



Impact of Cooling Fluid Temperature on the Structural Integrity of Gas Turbine Stator Blades

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HIGHLIGHTS

- Gas turbine engines demand efficient cooling due to high temperatures and material constraints from combusted gases in aircraft
- Optimum performance and prevention of thermal gradients require controlled cooling, as internal cooling alone is insufficient
- The study highlights the importance of additional measures to ensure efficient cooling and prevent parts failure

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ABSTRACT

The importance of gas turbine engines to the aviation industry cannot be overemphasized. Being a major part of aircrafts and jets, its reliability must be second to none. They are continuously subjected to extreme conditions during service making them the subject of constant studies. To produce the thrust and torque power required of them, they have to convert the intense heat and pressure inherent in hot combustion gases. To withstand the high combustion gas temperature without thermal failure, specialized materials and cooling are employed. This study numerically investigated the effect of cooling fluid temperature on the structural integrity of a (DS) GTD111 alloy gas turbine stator blade using COMSOL 5.5 software. Air was used as the cooling fluid in this study. The duct passages of the stator blade are significantly affected by the cooling fluid temperature values. Lower values of cooling fluid temperature proved beneficial for keeping the stator blade material below its metallurgical limit and is a positive for its total displacement, it however, negatively affects the yielding of the material. The cooling fluid temperature can be optimally selected to give optimal cooling effects in terms of total displacement and stress development. Based on this study, a cooling fluid (air) temperature of about 660 K will give optimal results. Internal cooling alone is not sufficient to produce the required cooling for turbine stator blades and this is evident in the output of the study, thus, coating and film cooling must be carried out to prevent thermal failure during service.

1. Introduction

Gas turbines are internal combustion engines as, unlike steam turbines which are external combustion engines. Its operation is based on the four basic steps of internal combustion engines; induction, compression, combustion, and exhaust. The aerodynamic and energy requirements demand changes in the pressure and velocity of air that passes through the turbine. Turbines are designed to turn the intense heat and pressure contained in the exhaust of combusted gases into thrust and torque power. And as such, turbine components must be able to endure extreme pressure and temperature conditions.

Thermal engines are subjected to Carnot's theorem; the efficiency of thermodynamic cycles is dependent on the temperature ratio between the hot and cold heat sources. Thus, the higher the combustion temperature, the better will be the theoretical efficiency. The combustion temperature of fuels is relatively high, and in piston-type internal combustion engines, it is in excess of 1000 K [1,2]. Most available materials cannot withstand the high combustion temperature in internal combustion engines, however, in piston-type internal combustion engines, the temperature is reached and maintained only for fractions of a second which does not allow the materials to attain the maximum combustion temperature coupled with cooling [3].

In turbine engines, the basic characteristics operations of internal combustion engines occur in separate compartments simultaneously, an indication that the turbine will at all-time be subjected to high temperature and pressure gas leaving the combustion chamber. And as such, the turbine blades are made from high-temperature resistant materials and cooling is also very important for normal operation. To this effect, Nickel-based superalloys are usually employed for turbine blades because of their high temperature, pressure, and oxidation resistance [4-7]. The turbine blades can either be the rotors or the stators and are subjected to high temperatures necessitating cooling through internal ducts and film cooling. A gas turbine jet engine showing the different stages of the process is depicted in Figure 1.

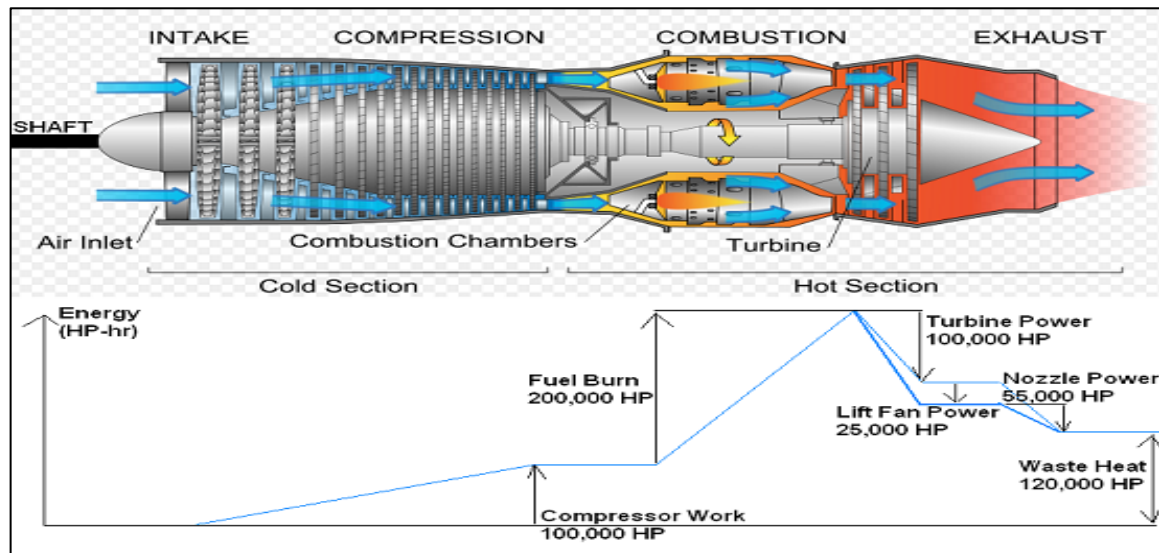


Figure 1: A typical Gas Turbine Jet Engine

Modern turbines have combustion temperatures in excess of 1500 K [7-9] which is higher than the normal limits of operation for the components [10]. This is designed so to optimize the efficiency; a performance characteristic dependent on the firing temperature. The increased temperature comes at a price, the requirement for efficient cooling. This is to prevent thermal deformation/degradation of the parts at high temperatures [11]. Turbine failure cannot be attributed to a single cause, as several factors with different conditions can which are interrelated can be responsible [7,12].

The indicators of failure in turbines include surface damage, fatigue, wear, and corrosion, and mostly occur at the hot sections like the blades [11,13]. These failures are generally classified as fatigue failure, thermomechanical fatigue failure, creep failure, corrosion failure, and erosion failure. They are directly and indirectly a consequence of the very high temperature that the turbine experiences [5, 14-17]. Of interest to this study is the thermomechanical fatigue failure which is a consequence of a combination of factors including tensile loads due to thermal gradients across components. Since thermal efficiency is a function of the attained maximum temperature of the working fluid and this is in turn limited by the metallurgical limit of the materials, cooling will ensure increased transfer of heat away from the materials thereby making it able to withstand higher working fluid temperature. Cooling will result in the creation of thermal gradients which can be a recipe for failure if not properly managed. The cooling in turbines is a very complex study, and to this end, only internal duct cooling of the stator blade is considered here because of the intricate complexities of film and coated cooling.

This study thus seeks to numerically examine the impact of internal cooling fluid temperatures on the development of stress on a turbine stator and the corresponding displacement of the stator.

2. Methodology

The numerical study was carried out using COMSOL Multiphysics 5.5 CFD tool and requires the structural mechanics module and the heat transfer module which was coupled using the Multiphysics module.

The governing equations for the heat transfer in the stator blade are:

$$\rho c_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{ted} \tag{1}$$

$$\text{where } q = -k \nabla T \tag{2}$$

and, the heat flux which is the heat per unit area;

$$q_0 = h \cdot (T_{ext} - T) \tag{3}$$

ρ – density, c_p – heat capacity, u – fluid velocity T – temperature, q – heat conduction, Q – heat transfer, k – thermal conductivity.

The stress developed and the structural displacement in the turbine stator is governed by the under-stated equation which is a derivative of the equation of motion;

$$0 = \nabla \cdot S + Fv \tag{4}$$

$$\text{where } S = S_{ad} + C : \epsilon_{el} \tag{5}$$

$$\text{and } C = C(E, v), \epsilon = \frac{1}{2} [\nabla u^T + \nabla u] \tag{6}$$

ν – Poisson’s ratio, $\nabla \cdot S$ – stress divergence, C – viscous damp, E – Young modulus, F_v – volume factor, v – volume, S – 2nd Piola – Kirchoff stress

The studied stator blade is made from (DS) GTD111 alloy with is characteristic high temperature and oxidation resistance. Studies on this material has shown that it has a yield strength of about 702.72 MPa and 645.62 MPa at room temperature and at 923 K respectively [3]. The stator blade geometry is similar to that available in COMSOL Multiphysics 5.5 model which was tailored towards the NASA power turbine. The mesh type is free tetrahedral with maximum and minimum element size of the mesh was taken to be 0.0182 m and 0.00228 m respectively, the maximum element growth rate is 1.45, curvature factor is 0.5 and the resolution of narrow regions is 0.6. Figure 2 shows a sample turbine stator blade in accordance to NASA power turbine.

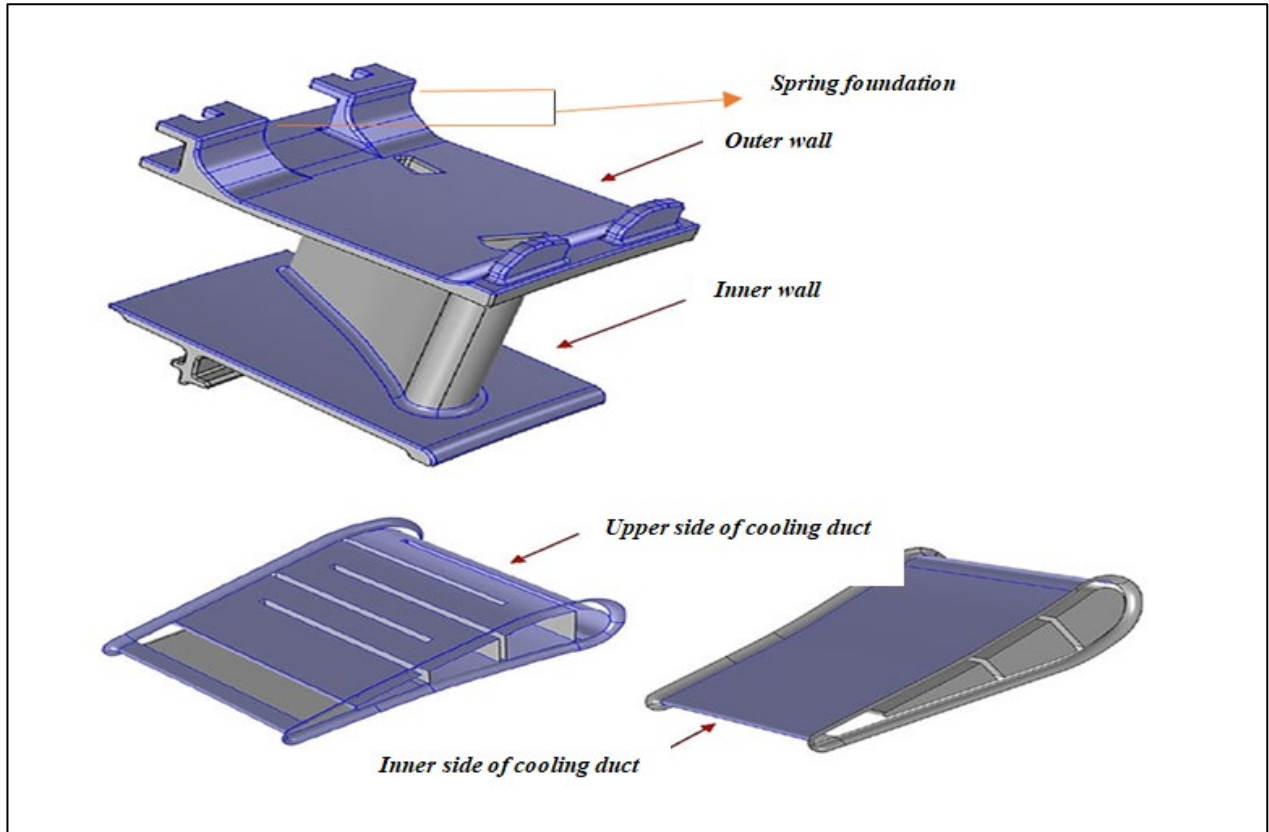
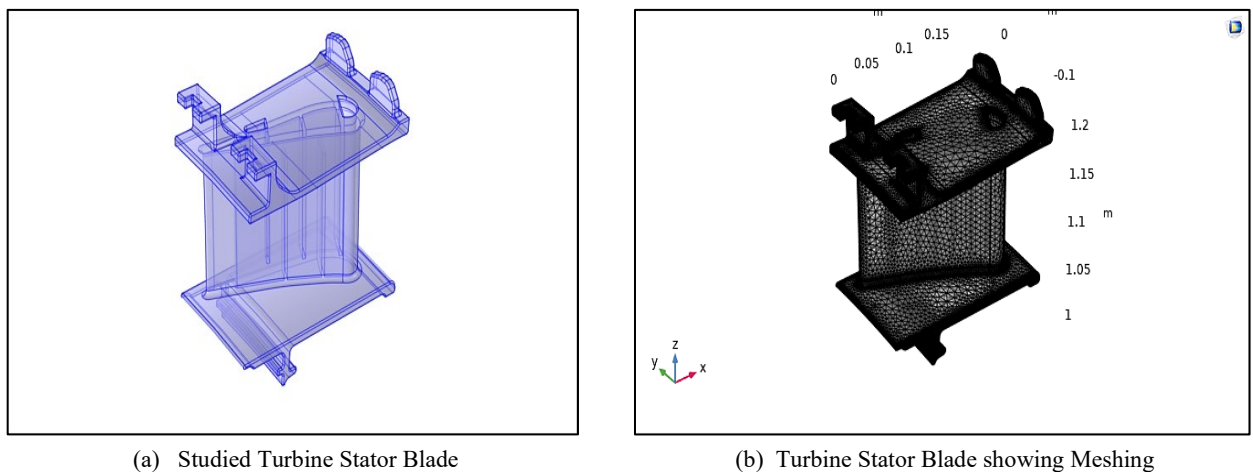


Figure 2: A Turbine stator blade [19]

The studied geometry and its discretized form using a free tetrahedral mesh with parameters spelt-out earlier is depicted in Figure 3 (a and b).



(a) Studied Turbine Stator Blade

(b) Turbine Stator Blade showing Meshing

Figure 3: Geometry of the Studied Turbine Stator Blade

The parameter values for the cooling fluid which was taken as air and the combustion gases employed for the study are provided in Table 1.

Table 1: Cooling fluid properties

Parameter	Values
Combustion gas temperature	1100 K
Combustion gas pressure	30 bar
Working temperature	900 K
Working pressure	30 bar
Stator pressure side gas velocity	300 m/s
Stator suction side gas velocity	450 m/s
Free stream velocity at platform walls	350 m/s

The characteristic length scale of the cooling channel is 0.01 m, its Nusselt number is 400, and the Poisson's ratio of the stator material is 0.33 at a set reference temperature of 300 K for linear elasticity. The following approximations and assumptions were made to simplify the problem:

- 1) Coating and film cooling are not taken into consideration.
- 2) The cooling duct geometry does not include the rib details thus enabling the use of an average Nusselt number correlation for the calculation of the heat transfer coefficient.
- 3) The suction and pressure sides of the duct are approximated as two flat plates
- 4) The turbine has a working temperature of 900 K and a heat transfer coefficient of 25 W/(m². K)
- 5) The combustion gases' temperature and pressure were approximated to 1100 K and 30 bar respectively.
- 6) The cooling fluid was taken to be air with pressure approximated to 30 bar.
- 7) Mach number for stators without film cooling was adopted for the suction and pressure sides and this corresponds to 0.7 and 0.45 respectively.

The cooling air temperature is varied to determine the resultant yield stress developed on the stator blade and its corresponding displacement. While it is proven according to the laws of thermodynamics that cooling will allow higher values of working temperatures with the material not failing thermally, however, this might not be true about the yielding of the material. The viscosity, Prandtl number, and heat capacity of the cooling fluid are dependent on the temperature. The corresponding values of these variables for the study temperatures are provided in Table 2.

Table 2: Study variables values

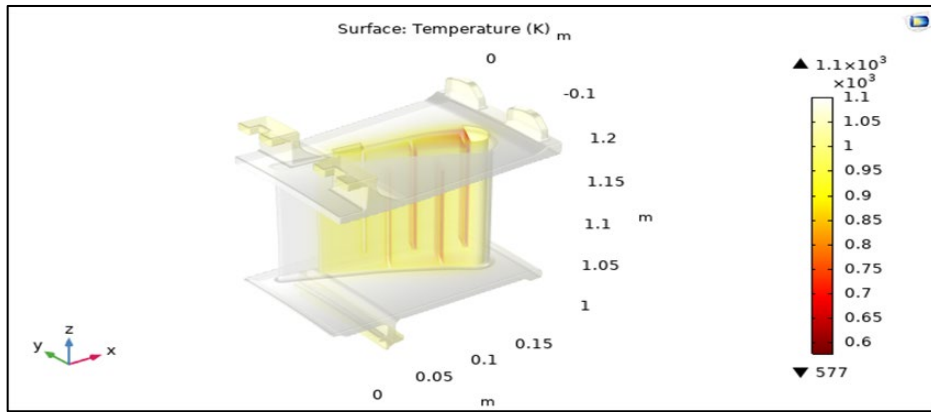
Cooling Air Temperature (K)	Viscosity (10 ⁻⁵ Pa.s)	Prandtl number	Heat capacity (J/kgK)
500	2.732	0.7048	742
520	2.807	0.7053	746.4
540	2.881	0.7058	750.8
560	2.956	0.7063	755.2
580	3.029	0.7070	759.6
600	3.098	0.7080	764
620	3.167	0.7092	768.8
640	3.236	0.7103	773.6
660	3.305	0.7114	778.4
680	3.372	0.7125	783.2
700	3.437	0.7137	788

3. Results and Discussion

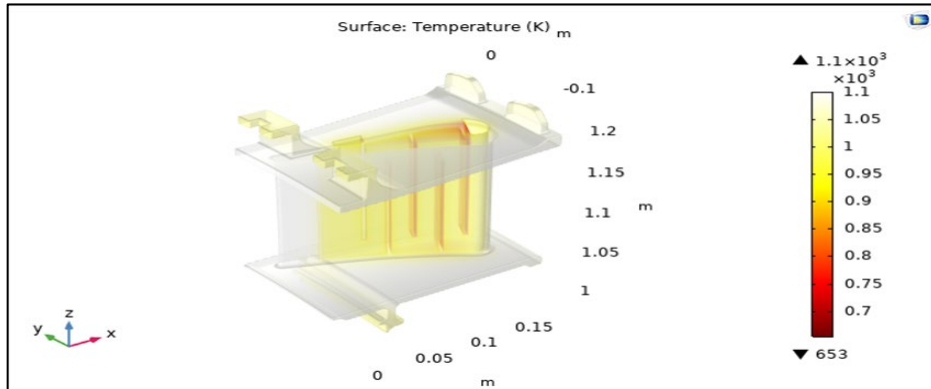
The variation of the cooling fluid temperature resulted in a corresponding variation in the average temperature of the stator blade, however, the maximum temperature attained by some parts of the stator blade remains unchanged. This is because internal cooling is responsible for the creation of temperature gradients within the blade, but does have a lesser significant impact on its trailing edge making it a necessity for additional cooling like coating and film cooling for the trailing edge. The surface temperature plots of some of the outputs at their respective cooling fluid temperatures and values of the attained temperature by the stator blade at different fluid cooling temperatures considered in this study are depicted in Figures 4 (a,b,c) and 5 respectively.

Cooling is required to ensure that the blade materials withstand the high working fluid temperature without exceeding its metallurgical limit, however, if not optimally managed can lead to failure due to the creation of thermal gradients causing stress build-up. The effect of cooling fluid temperature on the stress build-up on the studied stator blade for some selected surface plots and the different temperatures considered are depicted in Figures 6 (a,b,c) and 7 respectively.

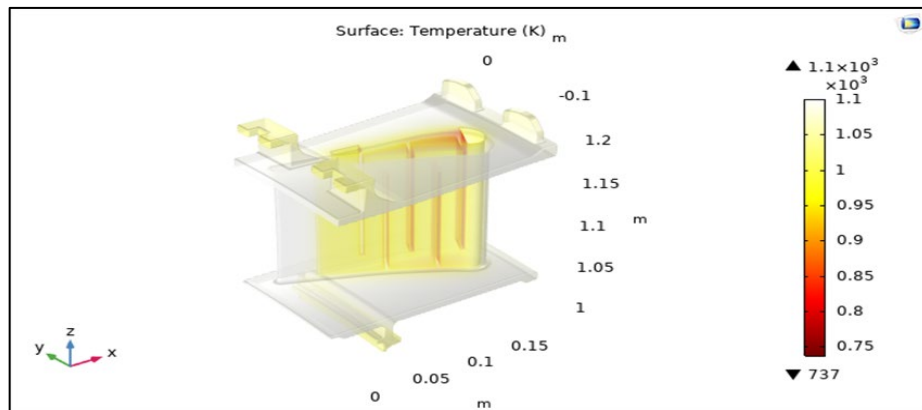
The area of least temperature on the stator blade corresponds to the vicinity of the highest stress development as depicted in Figures 3 and 5. This is an indication of the responsiveness of thermal gradients for stress development in the part. This developed stress at all times must be lower than the material yield stress if deformation and failure is to be avoided.



(a) Cooling fluid temperature of 500 K



(b) Cooling fluid temperature of 600 K



(c) Cooling fluid temperature of 600 K

Figure 4: Sample surface temperature plots for stator blade

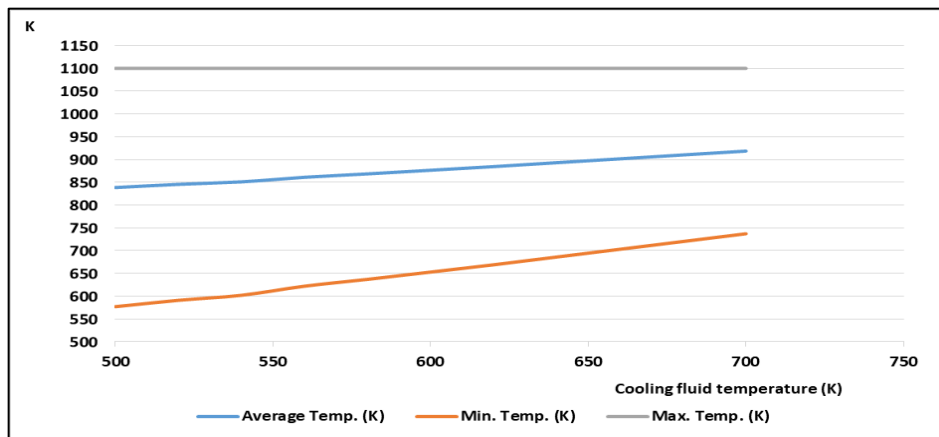
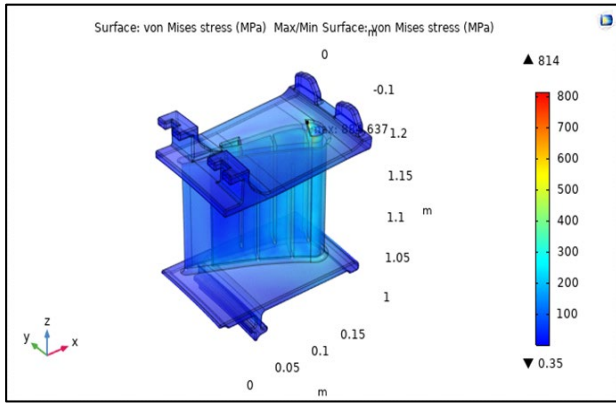
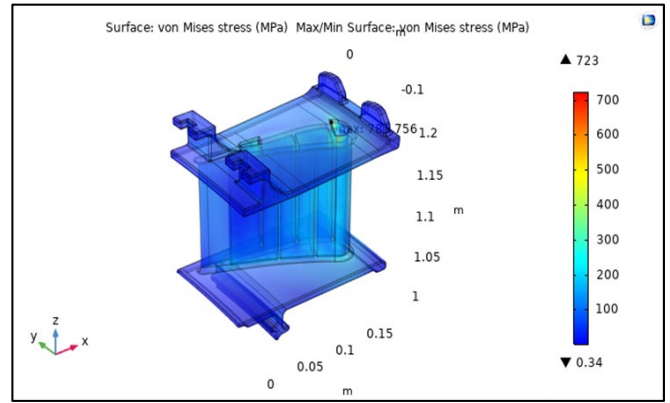


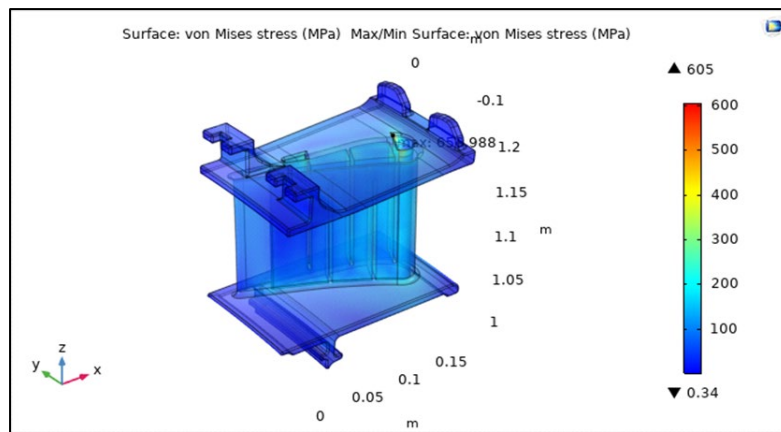
Figure 5: Effect of cooling fluid temperature of stator blade surface temperature



(a) Cooling fluid temperature of 500 K



(b) Cooling fluid temperature of 600 K



(c) Cooling fluid temperature of 700 K

Figure 6: Selected surface plots for stress developed in turbine stator

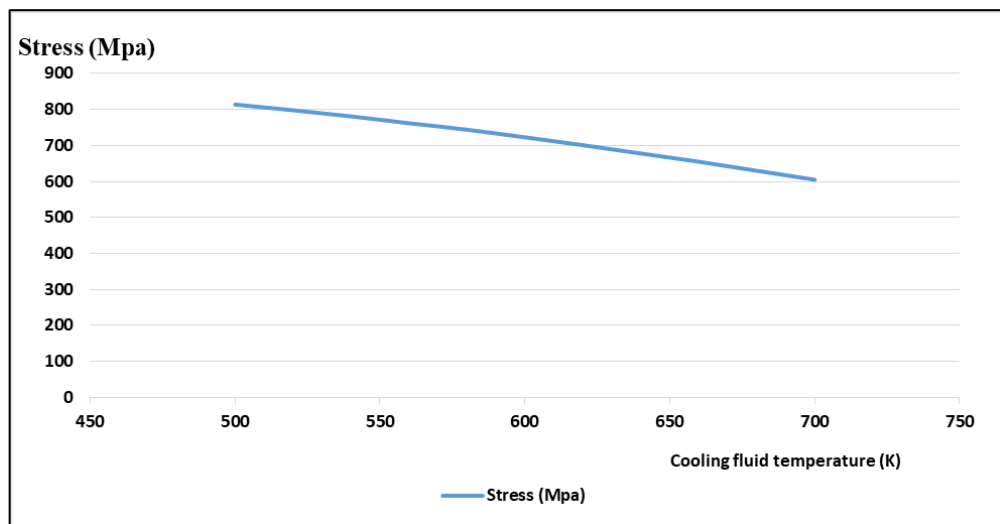


Figure 7: Stress developed in turbine stator blade

The high operating temperature in the turbine is a precursor to some displacement of the stator blade parts, this is due to the different levels of expansion that will occur in the material. The displacement of the stator parts will have an impact on the turbine performance due to the requirement of certain stator angle for optimal performance [20,21].

The surface plot of the stator blade at a cooling fluid temperature of 500 K showing the point of total maximum displacement is shown in Figure 8, while Figure 9 depicts the maximum deflection plots for the studied cooling fluid temperatures.

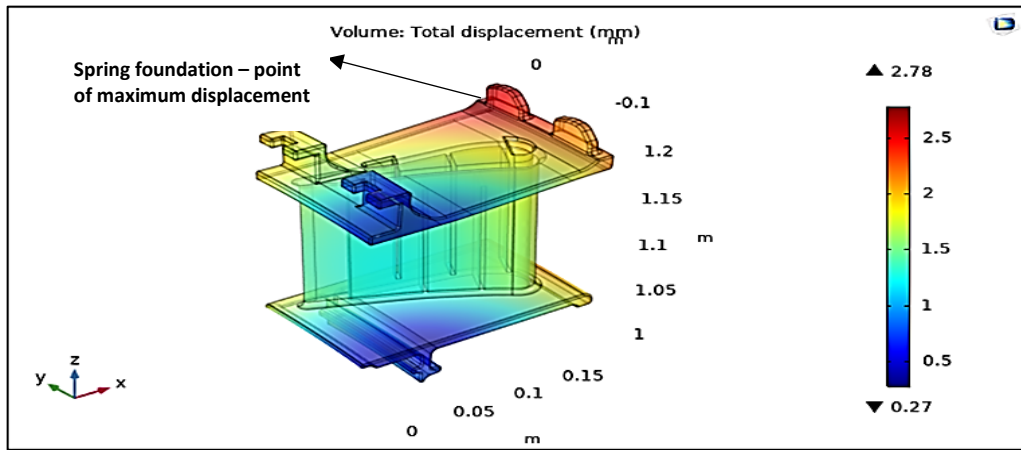


Figure 8: Sample output of simulation for stator blade displacement

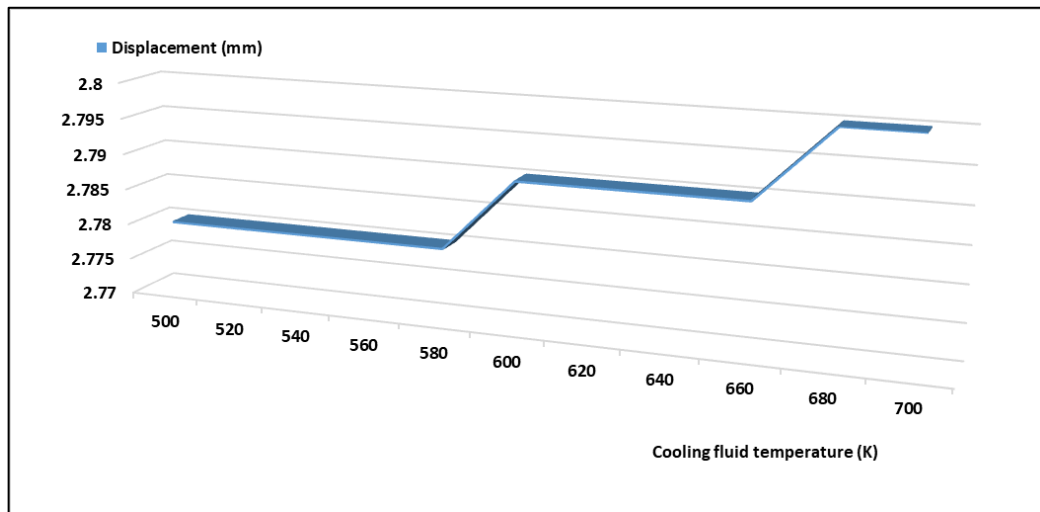


Figure 9: Maximum deflection of stator blade around spring foundation

While lower cooling fluid temperatures are required to ensure that the material stays below the metallurgical limit, this can lead to increased stress development which is a recipe for structural failure, increasing the cooling fluid temperature also leads to increase total displacement. A nexus therefore, has to be reached to allow for stress value below the yield value and to keep total displacement also at bay. A plot of the stress generated and the maximum displacement recorded for the studied cooling fluid temperatures is as depicted in Figure 10.

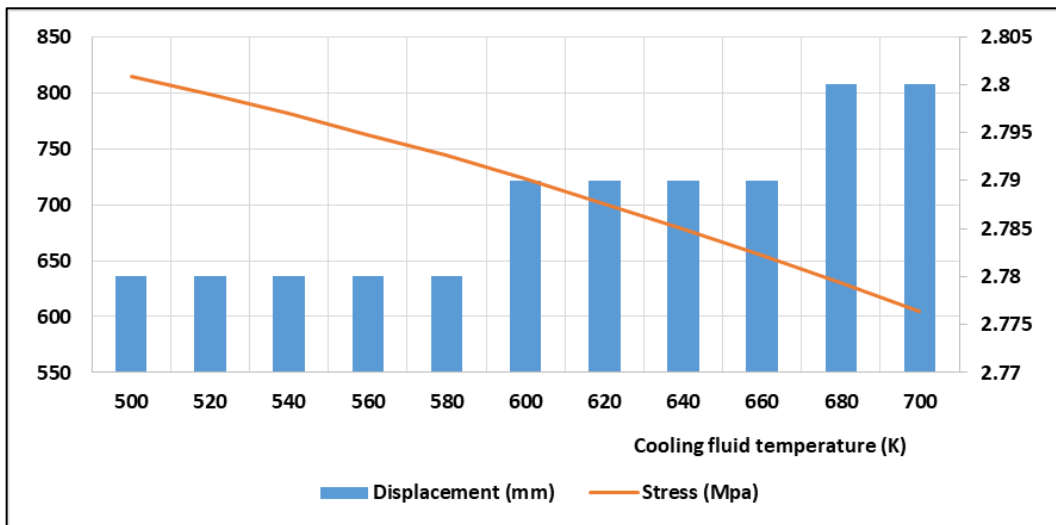


Figure 10: Stress – Displacement plots

It was documented earlier that the yield stress for (DS) GTD111 alloy at room temperature is about 702.72 MPa, and it can drop to about 645.62 MPa at 923 K. while at the least value of total displacement observed in this study, the resulting developed stress will be high as to allow the material to yield, an indication that the cooling fluid temperatures below 620 K might not be appropriate as evidenced in Figure 10. And as the total displacement is relatively equal for cooling fluid temperatures up to 660 K, but with a reduced value of developed stress (≈ 650 MPa), the cooling fluid temperature value of 660 K can be adopted.

4. Conclusion

While it has been stated earlier that only internal cooling was considered in this study, and thus, cannot be a full representation of the impacts that could have been obtained from a comprehensive cooling process, some deductions can still be made:

- 1) The cooling fluid temperature significantly affects the turbine stator blade at duct passage areas.
- 2) Lower values of cooling fluid temperature are beneficial for keeping the stator blade material below its metallurgical limit and is a positive for its total displacement, it however, negatively affects the yielding of the material.
- 3) The cooling fluid temperature can be optimally selected to ensure optimal values for the yield stress and total stator blade displacement.
- 4) Based on this study, cooling fluid (air) temperature of about 660 K will give optimal results.

The relative constant value of the peak temperature of the turbine stator blade as evident in the results is due to the absence of cooling fluid duct in the platforms. Hence, in order to avoid its thermal deformation, film cooling is a necessity.

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Data availability statement

Not applicable.

Conflicts of interest

The authors of the current work do not have conflict of interest.

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