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Simulation of temperature distribution in gas turbine stator blade subjected to different internal coolant gases

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A B S T R A C T

The gas turbine blade stator is subjected to a severe high temperature of hot incoming gases from the combustor. In order to avoid the melting of the stator, film and internal cooling techniques are applied by using a bypass stream of air from the compressor as a coolant fluid. These techniques have their own merits, but it is limited by some constraints like the value of specific heat of air. In this paper different gases with higher specific heat are used as a coolant in order to increase the thermal capacity of coolant fluid which in turn increases the amount of transferred heat. The selected gases are Helium, Steam, and Ammonia are applied in COMSOL Multiphysics® in order to simulate the cooling process and the temperature distribution. At first, the air is applied and the results show a good agreement with previous literature and then the other coolants to compare their results with the air. The results show that the Helium affects the cooling process strongly and it cools the blade to safer limits rather than air by about 50%, but it increases von Mises stress by about 71% in comparison with air. The two other coolants also have a good and effective cooling performance, but they almost show an identical performance.

1. Introduction

Regarding its merits, gas turbine engines become the most reliable and promising units in many industrial and aviation fields to generate power and thrust force and to compensate loads at peak load situations. Thermal and power output of these engines is still limited by the metallurgical limit of turbine blades. Any higher turbine inlet temperature beyond the fusion point of the blade alloy leads certainly to thermal failure of the unit especially in the presence of high rotational effect on the rotor. To avoid such a situation in the operation, a cooling technique is adopted by manufactures internally to reduce the severe temperatures and to increase the operational hours of the unit as long as it operates at safe limits [1-3]. Different cooling methods are proposed like film and internal cooling or both of them depending on the conditions of the application area of gas turbine engine itself. Among them, internal cooling, mostly incorporated via cooling passages inside the blade. Internal cooling configurations also

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Nomenclature:

		Greek symbols	
Q	Heat transferred (W)	α	Heat transfer coefficient (W/m2 K)
k	Turbulent kinetic energy	ε	Rate of energy dissipation
Nu	Nusselt number	Δp	Pressure drop (Pa)
p	Pressure (Pa)	μ	Fluid dynamic viscosity (Pas)
c_p	The heat capacity (J/kgK)	ρ	Density (kg/m3)
Pr	Prandtl number	λ	Thermal conductivity (W/mK)
qw	Wall heat flux (W/m2)	κ	The turbulence kinetic energy
A	Area (m2)	subscripts	
Re	Reynold number	a	air, ambient
T	Temperature (K)	c	characteristics length
ui	The velocity in the x_i direction, (m/s)	coolant	coolant gas used in cooling

imply different geometries and shapes to get better performance and effect [4-7] . Al Ali and Janajreh [8] performed a theoretical analysis of different configurations on the heat transfer via impingement cooling. Moskalenko and Kozhevnikov [9] estimated the gas turbine blade cooling efficiency by simulating two medium of cooling, i.e., water vapor and air. In their results, they found that water vapor is more efficient than air for the same working pressure and temperature by about 30%. Deepanraj et al. [10] studied by using different models with different holes by using a finite element method to find out the optimum number of holes for good performance. They found that when the numbers of holes are increased in the blade, the temperature distribution is decreased dramatically. The ribs in the cooling channels play an important role since they increase the turbulence level, which in turn enhances the heat transferred between the inner wall and coolant. Xie et al. [11] studied their effect on different paths at different Reynold numbers. They found an improvement in heat transfer, but the pressure drop should be accounted. Since the blade is mounted on the rotating disc which rotates, usually at very high rotational speed, the effect of rotation is also has been investigated. Burberi et al. [12] studied the effect of rotation on the heat transfer coefficient especially at the leading edge zone. Their findings indicate an effect at the tip region but it vanishes at the hub region. Optimization of internal cooling is also investigated by researchers in order to find the optimum parameters of the whole process [13-15]. Mousavi et al. were also interested in finding optimum cooling. In their works [16, 17] they performed a numerical analysis in three-dimensional model to optimize the hole of cooling serpentines and their distribution along the chord of the gas turbine blade. Their results show a huge reduction in mass flow rate of the cooling air extracted from the compressor which in turn positively affects the output power and thermal efficiency of the gas turbine engine. Weak attention was directed in previous studies to the type of coolant and its physical properties. Finding an effective coolant has become a challenge as it is influenced by a large number of flow and geometrical parameters. This paper is dedicated to analyzing the gas turbine blade when subjected to different coolant in three case studies to find its effect on the internal cooling and severe temperature distribution.

2. Mathematical model

The governing equation of the flow field of the flowing air can be expressed as follows:

- *Continuity equation*

$$\frac{\partial}{\partial x_i}(\rho_{coolant} u_i) = 0 \quad (1)$$

- *Momentum equation*

$$\frac{\partial}{\partial x_i}(\rho_{coolant} u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}\left[\mu_{coolant}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho_{coolant}\overline{u_i' u_j'}\right]$$

$$\frac{\partial}{\partial x_i}(\rho_{coolant} c_{p,coolant} u_i T) = \frac{\partial}{\partial x_i}\left(\lambda_{coolant}\frac{\partial T}{\partial x_i} - \rho_{coolant} c_{p,coolant}\overline{u_i' T'}\right) \quad (2)$$

- ***Turbulence model***

Where $\overline{u_i' u_j'}$ should be calculated by using a suitable turbulence model. Because of complex flow phenomena inside the cooling channels of the blade, the type of turbulence model should provide acceptable accuracy in the calculation of heat transfer cooling. Many models had been selected in previous studies to simulate the turbulent heat transfer, among them, the Shear Stress Transport (SST) turbulence model [5] and the Renormalized Group (RNG) k-ε model [18, 19] which show a good convergence in their result. A low-Reynolds number (LRN) k-ω turbulence model, with improved heat transfer predictions, is proposed by Bredberg J. in his works [20-26] which shows better results and convergence, especially as it takes into account the rotational effect of the gas turbine and thus it has been selected in this paper.

- **Heat transfer in a solid zone**

The dominant mechanism of heat transfer in the turbine of the gas turbine engine is the convection heat transfer. Since there's flowing hot gas outside the blades and relatively cold coolant inside the blade flowing through the cooling duct, this model of convective heat transfer seems to be reasonable which is usually defined by:

$$Q_{conv} = \alpha A(T_w - T_a) \quad (3)$$

The heat transfer coefficient (α) needs to be calculated accurately and accounted on well-known dimensionless parameter Nusselt number and the latter itself in the forced convection is a function of Reynold and Prandtl numbers, so

$$Nu = \frac{\alpha L_c}{\lambda} \quad (4)$$

The characteristic length Lc varies for different zones in the gas turbine blade. To obtain precise calculations of the magnitude of heat transfer quantity, the heat transfer coefficient will be calculated in different forms according to zones where a heat transfer occurs.

- *Heat transfer in the cooling ducts of the blade*

$$\alpha = \frac{Nu \mu_{coolant} Cp_{coolant}}{(Pr_{coolant} L_c)} \quad (5)$$

- *Heat transfer at the pressure and suction sides of the blade*

The heat transfer here is assumed to be external forced convection on a flat plate with local heat transfer coefficient

$$\alpha = \begin{cases} \frac{k}{x}0.332Pr^{\frac{1}{3}}Re_x^{\frac{1}{2}} & if\, Re_x \le 5\times10^5 \\ \frac{k}{x}0.0296Pr^{\frac{1}{3}}Re_x^{\frac{4}{5}} & if\, Re_x > 5\times10^5 \end{cases} \tag{6}$$

- *Heat transfer at the top and bottom sides of the blade*

The same equation above is adopted with a difference in the characteristic length.

3. Numerical simulation

The numerical simulation is performed using software package COMSOL Multiphysics® in order to model the different cases adopted in this study. In order to isolate the effect of the type of coolant, the operating conditions and other parameters are kept with no change. To obtain good results, a fine mesh was generated near the channel walls and the fluid flow domain so as to capture the temperature variations because of coolant fluid flow throughout the channels. The blade material was chosen to be a nickel super-alloy Inconel 718, which is being used widely in aerospace related applications. The physical properties of the coolant are chosen to be a function of temperature as illustrated in **Table 2**. The values of the constants are taken from the study of [27].

The case geometry is shown in **Fig. 1** with the mounting details of the blade. **Fig. 2** shows the cooling ducts and the passages where coolant fluid flows inside the gas turbine blade to reduce the severe temperature and hot spot which usually occur on the blade surface because of the hot incoming burned gases from the combustion chamber of a gas turbine engine. The duct geometry does not include any ribs or turbulators.

Table 2. Physical properties of the air coolant as a function of temperature [26]

Property	Function	Unit
Density	352.7*T*−1	[kg/m3]
Specific heat capacity	1093 − 0.6356*T* + 1.634 × 10−3*T*2 − 1.413 × 10−6*T*3 + 5.595 × 10−10*T*4 − 8.663 × 10−14*T*5	[J/(kg.K)]
Dynamic viscosity	3.893 × 10−6 + 5.754 × 10−8*T* − 2.676 × 10−11*T*2 + 9.710 × 10−15*T*3 − 1.356 × 10−18*T*4	[kg/(m.s)]

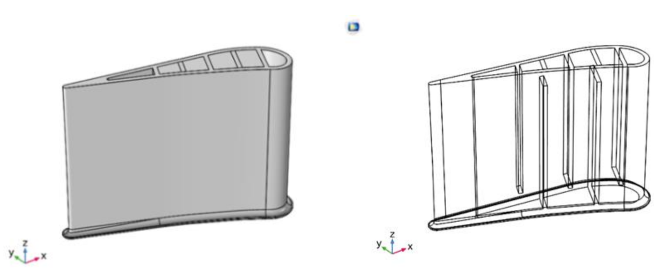
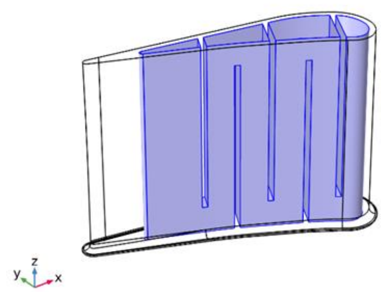
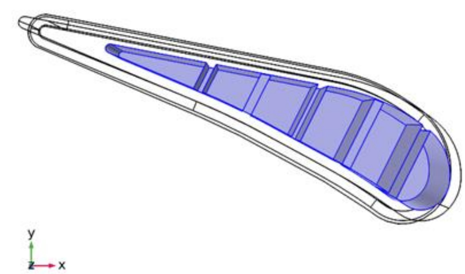


Figure 1. The geometry of the gas turbine stator blade



(a) 3D model



(b) Top view

Figure 2. The passages of cooling ducts inside the gas turbine stator

4. Mesh generation

In the first step, the blade geometry was built in the Solidworks software. Two camber lines were used to create the side boundaries. Then, this geometry was exported from Solidworks and later imported into COMSOL Multiphysics software to build up the mesh because of its flexibility for creating a mesh. For faster calculations and performance, as we go farther from the blade into the fluid domain, the mesh size becomes larger and larger as shown in **Fig. 3**. Complete mesh consists of 623212 domain elements, 137704 boundary elements, and 15913 edge elements. Minimum quality: 0.1604; average quality: 0.6555. The operating and boundary conditions are listed in **Table 1**.

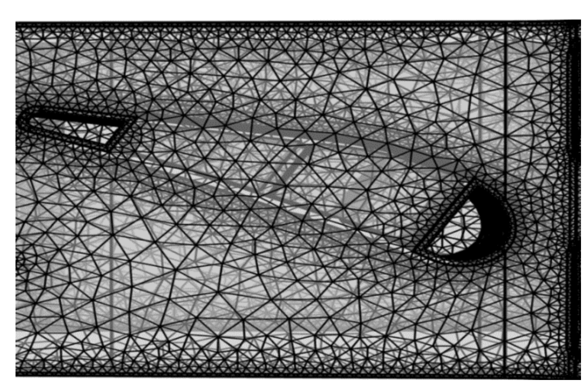


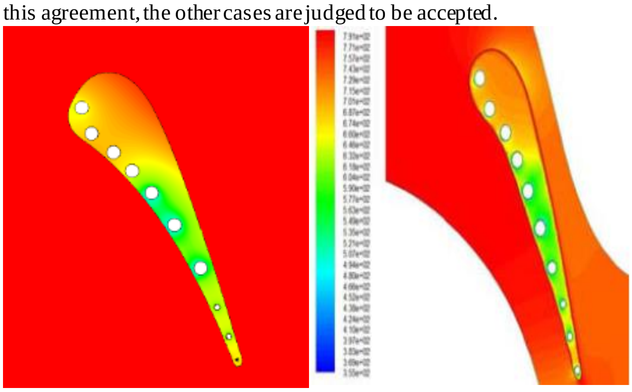
Figure 3. The mesh of the gas turbine blade

Table 1. The operating and boundary conditions of the case study

Description	Value	Parameter
Gas velocity on stator suction side	150 m/s	U_suction_side
Gas velocity on stator pressure side	100 m/s	U_pressure_side
Gas velocity along platform walls	100 m/s	U_platform
Working Gas temperature	1200 K	T_gas
High pressure level	14 bar	p_high
Cooling air temperature	600 K	T_cool
Characteristic length scale of cooling channels	0.01 m	H_cool
Working temperature	900 K	T_work

5. Results verification

The results of the current model of first common coolant (air) show a good and reliable agreement with the results of many authors who applied their numerical simulation and compared them with experimental data of many researchers, foremost among them Hylton et al. [28]. Among these cases study, the case study of [29] had been re-modeled and simulated in the current software program at the same geometry, boundary conditions and other numerical values, the results were approximately the same in terms of temperature distribution and heat transfer as shown in **Fig. 4**. Based on this agreement, the other cases are judged to be accepted.



A. The results of current model **B. The results of [29]**

Figure 4. The results verification with other research paper

6. Results and discussion

The main focus in the results section of the simulation process is dedicated to thermal stresses and the temperature distribution across the blade cross-section. Because of the great significance of these two parameters which indicate the metallurgical failure limit when the hot incoming gases from the combustion chamber exceed – generally or locally- the melting point of the alloy.

Beginning with the base case when the coolant is air, which represents the embark line to compare the three other cases with it. The von Mises stress is shown in **Fig. 5** which clearly indicates that maximum stress is occurring inside the cooling duct. This is because of the large temperature difference between the temperature of the inner side of the stator and the temperature of flowing coolant fluid causing thermal stress to be increased. On the other hand, the maximum stress in the case of other coolant is much larger than that of air, especially in the case of using Helium as a coolant as shown in **Figs 6-8**. The maximum percentage increase compared to air is 71% and the minimum is 45% as indicated in **Table 3**.

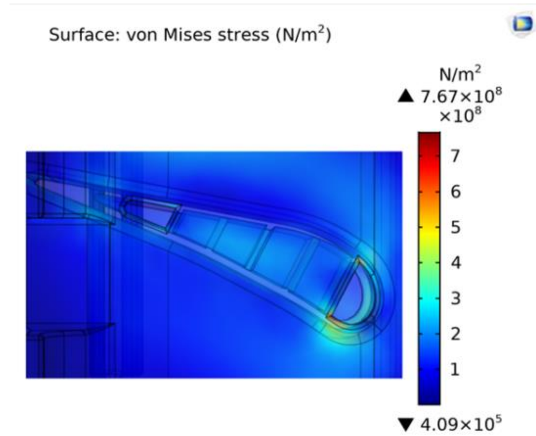


Figure 5. The von Mises stress in case of air coolant

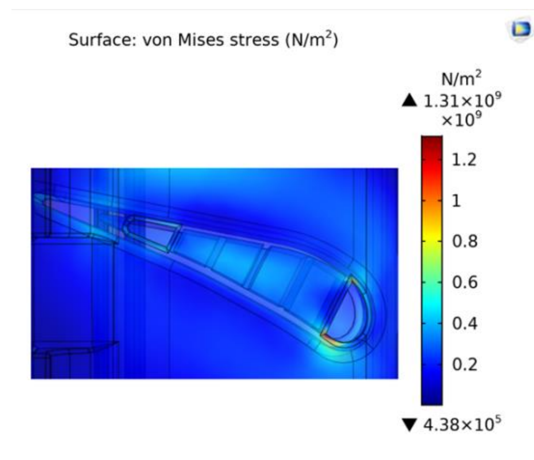


Figure 6. The von Mises stress in case of Helium coolant

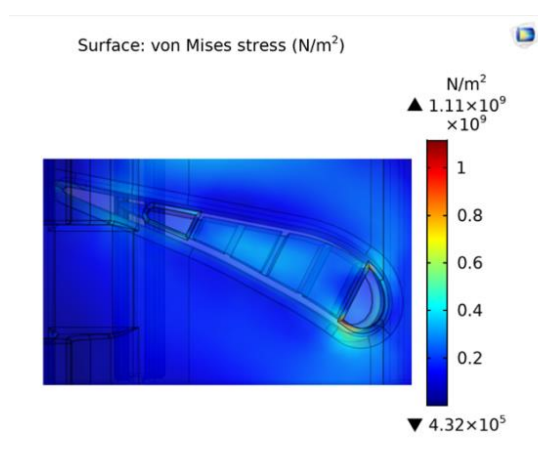


Figure 7. The von Mises stress in case of Ammonia coolant

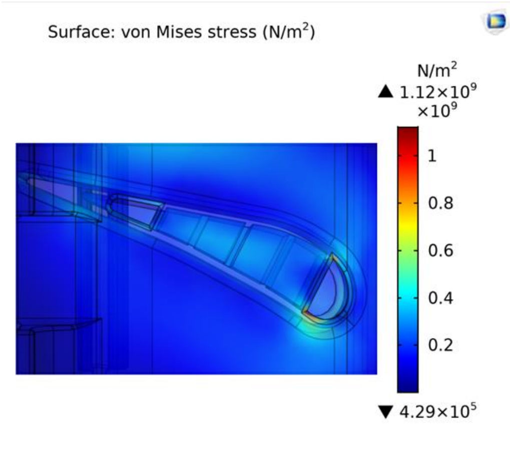


Figure 8. The von Mises stress in case of Steam coolant

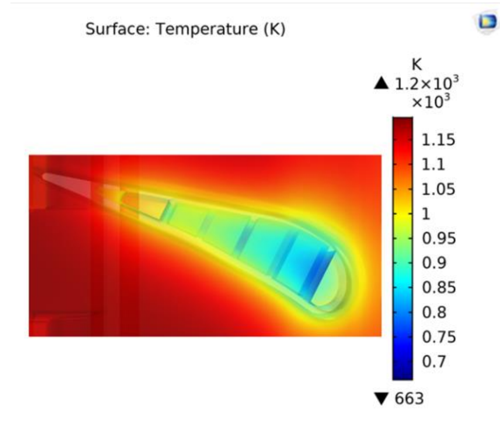


Figure 9. The temperature distribution in case of air coolant

Table 3. The maximum and minimum values of von Mises stress at different scenarios of cooling

Type of coolant	Max stress occurred (10^8 Pa)	Min stress occurred (10^5 Pa)	Percentage increase of max stress
air	7.67	4.09	---
Helium	13.1	4.38	70.80%
Ammonia	11.1	4.32	44.72%
Steam	11.2	4.29	46.02%

The most important parameter in the gas turbine engine is the turbine inlet temperature since it determines the magnitude of the power output. Designers often avoid hitting the maximum temperature of the alloy that the blade is made from. Because the temperature distribution is non-uniform, a hot spot may appear on the surface of the blade and causes thermal failure. According to the aforementioned, the temperature distribution and its contour have a great significance in this study to determine the maximum and minimum temperature occurred and its location to avoid the high and severe hot spot.

Fig. 9 shows the temperature distribution in case of using air as a coolant which is the reference case in this study. The value of maximum temperature is approximately the same temperature as the hot incoming gases surrounding the stator blade. The minimum temperature is higher than the coolant temperature entering the cooling channels from the bottom of the blade and it is 663 K in case of using air as coolant gas to minimize the hot spot temperature differences on the blade surface. The performance of the other coolant gases is much better than air where the minimum temperature recorded is 602 K, 609 K and 610 K in the case of Helium, Ammonia, and Steam consequently as shown in **Figs 10-12**. The minimum temperature difference of the multiple coolant gases compared to the minimum temperature difference in case of air is shown in **Table 4**.

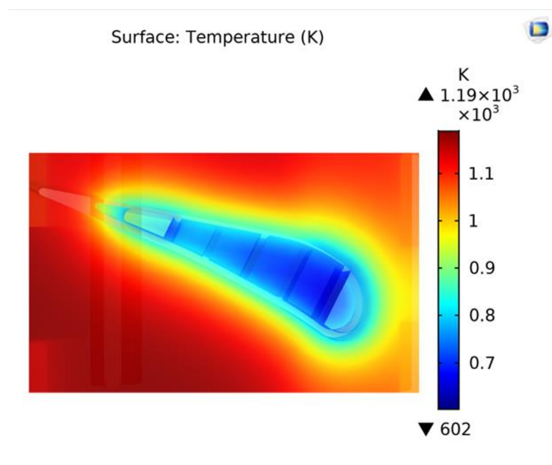


Figure 10. The temperature distribution in case of Helium coolant

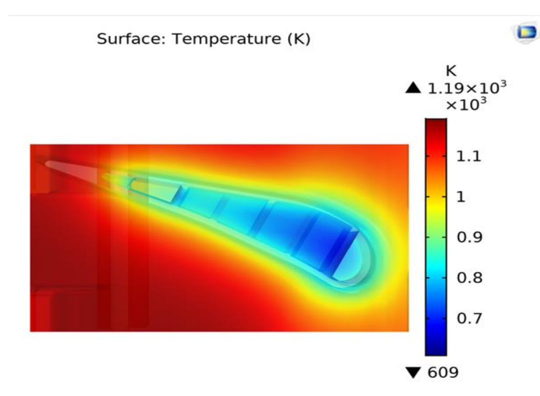


Figure 11. The temperature distribution in case of Ammonia coolant

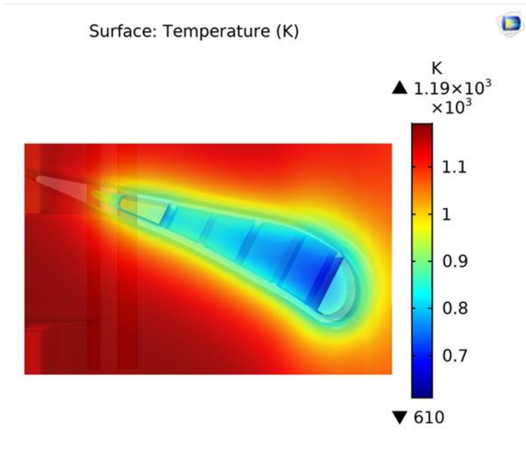


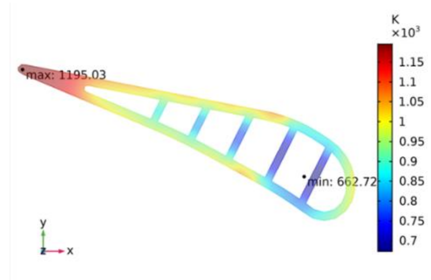
Figure 12. The temperature distribution in case of steam coolant

Table 4. The minimum values of temperature difference at the stator surface at different scenarios of cooling**.**

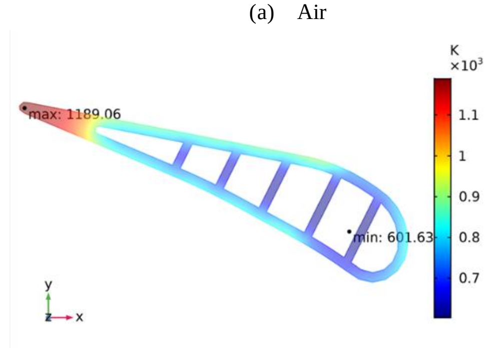
Type of coolant	Temperature of hot incoming gases (K)	Min temperature recorded in the stator (K)	Difference in temperature (K)	Percentage reduction of max temperature
air	1200	663	537	44.8%
Helium	1200	602	598	49.8%
Ammonia	1200	609	591	49.3%
Steam	1200	610	590	49.2%

The cooling effect as the convection process continues from the entering to exiting sections of the coolant gases is decreasing as the heat transfers from the hot wall to the cold fluid. Also, this reduction in cooling effect can be seen across the top view of the stator blade where the maximum temperature and hot spots tend to appear at the trailing edge of the stator while the leading edge has a moderate average temperature in general as shown in **Fig. 13**. This indicates that the mass flow rate of coolant gas is inadequate to cover all zones in the stator blade and to eliminate the hot spot at the trailing edge; the mass flow rate should be increased to overcome the high temperatures. Any increase in mass flow rate or the bleeding from the compressor may lead to a decrease in the efficiency of the gas turbine engine in terms of overall performance parameters, so a good and reasonable compromise should be taken into account.

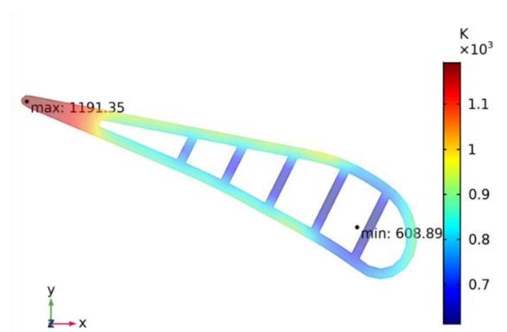
The behavior of three coolant gases is different from that of air as shown in **Fig. 14** which shows the temperature distribution along the blade in x-coordinate only from the trailing edge to leading edge. These values do not represent the most minimal values since the latter occurs at different spatial coordinates.



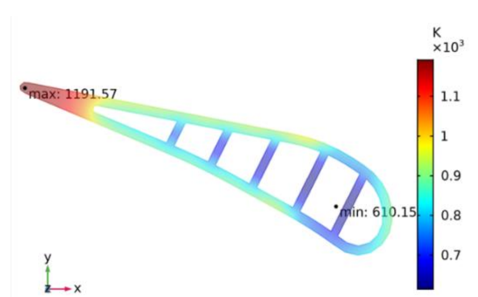
(a) Air



(b) Helium



(c) Ammonia



(d) Steam

Figure 13. The temperature distribution in a slice section for different coolant gases**.**

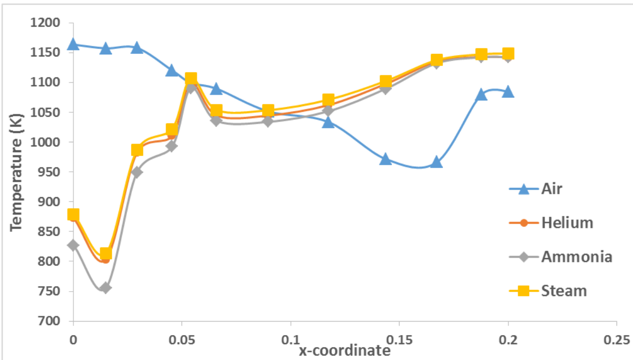


Figure 14. The temperature distribution from trailing edge to leading edge in case of different coolant gases

7. Conclusions

Gas turbine stator blade is subjected to severe high temperature and in order to operate it at the safe limit, a cooling process is proposed to eliminate the hot spots appear at the stator surface. In the common operation of the gas turbine engine, bleeding of air is drawn to cool the blade. The air shows a good and reliable performance in cooling the blade, but it still inadequate. According to the results of the current study, it can be concluded that:

1. The three different gases show a better scenario of cooling than air, but they increase the von Mises stress in the blade because of a relatively large temperature difference.

2. The Ammonia and Steam show the same performance approximately so the choice of one of them may be determined by economic justification.

3. In all cases mentioned earlier, the trailing edge zone of the stator still suffers from the high severe temperature the situation that indicates insufficient coolant gas mass flow rate.

4. A good compromise is needed to optimize these different factors to get an effective cooling process at justified economic level especially that using a different coolant rather than air, an extra kit of equipment will be incorporated.

REFERENCES

[1] Salazar, S., Conjugate Heat Transfer On A Gas Turbine Blade. 2010.
[2] Kim, K.M., et al., Analysis of conjugated heat transfer, stress and failure in a gas turbine blade with circular cooling passages. Engineering Failure Analysis, 2011. 18(4): p. 1212-1222.
[3] Nagaiah, N., Multiobjective design optimization of gas turbine blade with emphasis on internal cooling. 2012.
[4] Upalkar, B., An Investigation of Cooling Configurations in Gas Turbine Engines Using Jet Impingement, in Graduate Studies. 2015.
[5] Hwang, S., et al., Comparative study on steady and unsteady conjugate heat transfer analysis of a high pressure turbine blade. Applied Thermal Engineering, 2016. 99: p. 765-775.
[6] Garre, P. and C. Susmitha. Numerical simulation of gas turbine blade cooling in IOP Conference Series: Materials Science and Engineering. 2018. IOP Publishing.
[7] Dey, M., et al., MAXIMIZATION OF COOLING EFFECTIVENESS OF TURBINE BLADE SURFACES USING DIFFERENT ARRANGEMENT OF COOLING HOLES AND VARIOUS BLOWING RATIOS. Journal of Engineering Science and Technology, 2018. 13(4): p. 909-924.
[8] Al Ali, A.R. and I. Janajreh, Numerical simulation of turbine blade cooling via jet impingement. Energy Procedia, 2015. 75: p. 3220-3229.
[9] Moskalenko, A. and A. Kozhevnikov, Estimation of gas turbine blades cooling efficiency. Procedia Engineering, 2016. 150: p. 61-67.
[10] Deepanraj, B., P. Lawrence, and G. Sankaranarayanan, Theoretical analysis of gas turbine blade by finite element method. Scientific world, 2011. 9(9): p. 29-33.
[11] Xie, G., W. Zhang, and B. Sunden, Computational analysis of the influences of guide ribs/vanes on enhanced heat transfer of a turbine blade tip-wall. International Journal of Thermal Sciences, 2012. 51: p. 184-194.
[12] Burberi, E., et al., Effect of rotation on a gas turbine blade internal cooling system: numerical investigation. Journal of Turbomachinery, 2017. 139(3): p. 031005.
[13] Morrone, B., et al. Optimization of a gas turbine stator nozzle cooling using genetic algorithms. in Int. Symp. on Heat Transfer in Gas Turbine Systems, Antalya, Turkey, August. 2009.
[14] Nowak, G. and I. Nowak, Shape design of internal cooling passages within a turbine blade. Engineering Optimization, 2012. 44(4): p. 449-466.
[15] Kim, K.M., et al., Optimal design of impinging jets in an impingement/effusion cooling system. Energy, 2014. 66: p. 839-848.
[16] Mousavi, S.M., A. Nejat, and F. Kowsary, Optimization of turbine blade cooling with the aim of overall turbine performance enhancement. Energy Equipment and Systems, 2017. 5(1): p. 71-83.
[17] Mousavi, S.M. and S.M. Rahnama, Shape optimization of impingement and film cooling holes on a flat plate using a feedforward ANN and GA. Energy Equipment and Systems, 2018. 6(3): p. 247-259.
[18] Al-Shamani, A.N., et al., Enhancement heat transfer characteristics in the channel with Trapezoidal rib–groove using nanofluids. Case Studies in Thermal Engineering, 2015. 5: p. 48-58.
[19] Immarigeon, A. and I. Hassan, An advanced impingement/film cooling scheme for gas turbines–numerical study. International Journal of Numerical Methods for Heat & Fluid Flow, 2006. 16(4): p. 470-493.
[20] Bredberg, J., Prediction of flow and heat transfer inside turbine blades using EARSM,-and-turbulence models. 1999.
[21] Bredberg, J., On the wall boundary condition for turbulence models. Chalmers University of Technology, Department of Thermo and Fluid Dynamics. Internal Report 00/4. G oteborg, 2000.
[22] Bredberg, J., On two-equation eddy-viscosity models. Department of Thermo and Fluid Dynamics, Chalmers University of Technology, Göteborg, Sweden, 2001.
[23] Bredberg, J., Turbulence modelling for internal cooling of gas-turbine blades. 2002: Chalmers University of Technology Göteborg,, Sweden.
[24] Bredberg, J. and L. Davidson, Low-Reynolds number turbulence models: an approach for reducing mesh sensitivity. Journal of fluids engineering, 2004. 126(1): p. 14-21.
[25] Bredberg, J., L. Davidson, and H. Iacovides. Comparison of Near-wall Behavior and its Effect on Heat Transfer for k-omega and k-eps Turbulence Models in Rib-roughened 2D Channels. in Turbulence Heat and Mass Transfer 3/Nagano, Y., Hanjalic, K., Tsuji, T. 2000.
[26] Bredberg, J., S.-H. Peng, and L. Davidson, An improved k− ω turbulence model applied to recirculating flows. International journal of heat and fluid flow, 2002. 23(6): p. 731-743.
[27] Thongsanit, P. and T. Mookum, Numerical study of trailing edge cooling in a gas turbine blade.
[28] Hylton, L., et al., Analytical and experimental evaluation of the heat transfer distribution over the surfaces of turbine vanes. 1983.
[29] Hasanpour, A., M. Farhadi, and H. Ashorynejad, Hole configuration effect on turbine blade cooling. World Academy of Science, Engineering and Technology, 2011. 49(1): p. 240-244.