Feasibility of Self Powered Actuation for Flow, Separation and Vibration Control

Dillon Bak  
University of Notre Dame  
Notre Dame, IN, USA

Alain Izadnegahdar  
SAIC/NASA GRC  
Cleveland, OH, USA

Vikram Shyam  
NASA Glenn Research Center  
Cleveland, OH, USA

NASA INSPIRE high school intern at NASA GRC

Vikram Shyam
Research Aerospace Engineer, NASA GRC, contact author
Thermoelectric Generators

- TEGs make use of the Seebeck effect - if two dissimilar metals are connected in such a way that they form a circuit, and if the junctions of those two metals are held at different temperatures, an electric potential is generated between the hot and cold junctions.

\[ P = \eta Q_{TEG} = \eta \frac{T_{HJ} - T_{CJ}}{R_{TEG}} \]

\[ \eta = \frac{\Delta T}{T_h} \frac{\sqrt{1 + Z\bar{T}} - 1}{\sqrt{1 + Z\bar{T}} + T_c/T_h} \]

\[ Z\bar{T} = \frac{eS^2\bar{T}}{k} \]

\[ \bar{T} = \frac{T_H + T_C}{2} \]
Harvesting in a Jet Engine

- In a gas turbine engine heat is lost radially through conduction in the casing walls and through the exhaust nozzle.
- Energy harvested from this temperature difference can be stored in a capacitor or battery as part of a hybrid electric engine system. (Out of scope for this talk)
- Large temperature differences (~800K) also exist between the blade outer surfaces (air that’s been through combustion) and their internal surfaces (exposed to cooling air.)
- This heat transfer is not considered waste heat because the cooling air is returned to the main flow path and turns downstream blade rows.
- The benefit then of harvesting energy from the temperature difference across the thickness of a turbine blade is a local power source for active flow control, actuation or sensors.
100W
ΔT_{metal} = +10K
Figure 1. Cross section of a turbofan engine with representative temperatures obtained from NPSS [1] at cruise (Mach 0.85, 35k ft) for a high bypass ratio engine.

Figure 2. Turbine vanes with cooling holes

Figure 3. Self-powered DBD actuator system showing control of film cooling jet using a DBD actuator powered by energy harvested from an embedded TEG.

Figure 4. Schematic of a TEG (adapted from [2]).

Figure 5. Micro grooves and fins in the plenum [6].

Figure 6. Left - section of blade with TEG embedded. Right - thermal circuit for TEG embedded in blade.
Power Output Simplified

\[ P = \frac{\eta(T_H - T_C)}{R_{TEG}} \left\{ 1 - \frac{1}{1 + \left( \frac{k_{TEG}}{k_m} \right) \left[ k_m (h_c + h_H) + L_m h_c h_H \right]} \right\} \]

\[ \dot{p} \sim \dot{E} G \left\{ 1 - \frac{1}{1 + HT} \right\} \]

\[ G = \frac{\eta}{R_{TEG}}, E = T_H - T_C \]

\[ F = \frac{h_c h_H}{k_m (h_c + h_H)} \frac{L_{TEG}}{(1 - n)} \]

10/28/2015
Figure 11. Power output by TEG for various hot gas temperatures, $T_4$ as a function of % plenum surface area used for heat extraction.
Figure 13. TEG power as a function of % plenum surface area used for heat extraction and hot gas heat transfer coefficient.
Figure 16. TEG power as a function of TEG thickness, and % plenum surface area used for heat extraction.
Figure 18. Blade outer surface temperature as a function of % plenum surface area used for heat extraction.

- Blade thermal limit = 1350K (~2000°F)
- T4 = 1575K (2375°F).
- may use less than 70% of plenum surface for TEG.
Trying to collapse things…

- \( \bar{P} = \frac{P}{\eta \Delta T_{43}} \) (Power mainly depends on \( \Delta T_{43} \) for a given TEG)
- \( \theta = 1 - \frac{T_4 - T}{T_4 - T_3} \)
- \( \theta = 0 \) corresponds to \( T_3 \)
- \( \theta = 1 \) corresponds to \( T_4 \)
Melting point of SiGe is 1600K.

Assuming $T_4 = 1650K$ and $T_3 = 820K$, this corresponds to $\theta_{\text{limit}} = 0.9398$.

For $T_4 = 1950K$, $\theta_{\text{limit}} = 0.69$.

The nondimensional hot junction temperature, $\theta_{HJ}$, must remain below this value.

\[ \theta = 1 - \frac{T_4 - T}{T_4 - T_3} \]

Figure 13. Blade outer surface nondimensional temperature as a function of % plenum surface area used for heat extraction.
Figure 12. TEG corrected power as a function of % plenum surface area used for heat extraction.
Applying to realistic conditions...

- At take-off, $T_4 = 1850K$ and $T_3 = 950K$
- TEG is SiGe (high temperature limit)
- Blade thickness = 0.006m (~0.23in)
- Usable plenum surface area = 0.00322m$^2$ (0.5sq. in.)
- TEG thickness = 50% of the blade thickness
- 2 values of hot gas heat transfer coefficient, $h_H$ considered correspond to 2 extreme cases
  - 500 W/m$^2$K (trailing edge regions, no film cooling)
  - 2500 W/m$^2$K (leading edge of vane/blade).
- Similarly for the plenum,
  - $h_C = 1000$ W/m$^2$K, $h_C = 4000$ W/m$^2$K (simple ribs and microchannels respectively)
- Thermal conductivities - 25 W/mK, 90 W/mK (single crystal superalloys and conventionally cast superalloys)
TEG hot junction temperature at T.O.

\[ a. \] TEG hot junction temperature, \( T_3 = 950K, T_4 = 1850K, b = 0.006m, \text{SiGe} \]
Outer blade temperature at T.O.

b. Blade outer surface temperature, $T_3 = 950\,\text{K}$, $T_4 = 1850\,\text{K}$, $b = 0.006\,\text{m}$, SiGe

- $h_H = 500\,\text{W/m}^2\text{K}$, $h_C = 1000\,\text{W/m}^2\text{K}$, $k_m = 25\,\text{W/mK}$
- $h_H = 2500\,\text{W/m}^2\text{K}$, $h_C = 1000\,\text{W/m}^2\text{K}$, $k_m = 25\,\text{W/mK}$
- $h_H = 500\,\text{W/m}^2\text{K}$, $h_C = 1000\,\text{W/m}^2\text{K}$, $k_m = 90\,\text{W/mK}$
- $h_H = 2500\,\text{W/m}^2\text{K}$, $h_C = 1000\,\text{W/m}^2\text{K}$, $k_m = 90\,\text{W/mK}$
- $h_H = 500\,\text{W/m}^2\text{K}$, $h_C = 4000\,\text{W/m}^2\text{K}$, $k_m = 25\,\text{W/mK}$
- $h_H = 2500\,\text{W/m}^2\text{K}$, $h_C = 4000\,\text{W/m}^2\text{K}$, $k_m = 25\,\text{W/mK}$
- $h_H = 2500\,\text{W/m}^2\text{K}$, $h_C = 4000\,\text{W/m}^2\text{K}$, $k_m = 90\,\text{W/mK}$
Blades with thermal conductivity of 90W/m.K could generate anywhere from 0.5 - 8W
Conclusions

- As plenum heat transfer coefficient increases, power output increases
  - increase in power with heat transfer coefficient is more apparent as %TEG coverage increases
- Increasing TEG thickness from 50% to 90% only has significant benefits in the range $0.3 < n < 0.7$ and is a much smaller benefit than going from 10% to 50%.
- Increasing TEG layers leads to increased vane outer surface temperature.
Conclusions

- There is a tradeoff that can be made between TEG power extraction and technology in the plenum to increase heat transfer coefficient.
- Film cooling effectiveness provides another control parameter (0.1 increase in effectiveness ~ 100K thermal limit increase)
- Lower thermal conductivity blade provides more power but higher metal temperature
- Method to determine TEG material and parameters for integration has been shown
- Nusselt number at casing of HPT was used to get heat transfer coefficient approximations for hot gas path. The heat transfer coefficient in the hot gas path was approximated as \( h = \frac{k \cdot Nu}{L_{seg}} \). Average Nusselt numbers for HPT (2500), for LPT (1500) and for Nozzle (800) were used. Conductivity of air is based on local temperature.

- Bypass heat transfer coefficient is based on Nusselt number for a flat plate.