Turbine blade cooling using Coulomb repulsion

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Abstract

In order to preserve the integrity of the film cooling layer on a turbine blade, it is proposed that the blade is raised to a positive voltage with respect to a nearby negative electrode. The positive ions within the hot combustion products are repulsed from the blade, transferring that force to the surrounding neutrals. The neutral gas within the film cooling layer experiences no such body force. Therefore the boundary between the two fluids acts as a stably-stratified interface, analogous to the surface of the ocean. The flatness of the interface is determined by a Richardson number, the ratio of the potential energy of the Coulomb force to the kinetic energy of the turbulence. If Ri is greater than unity, the interface is relatively flat and the film cooling layer remains preserved.

1. Introduction

The Achilles heel of the turbine engine is the first stage turbine blades. Even with heroic effects at cooling and special alloys, they can not tolerate the full adiabatic flame temperature of the fuel. In order to protect the turbine blades from the hot combustion gases, the peak cycle temperature of the heat engine is deliberately lowered by adding relatively cool compressed air to the hot combustion gases. With the reduction in the turbine inlet temperature, the thermodynamic efficiency of the heat engine is degraded. Monsieur Carnot must be turning over in his grave.

Current technology uses internal impingement cooling of compressed air on the inside skin of the turbine blade to extract heat from the skin. This air is expelled through holes in the skin of the blade, supposedly forming a so-called “film cooling” layer around the outside of the blade, which is to protect it from the hot environment. However, the film cooling layer is typically not a layer adjacent to the surface, and it therefore does not cool much, except in the region immediately around the holes. In reality, after passing through the holes, the cooling air lifts up from the surface of the blade, no longer acting as an insulating blanket. Hot combustion gases reach the blade surface. Worse, the heat transfer coefficient may be increased downstream from each hole from the wake vortices under these transverse jets (Fric & Roshko 1994). Recent developments have reduced the lift-up of the transverse jet with special nozzle shapes (Kusterer *et al.* 2011), but it is still a problem, especially at density ratios near one (Feng *et al.* 2022).

2. Combustion ions

The combustion of a hydrocarbon like the kerosene in Jet A fuel naturally results in some ions among the combustion products. At atmospheric pressure, the ions are perhaps one part in a billion neutrals (Lawton & Weinberg 1969). The number fraction of ions will depend in general on the pressure and temperature of the combustion. Another important question is the rate of ion neutralization with free electrons.

3. Richardson number

With this supply of free ions at no extra charge, it opens the possibility of exploiting them to reduce the rate of heat transfer to the turbine blade. Imagine that relatively cool air is injected out of the blade at the front stagnation point. The air in this film cooling layer has essentially no ions. If the blade is elevated to a positive voltage with respect to a nearby negative electrode, free electrons within the hot gas will rapidly drift toward the blade. With much lower mobility, positive ions will more slowly drift away from the blade. Since the mean free path is small compared to the blade, the ions will make many collisions with the surrounding neutrals, transferring their momentum. In effect this Coulomb repulsion is a body force on the ion-containing hot gas.

However, there is no Coulomb force on the cooling film air, since it doesn't contain appreciable ions. The interface between the two fluids is stratified, like the surface of the ocean. For a stratified interface, the most important parameter is the Richardson number Ri, the ratio of potential to kinetic energy. The potential energy is the product of the ion number density n, the electric field strength E, the charge of an electron q and the thickness of the interface δ. The kinetic energy is proportional to the product of the fluid density ρ and the square of the turbulent velocity fluctuations ΔU.

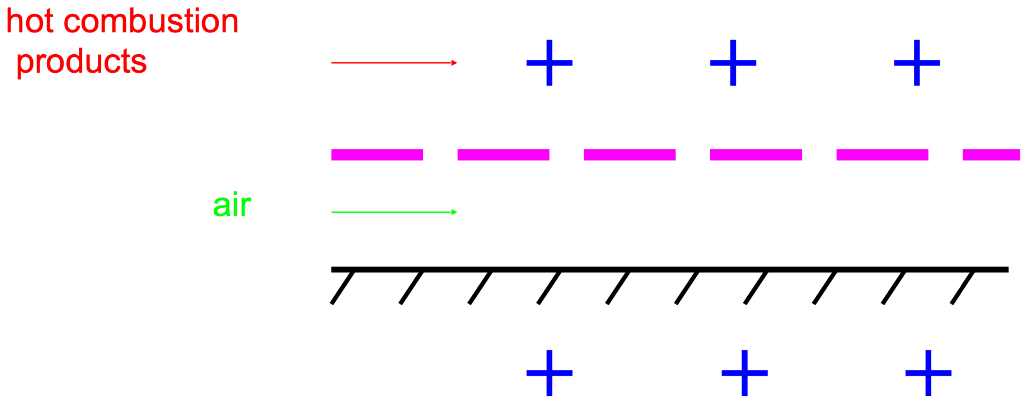
$$\mathrm{Ri} = nEq\delta/(\rho\Delta U^2). \tag{1}$$

If Ri is much less than one, the kinetic energy of the turbulence dominates the potential energy of the relatively weak stratification. Turbulent motions rapidly transport fluid across the layer. The film cooling layer is rapidly breached, and hot gases soon reach the blade surface.

On the other hand, if Ri is much greater than one, the kinetic energy of the turbulence is relatively anemic compared to the potential energy of the stratification. The interface remains essentially flat and the cooling layer remains intact. Hot gases do not reach the surface. The heat transfer is limited to radiation. If most other nearby surfaces are relatively cool and the combustion products do not contain much soot, then radiative heat fluxes may be relatively small. It may be possible to raise the turbine inlet temperature all the way to the full adiabatic flame temperature of the fuel. If so, then the thermodynamic efficiency of the turbine engine may achieve its full potential, corresponding to low specific fuel consumption and low CO_2 emissions (Breidenthal 2016).

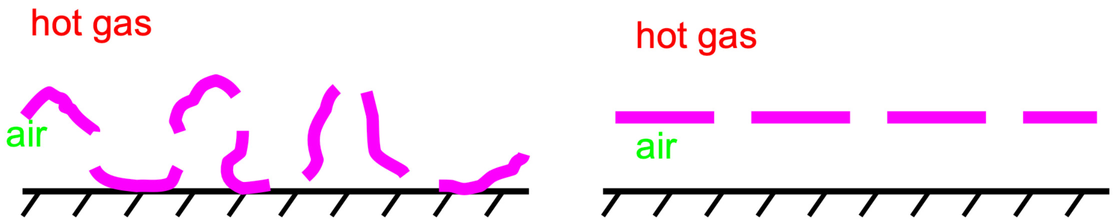
3. Experiment

Coulomb repulsion for film cooling was explored in a simple proof-of-concept experiment. As illustrated in Figure 1, stationary vertical plates formed the two electrodes. A nozzle adjacent to the positive electrode supplied an upward flow of air. Further away from the positive electrode, a flame supplied hot combustion products. The flow speeds of the two streams were both approximately 1 m/s.



$$Ri = \frac{nqE\delta}{\rho \Delta U^2}$$

Figure 1.



Ri << 1

Ri >> 1

Figure 2. Effect of Ri on the topography of the interface.

Figure 3 illustrates the geometry of the experiment. The film cooling slot, combustor, flat plate, and negative electrode are shown in a three-view drawing.

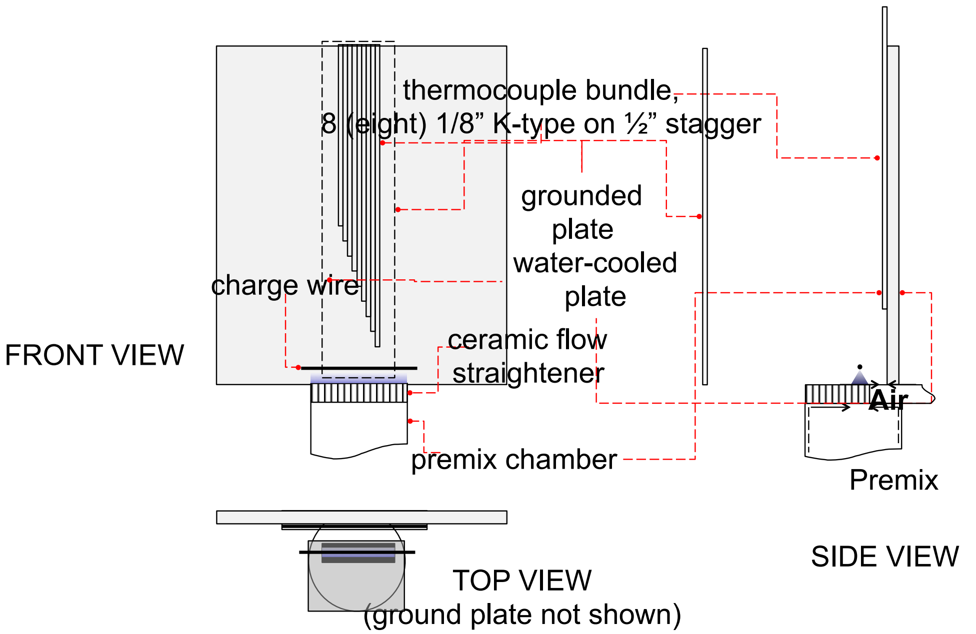


Fig. 3. Three-view of the experiment

The temperatures measured by the thermocouples are displayed in Figure 4. The blue temperatures are for the voltage turned off, and the red for the voltage turned on. The largest observed temperature drop was about 200K.

As noted by Giovanni Nino (private communication), there is a possibility that the electric field could affect the readings of the thermocouples.

Temp, K			
ON	**±**	**OFF**	**±**
1139	16	1150	11
1018	17	1020	15
840	28	812	24
891	19	988	11
776	22	881	18
813	17	1012	5
676	21	802	15
771	20	969	8

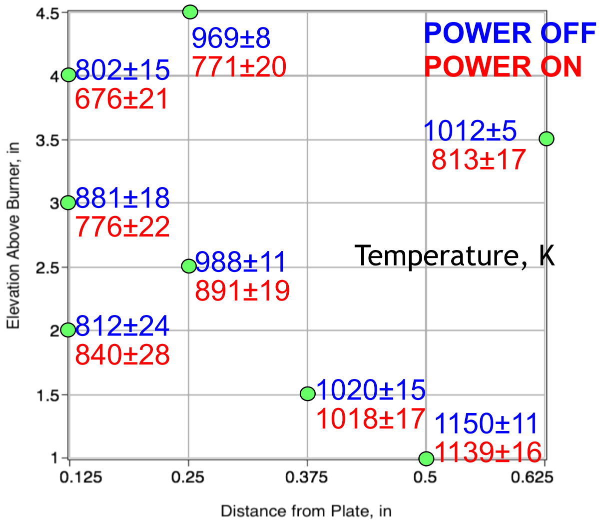


Fig. 4. Plate absolute temperatures with the electric field off in blue and on in red

The results are tabulated in these summary tables.

Summary Table

Elev	Distance	Temp, K		ΔT, K
in	in	ON	OFF	ON-OFF
1.0	0.500	1139	1150	-10.8
1.5	0.375	1018	1020	-1.8
2.0	0.125	840	812	28.4
2.5	0.250	891	988	-96.9
3.0	0.125	776	881	-105.0
3.5	0.625	813	1012	-199.3
4.0	0.125	676	802	-126.0
4.5	0.250	771	969	-198.1

Summary Table

Elev	Distance	Temp, K				ΔT, K
in	in	ON		OFF		ON-OFF
1.0	0.500	1139	±16	1150	±11	-10.8
1.5	0.375	1018	±17	1020	±15	-1.8
2.0	0.125	840	±28	812	±24	28.4
2.5	0.250	891	±19	988	±11	-96.9
3.0	0.125	776	±22	881	±18	-105.0
3.5	0.625	813	±17	1012	±5	-199.3
4.0	0.125	676	±21	802	±15	-126.0
4.5	0.250	771	±20	969	±8	-198.1

Summary Table

Elev	Distance	Temp, K				ΔT, K	% difference with ref. to		
in	in	ON		OFF		ON-OFF	0 K	298 K	500 K
1.0	0.500	1139	±16	1150	±11	-10.8	-0.9%	-1.3%	-1.7%
1.5	0.375	1018	±17	1020	±15	-1.8	-0.2%	-0.3%	-0.4%
2.0	0.125	840	±28	812	±24	28.4	3.5%	5.5%	9.1%
2.5	0.250	891	±19	988	±11	-96.9	-9.8%	-14.0%	-19.9%
3.0	0.125	776	±22	881	±18	-105.0	-11.9%	-18.0%	-27.5%
3.5	0.625	813	±17	1012	±5	-199.3	-19.7%	-27.9%	-38.9%
4.0	0.125	676	±21	802	±15	-126.0	-15.7%	-25.0%	-41.8%
4.5	0.250	771	±20	969	±8	-198.1	-20.4%	-29.5%	-42.2%

Conclusions

A proof-of-concept experiment has demonstrated the reduction of heat flux due to Coulomb repulsion on a non-rotating, flat plate at one atmosphere. The observed plate temperature dropped about 200K when the electric field is applied.

Of course, rotation of an actual turbine blade may tend to reduce the Richardson number due to Ekman-layer pumping, possibly increasing the heat transfer coefficient. At high pressures and temperatures, the plasma neutralization rate may be different than that at atmospheric pressure. Increasing pressure tends to increase the neutralization rate, while increasing temperature may have the opposite effect (Lawton & Weinberg 1969). The Coulomb force on the combustion products can only persist as long as there are still un-neutralized positive ions.

It remains to explore the effects of rotation and high pressure on the cooling performance. They would be directly addressed with an instrumented turbine blade of an operating engine in a ground test stand.

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