3D Printed Turbine Blades for Jet Engines

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Abstract

The issue this paper seeks to address is improving aircraft range by increasing turbine efficiency. This is done by using 3D printing to create turbine blades with optimized internal cooling passages which can survive at higher turbine inlet temperatures and not melt, thereby increasing turbine efficiency. A relation between range and turbine inlet temperature was leveraged to deduce how much of a temperature increase was needed to obtain range increases of 250 and 500 nautical miles. A MATLAB finite element analysis was then implemented to investigate the needed heat transfer coefficients for blades operating at these increased temperature values. A maximum value of 138 $\frac{w}{m^2K}$ was found to be needed for a 500 nautical mile range increase which is well within current state of the art 3D turbine blade internal cooling passage designs.

Introduction

The development and advancement of jet engines over the last century has been integral in increasing global connections through the transport of people and goods. Since their invention in the 1930s, a number of milestone breakthroughs have allowed for major leaps in fuel economy and thrust production. Unlocking the next big step has become increasingly critical in recent years, as fuel prices rise, travel demands grow, and an increasing emphasis is placed on regulating greenhouse gas emissions.

As shown in Figure 1, fundamentally, a jet engine operates through four stages. First, outside air is sucked in at the front through the intake (1), and then it is compressed in the compressor stage (2). Next, in the combustor, the oxygen reacts with fuel, causing an explosion, and forcing exhaust out the back (3). This exhaust, or thrust, in turn propels the aircraft forward (4).

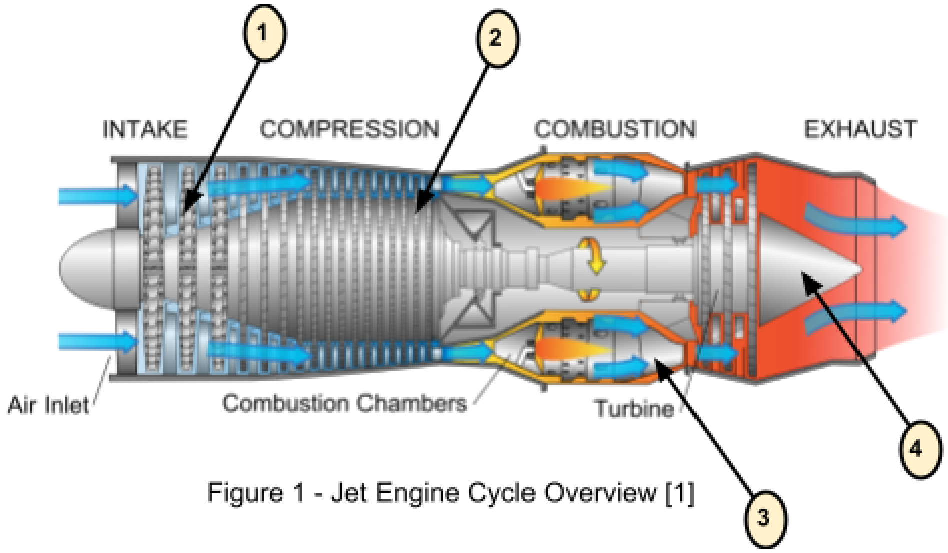


Figure 1 - Jet Engine Cycle Overview [1]

Typically, it has been the application of novel materials in the construction of turbine fan blades which allows for significant jumps in efficiency. This trend is visible in Figure 2.1. These substances are capable of surviving at higher temperatures than their predecessors, which, following the laws of thermodynamics, means that more thrust is produced. Without adjusting other jet engine components, and without the creation of alloys able to survive at new, higher temperatures, the only way to increase the efficiency of a jet engine is by increasing the cooling of its blades. Similarly to the application of heat resistant materials, advancements in cooling have historically also yielded jumps in efficiency, as exhibited by Figure 2.2.

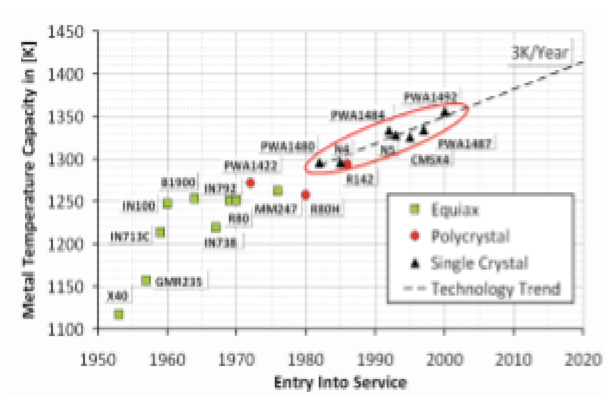


Figure 2.1 - Timeline of Material Improvement [2]

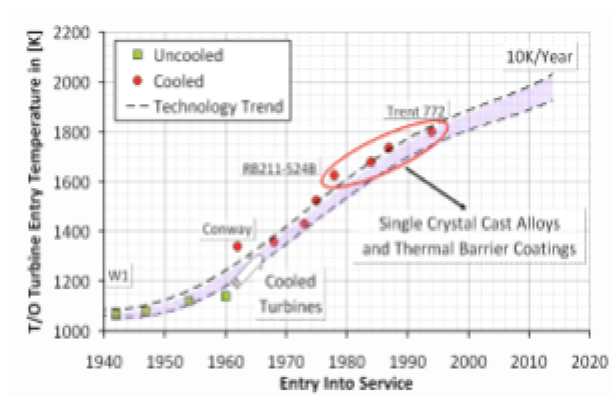


Figure 2.2 - Timeline of Cooling Improvement [2]

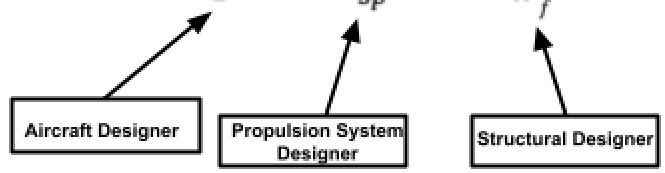
Currently, turbine blades are cooled by air which flows from the compressor through channels in the blades themselves. Theoretically, these passages could be optimized with additive manufacturing (i.e., 3D printing). This improvement in cooling would allow the turbine inlet temperature to run hotter, thus making the engine produce more thrust.

The values used in this paper, along with the calculations performed, correspond with the Boeing 787-9, using Rolls Royce Trent 1000 jet engines. It is a common aircraft for commercial flight, and the Trent 1000 is currently a cutting edge design. Note that its turbine blades are constructed from the alloy Inconel 718.

Methodology

The goal of this paper is to investigate how 3D printed turbine blades could improve jet engine performance and therefore range. The Breguet Range Equation, shown by Equation 1, highlights the relationship which determines the range of a jet aircraft in steady level flight.

$$Range = V \times \left(\frac{L}{D}\right) \times I_{sp} \times ln\left(\frac{W_i}{W_f}\right)$$



Equation 1 - Breguet Range [3]

Next, range can be represented as a function of overall efficiency. This is written in Equation 2. Finally, overall efficiency can be plotted as a function of compressor exit temperature. For this analysis, it will be approximated that turbine inlet temperature is 500K greater than compressor exit temperature. This is used in Equation 3 [4]. Through substitution, the relationship between Range and Turbine inlet temperature has now been established, and is written shown in Equation 4.

By plotting a thorough set of data points, a line of best fit can be established to represent the relationship. For this analysis, hypothetical range increases of 250 and 500 nautical miles are sought. To achieve these goals, the 3D printed turbine blades must be capable of surviving at the correlated temperatures, which can be found using the fit equation.

$$Range = \frac{\Delta h_{fuel}}{g}(\eta_{overall})\left(\frac{L}{D}\right)ln\left(\frac{W_i}{W_f}\right)$$

$$\eta_{overall} = \frac{g}{\Delta h_{fuel}} V I_{sp}$$

Equation 2 - Range as a Function of Overall Efficiency [3]

$$\eta_{overall} = 1 - \frac{T_{atmospheric}}{T_{compressor\ exit}} = 1 - \frac{T_{atmospheric}}{T_{turbine\ inlet} - 500}$$

Equation 3 - Overall Efficiency as a Function of Turbine Inlet Temperature [3]

$$Range = (\frac{\Delta h_{fuel}}{g})(1 - \frac{T_{atmospheric}}{T_{turbine\ inlet} - 500})(\frac{L}{D})ln(\frac{W_i}{W_f})$$

Equation 4 - Range as a Function of Turbine Inlet Temperature [3][4]

As previously mentioned, hypothetically, 3D printed blades could survive at a higher temperature because of their ability to house optimized air cooling channels. Newton's Law of Cooling, depicted in Equation 5, relates the rate of heat transfer out of the body to change in temperature, surface area, and heat transfer coefficient. The significant variable is *h*, the heat transfer coefficient. Its value would increase in blades created with additive manufacturing which contain optimized cooling channels.

$$Q = h \cdot A \cdot (T(t) - T_{env})$$

Equation 5 - Newton's Law of Cooling [5]

To solve for the minimum increase in cooling which must occur, a MATLAB simulation can be used to calculate the threshold heat transfer coefficient which successfully lowers the stresses on the blade to an acceptable level. If the stress on the blade is two high, it will catastrophically deform, or snap off the shaft.

Results

First, the values for the constants in Equation 3.3 must be imputed, leaving range and turbine inlet temperature as the sole variables. The heat of combustion for Jet A1 (Δh), the fuel used by the 787-9, is 42.80 $\frac{MJ}{kg}$ [6]. The acceleration of the Earth's gravity (g) is constant at 9.81 $\frac{m}{s^2}$. The lift to drag ratio is 20, and the max takeoff weight (W_i) and max zero fuel weights (W_f) are 254,011 kg and 181,437 kg respectively [7]. These are factors determined by the manufacturing of the aircraft itself, and are outside the scope of this analysis, which concerns only the engines themselves. It is assumed that the plane flies at standard constant velocity of 0.8 Mach, or 530.8 mph (V) [7].

Temperature values between 1500K and 3000K, incremented by 10K, provide a spread which incompasses all reasonable values. Plotting the turbine inlet temperatures and their corresponding range values yields the graph shown in Figure 3.

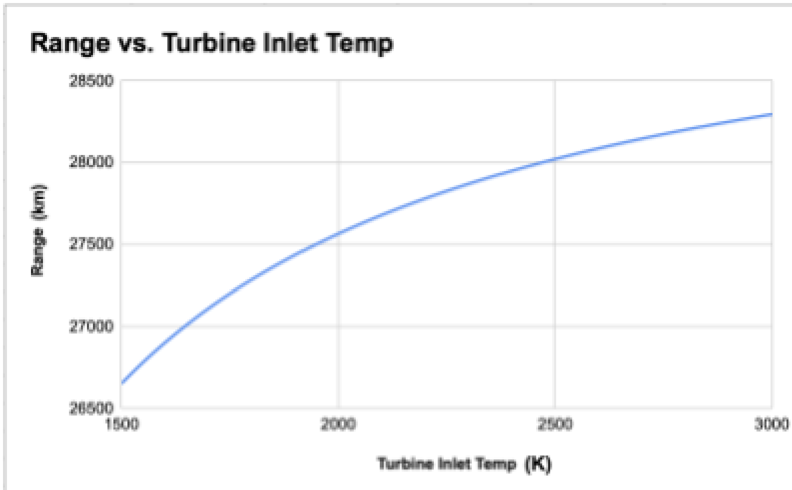


Figure 3 - Range vs Turbine Inlet Temp

To understand the reason for its shape, range can be plotted as a function of overall efficiency, and overall efficiency can be plotted as a function of compressor exit temperature. These plots are shown below in Figure 4. As temperature increases, overall efficiency increases at a decreasing rate. Because overall efficiency and range are directly proportional, that means that in turn, the rate at which range increases also decreases.

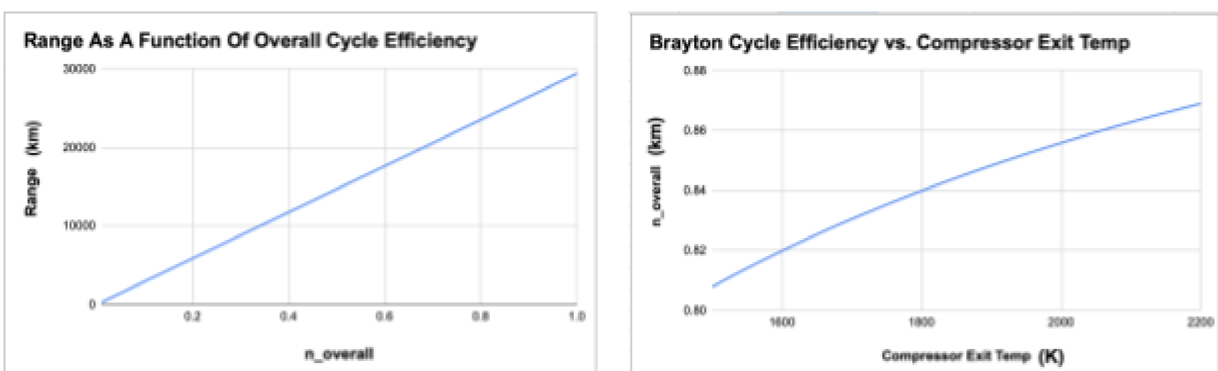


Figure 4 - Range vs Overall Efficiency and Overall Efficiency vs Compressor Exit Temperature

Plotted in MATLAB, the quadratic line of best fit for the data in Figure 3 is found to equal $y = -0.0006073x^2 + 3.742x + 2.249x10^4$.With its current single crystal blades, the turbine inlet temperature of the Trent 1000 is 1810K. This corresponds to a range of 27300 km.

Additions of 250 and 500 nautical miles, or 463 and 926 km, give desired ranges of 27763 and 28226 km. When substituted for *y* in the best fit equation, new turbine inlet temperatures of 2181.44K and 2865.1K are found. These findings are displayed in Figure 5.

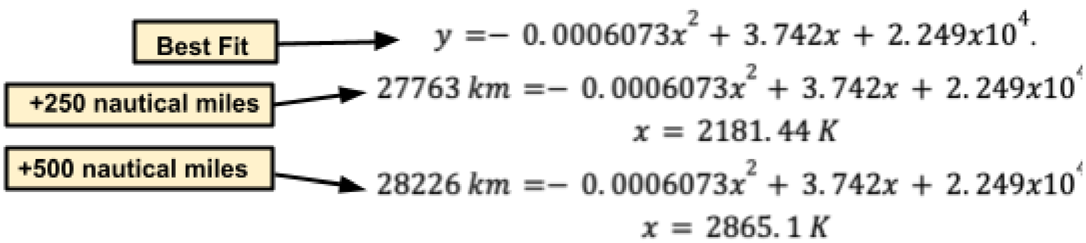


Figure 5 - Solving for New Temperatures With a Best Fit Line

As expected, in the MATLAB simulation, the turbine blades show unsurvivable levels of stress. Calculating the heat transfer coefficients which allow the blades to survive at these two temperatures yields 116 $\frac{W}{m^2K}$ and 138 $\frac{W}{m^2K}$.

Figure 6 shows the output of the MATLAB finite element analysis (FEA) for the given temperature and pressure stresses on the blade. Note that the deflections/deformations are exaggerated to assist in visualizing the shape of the blade under the given stresses.

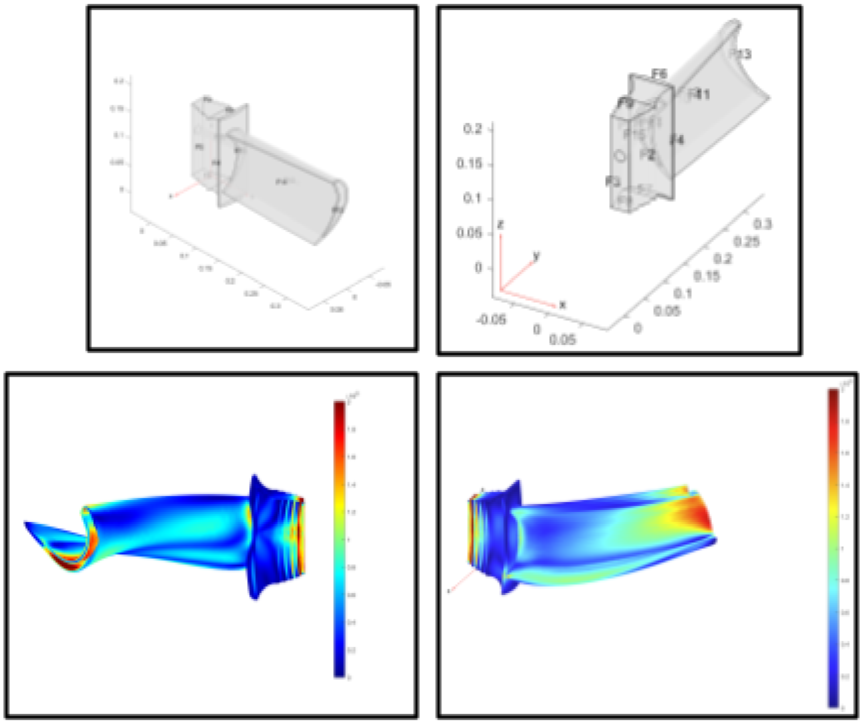


Figure 6 - MATLAB Blade Analysis (Stress in Pa) [8]

Analysis

Typically, for the Rolls Royce Trent 1000, the turbine blades internal cooling passages have a heat transfer coefficient of 92.3 $\frac{w}{m^2K}$. As shown in Figure 7, graphing this value and its corresponding temperature of 1810K, alongside the corresponding points for increased ranges of 250 and 500 nautical miles yields a graph with an increasing slope. This follows that an increase in heat transfer efficiency occurs as the turbine inlet temperature gets hotter. The heat transfer coefficients found during the calculations fall within a typical range of those expected for a turbine blade and achievable for 3D printing [9].

Heat Transfer Coefficent (W / m K)	Temperature (K)
92.3	1810
116	2181.44
138	2865.1

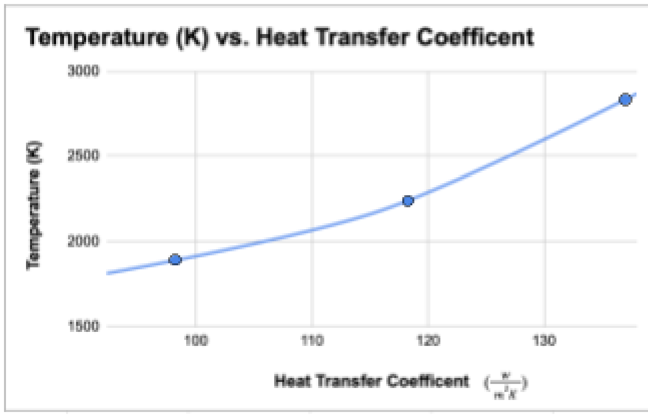
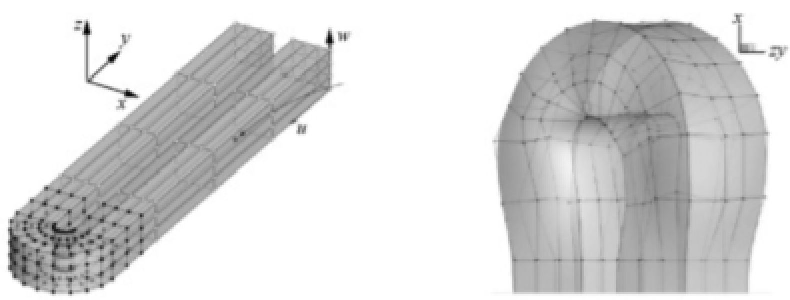


Figure 7 - Temperature vs Heat Transfer Coefficient

A number of different cooling passage designs have been studied and been proven to increase the heat transfer coefficient. These shapes include the addition of ribs, dimples, pin–fin arrays, and U-bends. By lining channels with rib structures, and adjusting their geometry, angle and size, researchers have been able to improve various heat transfer metrics by up to 21.5%. Arrays of pins lining opposite walls of the passages have also been shown to yield similar optimizations. Similarly, linings of cylindrical and elliptical dimple patterns have also provided cooling benefits. [11]

U-bend channels are typically featured in modern turbine fan blades, and turn the flow of air 180°. Calculations and computer simulations have shown that their shape can be optimized. The optimal shape is shown in Figure 7. Coupling optimized bends with the enhancement features previously discussed (i.e. ribs, dimples, and pin-fin arrays), could yield even greater jumps in the heat transfer efficiency. [11]



Current Geometry　　Optimal Geometry

Figure 8 - U Channel Geometry [11]

Another typical route for increasing the heat transfer coefficient is maximizing the surface area contact between the air and the metal of the blade. The next progression of this method is a honeycomb style design. Unfortunately, when produced in the traditional manner, it is unstable and imperfect. Additive manufacturing can resolve this, as it offers the ability to create robust porous compounds. For example, Raytheon Tech Corp has made an innovative design, in which a cavity inside the blade is filled with a metal lattice. The technique has been proven to enhance the blades ability to withstand temperature stresses. [12]

Beyond improving cooling channels, creating turbine blades using additive manufacturing has been shown to offer benefits in economy, weight reduction, ease of repair, and stress detection. They are cheaper to produce than current single crystal designs, which are immensely technical, time consuming, and costly. Furthermore, their ability to house larger hollowed channels means they can be lighter, and thus more efficient. Optomec, a New Mexico based company, has even been able to implant advanced stress monitoring sensors using the 3D printing process. These improve the longevity and safety of the engine. [12]

Conclusion

In this paper we looked at increasing range by optimizing jet engine efficiency. We calculated the heat transfer coefficients which would be needed to increase range by 250 and 500 nautical miles. Finally, we discussed how optimized internal cooling channels could be constructed inside turbine blades using 3D printing in order to obtain these boosts. We discussed some possible channel layouts which could achieve superior cooling and touched on other benefits of manufacturing blades with additive methods.

Sources:

[1] “What does the actual path of air within a turbojet engine look like?,” Aviation Stack Exchange, https://aviation.stackexchange.com/questions/33121/what-does-the-actual-path-of-air-within-a-turbojet-engine-look-like (accessed Aug. 7, 2024).

[2] K. G. Kyprianidis, “Future Aero Engine Designs: An Evolving Vision,” Cloudfront.net, https://dpl6hyzg28thp.cloudfront.net/media/22893.pdf (accessed Aug. 7, 2024).

[3] 13.3 Aircraft Range: The Breguet Range Equation, https://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node98.html (accessed Aug. 7, 2024).

[4] Rolls royce - the jet Engine.pdf, https://www.valentiniweb.com/Piermo/meccanica/mat/Rolls%20Royce%20-%20The%20Jet%20Engine.pdf (accessed Aug. 11, 2024).

[5] “Newton’s law of cooling,” Wikipedia, https://en.wikipedia.org/wiki/Newton%27s_law_of_cooling (accessed Aug. 7, 2024).

[6] ExxonMobil Jet A-1, https://www.exxonmobil.com/en/aviation/products-and-services/products/exxonmobil-jet-a-1 (accessed Aug. 10, 2024).

[7] “Boeing 787 Dreamliner,” World Airports Wiki, https://world-airports.fandom.com/wiki/Boeing_787_Dreamliner (accessed Aug. 10, 2024).

[8] “Thermal stress analysis of Jet Engine Turbine Blade,” Thermal Stress Analysis of Jet Engine Turbine Blade - MATLAB & Simulink, https://www.mathworks.com/help/pde/ug/thermal-stress-analysis-of-jet-engine-turbine-blade.html (accessed Aug. 7, 2024).

[9] F. Satta and G. Tanda, “Measurement of local heat transfer coefficient on the endwall of a turbine blade cascade by liquid crystal thermography,” *Experimental Thermal and Fluid Science*, pp. 209–215, Jul. 2014.

[10] I. Kaur, Y. Aider, K. Nithyanandam, and P. Singh, “Thermal-hydraulic performance of additively manufactured lattices for gas turbine blade trailing edge cooling,” *Applied Thermal Engineering*, vol. 211, Jul. 2022.

[11] G. Zhang, R. Zhu, G. Xie, S. Li, and B. Sunden, “Optimization of cooling structures in gas turbines: A Review,” *Chinese Journal of Aeronautics*, vol. 35, no. 6, pp. 18–46, Jun. 2022.

[12] A. Sinha, B. Swain, A. Behera, P. Mallick, and S. K. Samal, “A Review on the Processing of Aero-Turbine Blades Using 3D Print Techniques,” *Journal of Manufacturing and Materials Processing*, pp. 1–34, Jun. 2022.