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Research Article

Investigation of The Use of Some Metallic Oxides Nanoparticles on The Internal Cooling Performance of Air in a Gas Turbine Stator Blade

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Abstract: The need to operate gas turbines at high temperatures for better performance places a high demand on their material selection and limits them to only a few. The required operating high temperatures also make efficient cooling imperative to prevent thermal failures. The cooling of gas turbine blades is achieved through a combination of methods, including internal cooling, film cooling, and coated cooling. Air is the commonly adopted cooling medium in internal cooling. This study, therefore, seeks to determine the impact of adding metallic oxide nanoparticles to it. The effect of using Aluminium oxide, Copper oxide, Silicon oxide and Zinc oxide nanoparticles as dispersants in the cooling fluid was investigated on the Alpha-beta titanium alloy (Ti-6Al-4V) turbine stator blade. The size of the nanoparticles studied was 20 nm, and the volume fraction was 0.04. The effective nanofluid parameters were determined using appropriate relations, and the performance of the respective nanofluids as a cooling fluid was modelled using COMSOL Multiphysics 5.5 Software. The nanofluids resulted in an enhanced heat transfer away from the stator blade and also led to an improvement in total blade displacement. However, this came at the high cost of increased developed stress and is a recipe for failure.

Keywords: Displacement; Nanoparticles; Stress; Temperature; Thermo-physical properties

I. INTRODUCTION

The statutory need to operate gas turbines at very high temperatures and pressures for high efficiency poses a challenge to its materials selection. Although several factors can cause gas turbine failures, they are, however, interrelated. These failures usually occur at its' hot sections and are, as such, direct and indirect consequences of high temperatures [1-4]. The blades form the hot section of gas turbines, and the high-temperature conditions limit their production materials to only a select few super-alloys including Nickel, Rhenium, and Titanium [5-6]. Combustion temperatures in gas are more than 1500 K, which is above the metallurgical limit, necessitating cooling. This makes effective cooling a necessity for the operation of gas turbines to prevent breaching the metallurgical limit [6-7].

Previous studies on gas turbine blade cooling to determine the impact on its structural integrity reveal that cooling not only leads to temperature reduction but also has impacts on its' yield stress and displacement of the parts. The rate of cooling impacts stress retention in metals and hence its yield stress. Likewise, the conclusion from studies have it that internal cooling alone is not sufficient for turbine blade cooling [2]. Studies on the use of some different super alloys with only internal cooling reveal the superiority of Alpha-beta titanium alloy (Ti-6Al-4V) over Directionally Solidified (DS) GTD111, Inconel 718, CMSX-4, and Nimonic 80A [6]. Titanium super alloy has high-temperature resistance, high corrosion resistance, and high strength [8]. The peak gas turbine blade temperature, however, remains high, and finding means of reducing it will not be an effort in futility as the importance of turbines to power generation and national defence cannot be overemphasised [9-11]. The increasing need for more efficient gas turbines to meet performance and emission benchmarks continues to place high demands on material selections due to the need for increased operation temperatures [10-11]. To cope with these increasing demands, more efficient cooling processes have to be sought. Some devised methods for improving internal cooling entail the adoption of jet impingement cooling and the use of steam instead of air as the cooling fluid [11-12].

In furtherance for the search for better internal cooling, studies shifted to the use of nanofluids. Several studies have shown that metal oxide nanoparticles can be used to enhance heat transfer in fluids [13-16]; Oxides of Silicon, Copper, Zinc, and Aluminium nanoparticles in water exhibit better thermal conductivity in comparison to water and enhance the cooling of Concentrated Photovoltaic Thermal collectors (CPVT) [13] and the performance of a double pipe heat exchanger was improved with the use of iron oxide nanoparticles [15], while the same was the outcome with the oxides of Silicon, Copper, Zinc, and Aluminium nanoparticles in heat exchangers [16]. Also, studies have shown that the use of nanofluids enhance the performance of thermoelectric generated installed systems [17-18] an indication of the desirable properties of nanoparticles for the enhancement of cooling. Studies on the application of nanoparticles for performance enhancement in gas turbines that appear in the literature are along the lines of the intercoolers in optimising the performance of heat exchangers [19-22]. Literature is however, sparse on the use of nanoparticles for the internal cooling of the turbine stator blade itself, and this study seeks to investigate the effect of using suspended metal oxide nanoparticles in the cooling fluid for internal cooling of a gas turbine stator blade made from Ti-6Al-4V.

II. METHODOLOGY

The study was conducted numerically using the COMSOL Multiphysics version 5.5 Computational Fluid Dynamic (CFD) tool that employs the finite element method. The finite element method of solution was taken to be static with fixed working and combustion temperatures. It entails a multiphysics coupled thermodynamic and mechanics simulation using the built-in heat transfer and structural mechanics modules of COMSOL Multiphysics to determine the heat transfer, structural displacement, and stress of the gas turbine stator blade. The governing equations for the determination of the heat transfer and developed stress/structural displacement on the stator blade [6] are respectively;

$$\rho C_p \boldsymbol{u}.\nabla T + \nabla.\mathbf{q} = \mathrm{Q} + Q_d \quad (1)$$

$$0 = \nabla.S + \boldsymbol{F}v \quad (2)$$

where ρ−density, C_p−heat capacity, u−fluid velocity, T−temperature, q−heat conduction, Q−heat transfer, Q_d −thermoelastic damping, ∇.S−stress divergence, Fv−volume factor, v−volume, S−2nd Piola−Kirchoff stress.

The procedure for solving the governing equation is detailed in the literature [6]; the boundary condition is the specified heat flux, *h*, and represents all the physics occurring between the boundary and "far away. The governing equation for heat transfer is simplified with the assumption of steady state temperature over time and applies only to the stator, while the equation of motion is coupled-in using the multiphysics module to determine the stresses. The stator geometry design is tailored to that of the National Aeronautics and Space Administration (NASA) power turbine and discretised using a free tetrahedral mesh with minimum and maximum sizes of 0.00228 m and 0.0182 m, respectively. It has a curvature factor of 0.5, a maximum element growth rate of 1.45, and a resolution of the narrow region of 0.6. The material of the gas turbine stator blade is Ti-6Al-4V, based on literature, and its generated mesh is presented in **Fig.1**.

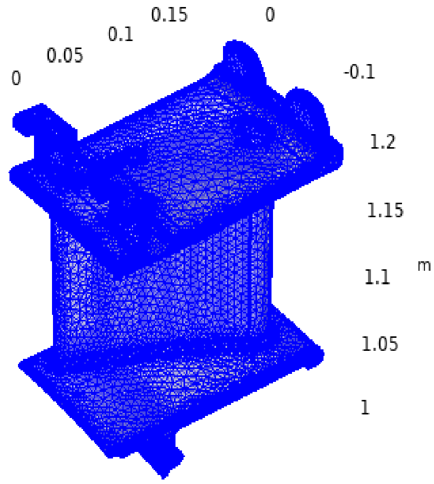

Figure 1. *Turbine Stator Blade Meshing (Ti-6Al-4V)*

The internal cooling fluid is suspended nanoparticles of metal oxides in air, making it necessary to determine its thermo-physical properties: density, viscosity, heat capacity, and Prandtl number, required in the computation for the air-nanoparticles mixture. The relations used for the determination of effective density, heat capacity, and viscosity of the nanofluids mirror the work of Hassan et al., [13] are respectively;

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_p \quad (3)$$

$$(C_p)_{nf} = \frac{1}{\rho_{nf}}[(1-\varphi)\rho_f(C_p)_f + \varphi\rho_p(C_p)_p] \quad (4)$$

$$\mu_{nf} = \mu_f\left[\frac{1}{1-34.87\left(\frac{d_p}{d_f}\right)^{-0.3} x\, \varphi^{1.03}}\right] \quad (5)$$

where ρ_{nf} – density of nanofluid, ρ_f – density of base fluid (air), ρ_p – density of metal oxides nanoparticles, φ – volume fraction, $(C_p)_{nf}$ – heat capacity of nanofluid, $(C_p)_f$ – heat capacity of base fluid (air), $(C_p)_p$ – heat capacity of metal oxides nanoparticles, μ_{nf} – viscosity of nanofluid, μ_f – viscosity of air, d_p – diameter of metal oxides nanoparticles, and d_f – fluid molecular diameter.

The fluid molecular diameter was determined using the expression;

$$d_f = \sqrt[3]{\frac{6M}{N\pi\rho_{f0}}} \quad (6)$$

where ρ_{f0} – density of base fluid (air) corrected to temperature of 293 K, N – Avogadro's constant, and M – molecular weight of base fluid (air).

The under-listed assumptions were made to simplify the study alignment with previous works [2,6];

1. An average Nusselt number correlation was used for calculating the heat transfer coefficient.
2. The pressure and suction sides of the duct are flat plates.
3. The adopted Mach numbers for the pressure and suction sides are 0.45 and 0.7.
4. A heat transfer coefficient of 25 W/ (m^2. K) was adopted
5. Gas turbine stator blade cooling is only internal with the use of nanofluid with air as the base fluid

The parameters used for the study are presented in **Table 1**.

Table 1. Gas Turbine Operating Conditions

Combustion Temperature	1100 K
Working Temperature	900 K
Combustion Pressure	30 bar
Working Pressure	30 Bar

The stator pressure and suction sides gas velocities were selected to be 300 m/s and 450 m/s respectively, and the free stream velocity at the wall of the platforms is 350 m/s.

The thermos-physical properties of the selected metallic oxide nanoparticles (Aluminium Oxide - Al_2O_3, Silicon Oxide – SiO_2, Zinc Oxide – ZnO, and Copper Oxide – CuO) used for this study mirror that reported by Hassan et al., [13] for particle sizes of 20 nm and is as presented in **Table 2**. The metallic oxide nanoparticles were selected due to their unique properties which includes thermal and chemical stability, biocompatibility, high surface area, and cost effectiveness which are crucial for use in gas turbines [23-26].

The thermo-physical properties of air used are in tandem with those presented in previous work by Towoju [2].

III. Results and Discussions

The effective densities, heat capacities, and viscosities of the cooling fluids with dispersed metallic oxide nanoparticles, taking the particle sizes to be 20 nm and the volume fraction as 0.04, using the properties of air at the considered temperatures and computed with the earlier stated formulas, are depicted in **Table 3**.

The attained minimum temperature, displacement, and developed stress of the studied gas turbine stator blade with cooling fluid inlet temperature of 660 K using only air, and metallic oxide nanoparticles of Al_2O_3, SiO_2, ZnO, and CuO dispersed in air are presented in **Fig. 2**, **Fig. 3**, and **Fig. 4** respectively. The results showed that the use of metallic oxide nanoparticles led to an improvement in the cooling of the stator blade around the region of the tubes where the fluid flows since these are the areas of concern for internal cooling, with the performance most enhanced with the use of Al_2O_3. An improved performance was also observed in the stator blade displacement with the use of the metallic oxide nanoparticles as is presented in **Fig. 3**. The developed stress was, however, observed to increase with the use of the selected metallic oxide nanoparticles as a dispersant in air, increasing far beyond the yield stress of the stator blade material

Table 2. *Thermo-physical Properties Some Selected Nanoparticles*

Thermo-physical Properties	***Al_2O_3***	***SiO_2***	***ZnO***	***CuO***
Density (kg/m^3)	3600	2200	5600	6500
Specific heat (J/kg K)	765	703	495.2	535.6
Viscosity (Ns/m^2)	0	0	0	0

Table 3*: Nanofluid Properties used for the Studies*

T(K)	***ρ_{nf} (kg/m^3)***				***$(C_p)_{nf}$ (J/kg.K)***				***μ_{nf} x 10^{-5} (φ =0.04)***	***Prandtl number***
	Al_2O_3	***SiO_2***	***ZnO***	***CuO***	***Al_2O_3***	***SiO_2***	***ZnO***	***CuO***		
660	144.51	88.51	224.51	260.51	765.07	703.47	495.86	536.09	16.138	0.7114
700	144.48	88.48	224.48	260.48	765.1	703.51	495.84	536.08	16.783	0.7137
750	144.45	88.45	224.45	260.45	765.12	703.51	495.82	536.06	17.573	0.7166
800	144.42	88.42	224.42	260.42	765.16	703.56	495.81	536.06	17.769	0.718
900	144.38	88.38	224.38	260.38	765.17	703.55	495.77	536.03	19.131	0.724

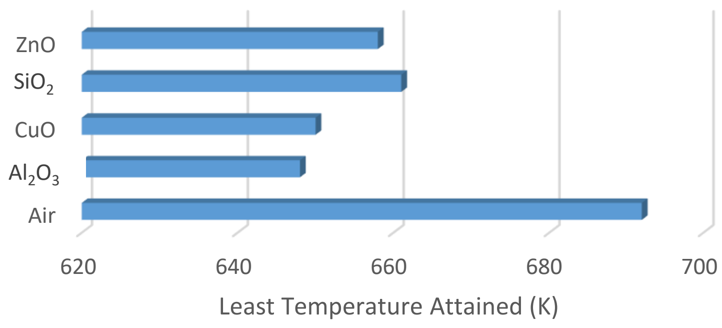

Figure 2. *Minimum Temperature Values attained on Stator Blade with Cooling Fluid Inlet Temperature of 660K*

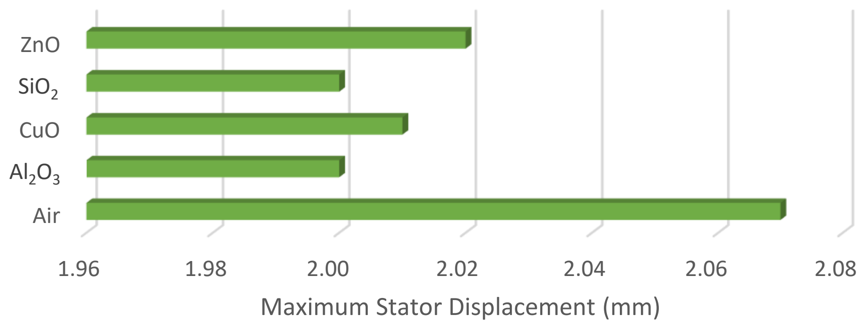

Figure 3. *Displacement for Stator Blade at Cooling Fluid Inlet Temperature of 660 K*

which is put at 350 MPa [6], and this is a recipe for structural failure. The increased stress level can be attributed to the enhanced cooling rate causing significant temperature difference and hence non-uniform thermal contraction [27].

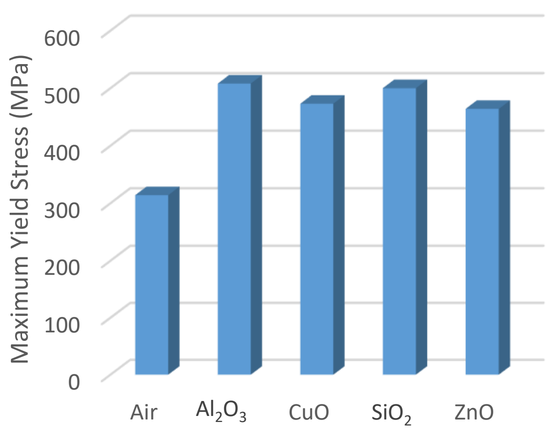

Figure 4. *Developed Stress for Stator Blade at Cooling Fluid Inlet Temperature of 660 K*

To prevent structural failure of the gas turbine stator blade, it is impossible to use a cooling fluid of air dispersed with the selected metallic oxide nanoparticles at an inlet temperature of 660 K, an increased cooling fluid inlet temperature will however lead to a reduction in the temperature gradient. The noticeable reduction in the temperature of the blade temperature in the region of the cooling fluid gives an impetus that the use of the metallic oxide nanoparticles can allow for an increase in its inlet temperature while still allowing for a comparable cooling rate with just air as the cooling fluid having an inlet temperature of 660 K.

It is, however, to be noted that the stator blade displacement increases with the increase in the cooling fluid temperature and this is also to be kept below a limit to prevent misalignment and subsequent failure of the system.

The plots of the maximum yield stress and displacement of the stator blade for the selected dispersed nanoparticles in the air at temperatures of 700 K, 750 K, 800 K, and 900 K, respectively, are depicted in **Fig. 5** and **Fig. 6**.

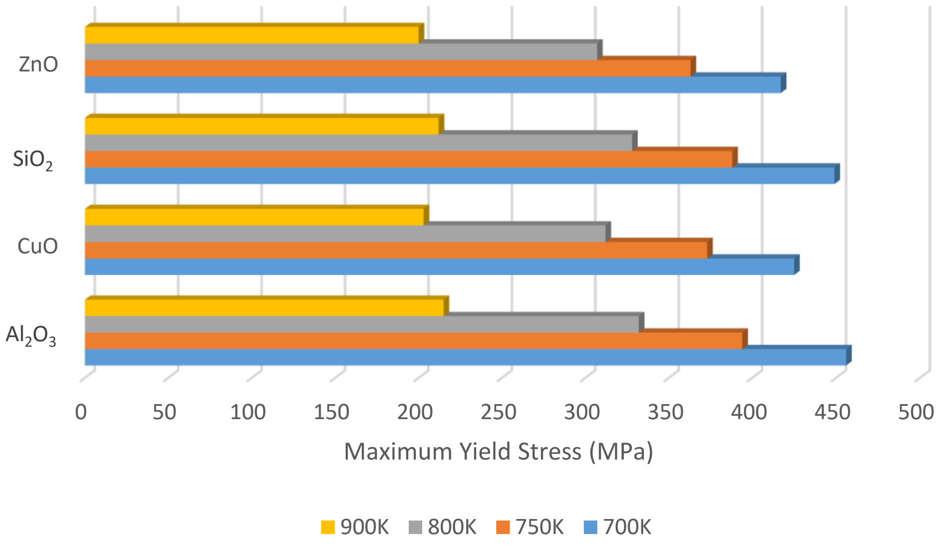

Figure 5. *Yield Stress values with the use of some metallic oxides nanoparticles at different cooling fluid temperatures*

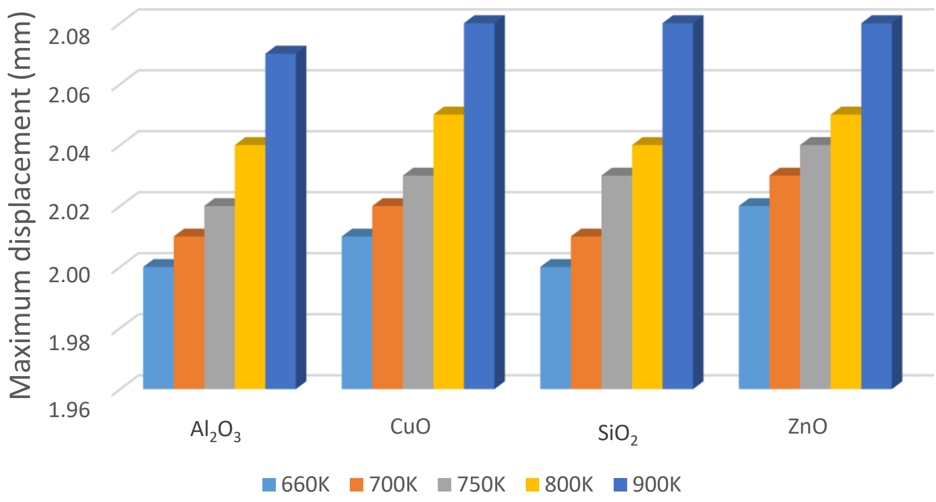

Figure 6. *Total Displacement values of stator blades with use of some metallic oxides nanoparticles at different cooling fluid temperatures*

With the yield stress of Ti-6Al-4V at 350 MPa, the entry cooling fluid temperature using the selected metallic oxide nanoparticles has to be in the region of 800 K, and at this temperature value, the total displacements of the stator blade are also below that for only air as the cooling fluid at entry temperature of 660 K [2]. Using a higher entry temperature for the cooling fluid will result in improved yield stress value but increased displacement.

The impact of using an entry temperature of 800 K on the stator blade temperature around the flow path of the cooling fluid in comparison to that of just using only air at the earlier reported optimised temperature of 660 K is depicted in **Fig. 7**.

The plots show that the cooling achieved with the use of the metallic oxide nanoparticles in the region of internal cooling is comparably better than that of only air as the cooling fluid, despite the latter having a lower entry temperature. The minimum temperature of the stator blade part achieved with the use of the selected nanoparticles is depicted in **Fig. 8** to project the differences in cooling performance of the nanoparticles.

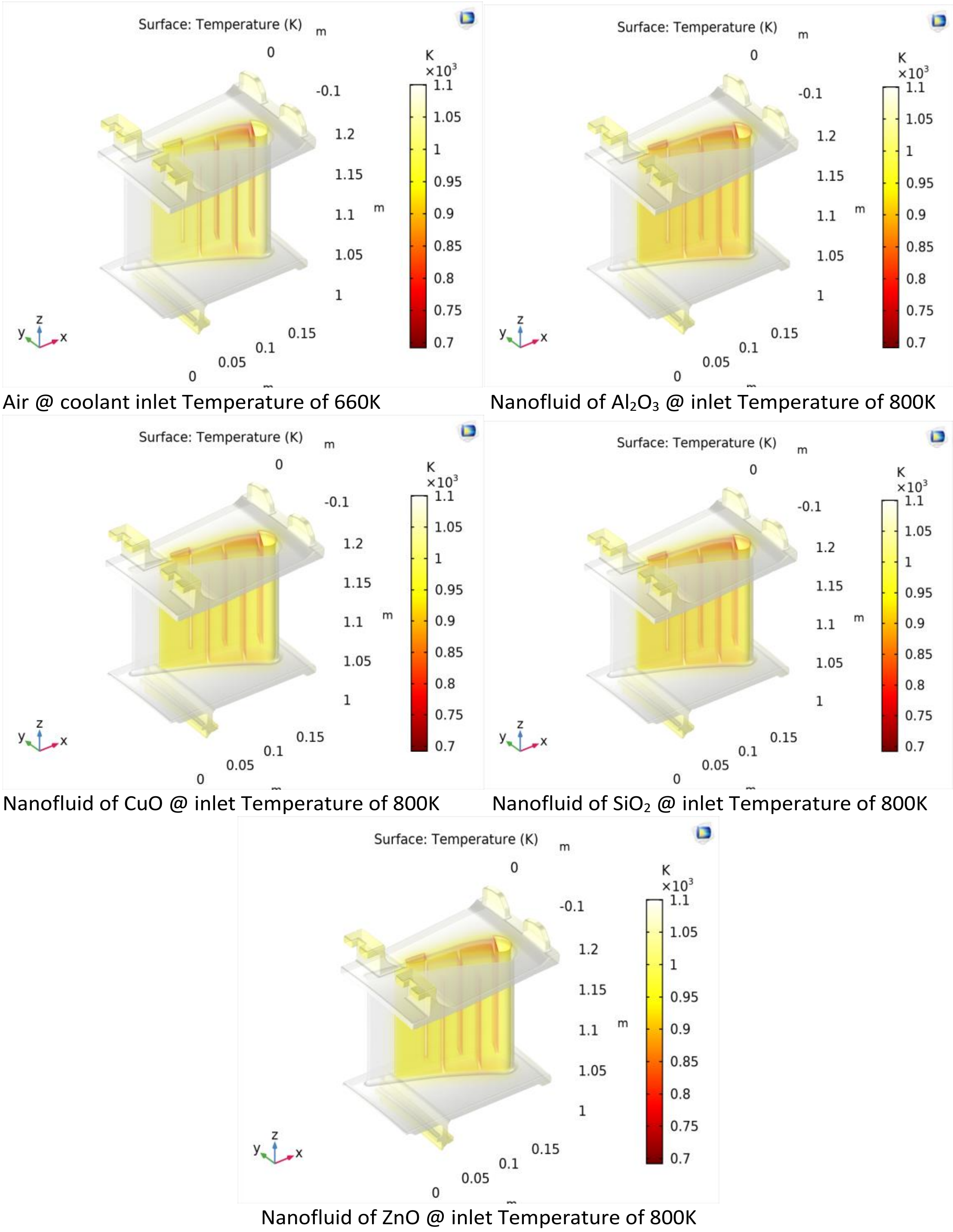

Figure 7*. Temperature Surface Plots for Stator Blade at Cooling Fluid Inlet Temperature of 660 K for air only and 800 K for air with dispersed nanoparticles*

More work will be required to raise the cooling fluid inlet temperature above 660 K which is used for air. However, this can be minimised with improved efficiency of the compression system, which is favourably inclined to increased compression ratio [11].

All the studied metallic oxide nanoparticles can be utilised in the cooling fluid for an inlet temperature of 800 K. However, the metallic oxides of ZnO and CuO will result in lower yield stress values, guaranteeing a reduced possibility of structural failure due to thermal stress. Al_2O_3 and SiO_2 dispersed nanoparticles in the cooling fluid result in the least displacement of the stator blade of the studied nanoparticles.

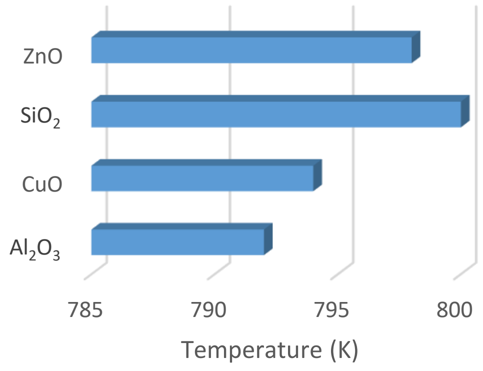

Figure 8. *Minimum Stator Blade Temperature achieved with the use of dispersed nanoparticles at Inlet Temperature of 800K*

IV. Conclusion

The study employed Ti-6Al-4V as the gas turbine stator blade material based on its better performance from previous studies and introduced nanoparticles of Al_2O_3, CuO, SiO_2 and ZnO as a dispersant in the cooling air for only internal cooling. The following deductions were made from the study;

1. The use of the selected metallic oxide nanoparticles led to an enhancement in the cooling of the gas turbine stator blade. This is consistent with past studies on the use of nanoparticles for the enhancement of heat transfer in heat exchangers.

2. The selected metallic oxide nanoparticles also led to improvement in the stator blade, however, the developed stress in the blade increased beyond the yield stress, making it impossible to use the cooling fluid entry temperature of 660 K. This increase in developed stress can be attributed to the enhanced cooling rate causing significant temperature difference and hence, leading to non-uniform thermal contraction and stress retention.

3. Increasing the cooling fluid entry temperature to 800 K will allow for the use of the selected metallic oxide nanoparticles and result in improved stator blade displacement and lower temperatures at the internal cooling regions in comparison to using only air as the cooling fluid with an entry temperature of 660 K. While also resulting in total developed stress below the yield stress value due to the reduced temperature difference between the cooling fluid and the blade thus, minimizing the non-uniform thermal contraction.

4. ZnO and CuO nanoparticles led to the lowest values of yield stress among the others, while Al_2O_3 and SiO_2 nanoparticles resulted in the lowest displacement values.

The use of nanoparticles as dispersant in the cooling fluid for internal cooling of gas turbine blades and can pave the way for its operation at increased combustion temperatures which will lead to improved efficiency.

Studies have proved that nanoparticles can reduce the corrosive action of steam on metals, and the inference from this work also points to it improving the cooling performance. It will thus, not be out of place to conduct further studies to investigate the use of nanoparticles dispersant in steam as the cooling fluid for the cooling of turbine stator blades.

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AUTHOR CONTRIBUTIONS

O. A. Towoju: Conceptualization, Theoretical analysis. Finite element modelling, Writing, Review and editing.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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