cooling mass flow rates might be inherently low, e.g., transpiration cooling.

The effect of higher engine pressures is twofold. As the pressure in the turbine increases, the dew points of potential deposits will increase, resulting in an extension of the problem to higher temperatures. Secondly, calculations of deposition rates from combustion gases, ref. 4, indicate an almost linear increase with pressure. While the data shown here in figure 5 are for Na_2SO_4, the trend should be the same for any condensate. This indicates that the atmospheric burner rig test described here (dopant level ~ 30 times actual fuel impurity level) might not be as accelerated as at first expected.

CONCLUSIONS

As a result of doping combustion products during burner rig testing of aircooled blades, the following conclusions may be drawn:

(1) Plugging of film cooling holes is likely to be a problem for gas turbines burning coal-derived fuels.

(2) The severity of the problem will depend greatly on the impurity composition and concentrations.

(3) High cooling hole flow rates may reduce the problem at the expense of overall efficiency.

(4) As turbine pressures increase, the problem will probably become more severe.

REFERENCES

1. Suciu, S N.: High Temperature Turbine Design Considerations Aeronaut. J., vol. 75, Aug. 1971, pp. 577-586.
2. Deadmore, Daniel L.; and Lowell, Carl E.: Plugging of Cooling Holes in Film-Cooled Turbine Vanes. NASA TM X-73661, 1977.
3. Cutrone, Martin B.: High Temperature Gas Turbine Engineering Component Materials Testing Program Task 1. FE-1765-40, U. S. Dept of Energy, 1978.
4. Rosner, Daniel E.; et al.: Chemically Frozen Multicomponent Boundary Layer Theory of Salt and/or Ash Deposition Rates from Combustion Gases. NASA TM-79770, 1978.

TABLE I. - DOPANT COMPOSITIONS IN PPM BY WEIGHT OF COMBUSTION PRODUCTS

Element	Dopant A	Dopant B
Fe	2.0	2.0
Pb	.05	.05
Ca	.1	.1
Na	.5	.5
K	.1	.1
P	----	.5

TABLE II. - RELATIVE MASS FLOW

Flame temperature		$\frac{(\rho V)_C}{(\rho V)_H}$*
°C	°F	
1100	2012	0.4
1220	2228	.9
1300	2374	1.0
1550	2822	2.3
1800	3272	3.8

*$(\rho V)_C$ - mass flow, cooling air.
$(\rho V)_H$ = mass flow, combustion products.

TABLE III - RUN SUMMARY

Number	Flame temperature* °C (°F)	Dopant	$\frac{(\rho V)_C}{(\rho V)_H}$	Leading edge Δ T	$\frac{\text{Total cooling flow}}{\text{flame temp}}$
SH-1	1300 (2374)	A	1.0	72°±10° C	11×10^{-5}
SH-2	1550 (2822)	A	2.3	11	27
SH-3	1800 (3272)	A	3.8	28	40
SH-3A	1100 (2012)	B	.4	39	4
SH-1A	1220 (2228)	B	.9	89	9
SH-4	1300 (2374)	B	1.0	111	11
SH-5	1550 (2822)	B	2.3	56	24

*Measured with a sonic velocity thermocouple probe.

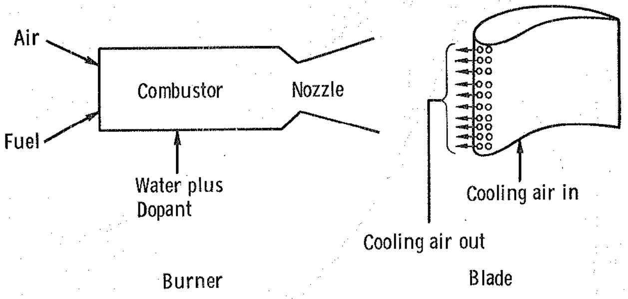
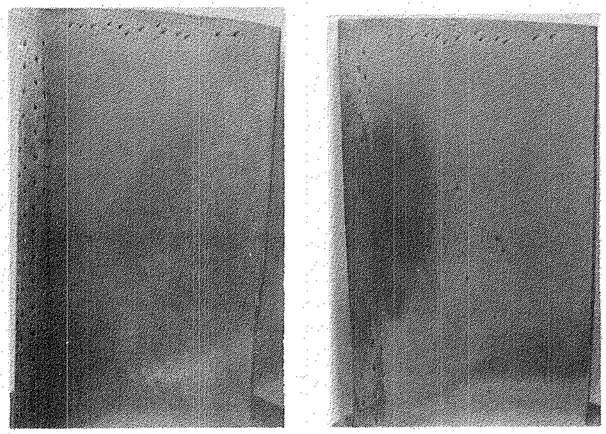


Figure 1. - Schematic diagram of burner rig.



(a) Flame temperature, 1550^0 C. Dopant A, $(V\cdot \rho)_C/(V\cdot \rho)_H = 2.3$.

(b) Flame temperature, 1100^0 C. Dopant B, $(V\cdot \rho)_C/(V\cdot \rho)_H = 0.4$.

Figure 2. - Mass flow - temperature effects on cooling hole plugging.

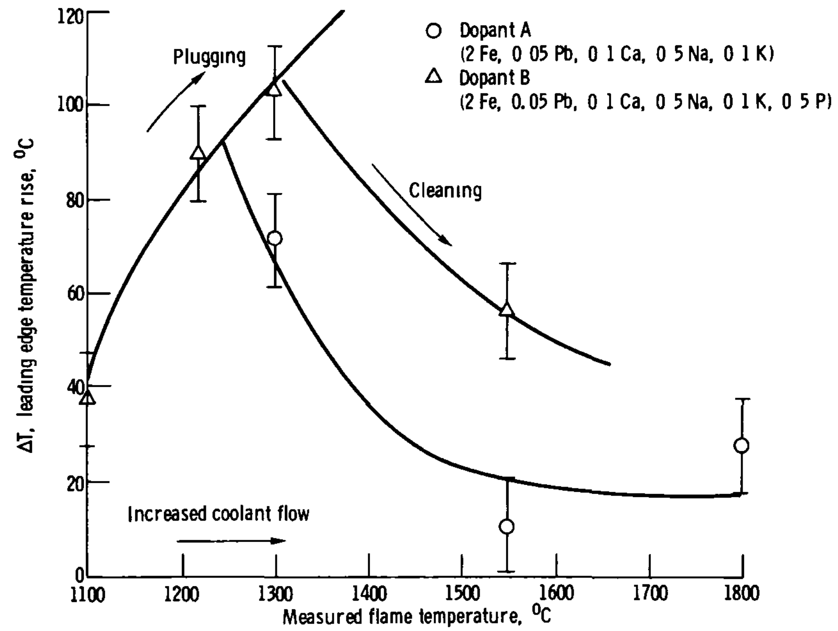


Figure 3 - Large cooling flows required to maintain leading edge temperature at 815° C reduce cooling hole plugging

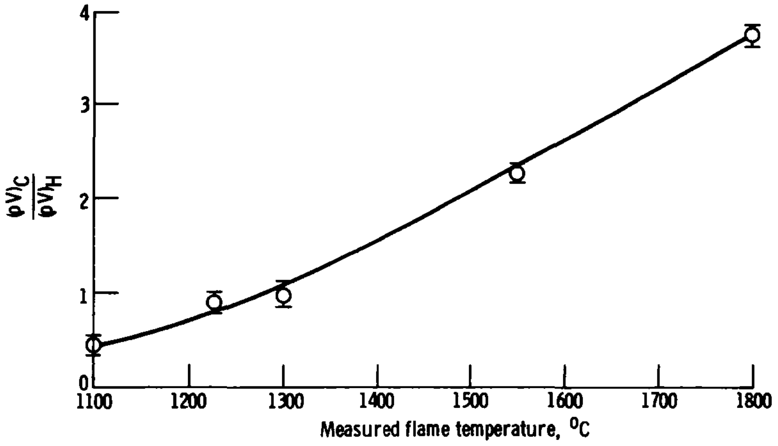


Figure 4 - Effect of flame temperature on cooling mass flow required to keep leading edge temperature at 815° C

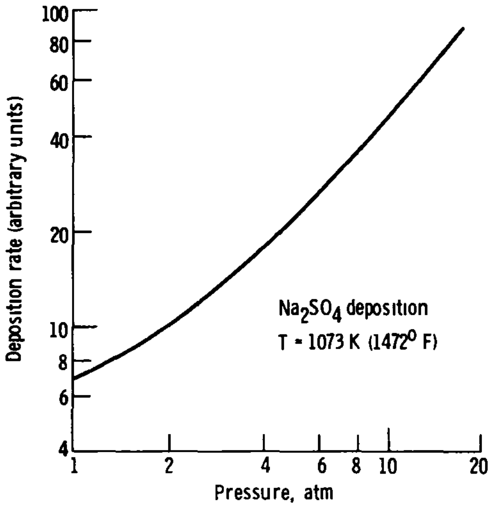


Figure 5 - Calculated effect of pressure on deposition rates, after Rosner, et al , ref 4

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