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# **Investigate Turbine Blades Cooling Ways for Micro-Jet** Engines

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Abstract. In recent years, the use of micro-jet engine increased is likely to continue to grow because of the ever-increasing applications such as: an unmanned aerial vehicle and small missiles. Many industrial applications used different technics to provide an effective means for the turbine blades heat transfer. The paper presents an approach to investigate turbine blades cooling ways for microjet engines based on internal cooling passages for the blade manufacturing from Nickel base Superalloy. The numerical model considered include fluid flow and heat transfer in the turbine blade. The results agreed with experimental data. The novelty of this work to gain more in physical insight process and sensitivity analysis of cooling small size turbine blades with size 160 mm<sup>2</sup> cross section.

#### 1. Introduction

In recent years, significant the number of Unmanned Aerial Vehicle(UAV) has increased. Most of UAVhas micro jet engines for thrust generation and maneuver.Jet engines turbine blades are working under high temperature, high pressure, high rotational speed, and cooled by air flowing through internal passages. Turbine blades internal cooling in the case of UAV engines is very critical for improve turbine efficiency and extending blades life fatigue as well as increase vehicle working range. Globally there is a limited number of researchers contributed to progress in the field of improving turbine blades internal cooling system for micro jet engines. Most of the research working in this field concentrate on the manufacturing materials improvements [1]. Materials development with high strength to weight ratio high-temperature support for weight reducing. There is a wide range of highperformance materials-special that's used in micro jet engine manufacturers such as steels, titanium alloys, and superalloys. These materials often involve advanced processing techniques [2]. In the literature a few studies concentrate on modeling and experimental investigation for normal and micro jet engines cooling improvements.

Based on the pioneering work done by Al Ali and Janajreh [3] a numerical analysis has been performed for jet impingement cooling on the curved concave surface subjected to constant heat flux. The results found insight on the underlining physics of the flow and a sensitivity analysis on the jet impingement configuration and flow conditions conducted. An experimental investigation of the internal channel for cooling jet engine turbine blades done by Elnajjar et al. [4]. The results of that experimental test show very difficult to conduct a detailed sensitivity study for understanding the turbine blade thermal behaviour. An investigation of turbulent slot jet cooling exposure on concave plates with different surface curvature has done by Öztekin et al. [5]. The results show that the best cooling was for R/L=1.3 and abstracted that the Nusselt number stagnation point increase when the Reynolds number increases. For the flow field and heat transfer with a constant heat flux of the slot

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turbulent jet effect, a research study was performed by Yang et al. [6] and the results illustrated that the stagnation point achieved maximum value of the Nusselt number. For the wide range of Reynolds number Hamdan et al. [7] shows an experimental and numerical analysis on the circular heated surface for slot jet. By means ofvarious turbulence models for convective heat transfer jet impinged on both concave and flat surface was study by Sharif and Mothe [8]. They mentioned the correct turbulence model is essential for blades cooling analysis. By using Computational Fluid Dynamics (CFD) simulation Choo et al. [9] analyse microjet engine impingement on a heated flat plate in order to determine heat transfer characteristics. Numerical analysis and validation for jet flow over the micro cylindrical surface was done by Zuckerman and Lior [10]. The results after compared with various models were satisfactory. Wang et al. [11] make a new design for gas turbine guiding vane. The results illustrate uniformly distributed cooling for the whole blade surface. Liu et al. [12] carried out a numerical simulation on impingement and film composite cooling of the blade leading edge model for a gas turbine. They observed rapid cooling for the external film of theblade. A study was done by Schall et al. [13] for execution of a specific cooling system for four air jet engines impacting on cylinder has been used in order to improve turbine blades cooling efficiency. For predicting air temperature in jet engine turbine blades with a high Mach number jet engine, a research study were performed by Nacke et al. [14].

Cornaro et al. [15] study flow projections made for the turbulent jet affecting the circular and convex surfaces. Choi et al. [16] performed an experimental study for fluid flow and heat transfer for jets on a semicircular concave surface. A numerical modeling of the turbine blades cooling jet engine was done by Souris et al. [17] the modeling has applied on these micircular concave surface which results show high performance of two-equation turbulence models (error percent about 8%). Kayansayan and Küçüka [18] performed an experimental study for a slot jet impingement cooling on a concave surface. The results show that nozzle jet speed and the configuration as well as curvature has a high impact on the heat transfer efficiency. The characteristics of the surface heat transfer on the convex surface of the ring shape were studied by Chan et al. [19]. Authors provided the local relationships with the Reynolds numbers and the opening of the dimensions to the distance between the surface nozzles and stagnation point with the surrounding flow distribution.

Micro-jet engines turbines have complex thermal behaviour which is not available in standard jet engines. In both engines design, the compressor bleed air to use for cooling turbine blades. In the present work an analysis has been carried out for cooling turbine blades for micro jet engines by average

Improving the efficiency of the turbine depends on the performance of the blades as the reduction of the temperature of the blades. Designing internal passages in a small blade size for cooling is a verycomplicated process. Wróblewski et all [20] investigate supercritical steam turbine blade cooling numerically. The results reported that the blade leading edge has the high temperature and this raises the level of turbulence resulted in a higher blade surface temperature. Particularly on the leading/trailing edges where the temperature is reaching a maximum value. Weigand et al. [21] investigate different solutions include thermal barrier coating, bypass cooling, leading and trailing edges blowing to improving the turbine efficiency.

In this work a numerical analysis performed by using SolidWorks 2016 for investigate micro-jet engine turbine blades cooling possibilities.

## 2. Problem Statement

Most of the turbine blades in the micro-jet engines has no contain cooling methods used in jet-engines for the small size of both rotor and stator blades. Designing of cooling passages inside the small size turbine blades is essential and very complicated process, especially with high-temperature resistance materials.

This work has two designs configurations for cooling microjet engine turbine blades based on Nickel base Superalloy (CMSX-10) alloy to find an efficient way for cooling turbine blades in microjet engines.

A typical cooling turbine vane appears in Figure 1. It is tough to make the passages and pin-fins on the blade of a micro-jet engine for the smallest size of blades. Small passages in turbine blades reduced the blade ability from the applied stresses.



Figure 1. Schematic of a turbine vane cross-section with impingement and trailing edge Pin-Fin cooling [22].

#### 2.1 Material and Structural Analysis of micro jet engine Turbine Blade.

Nickel base superalloy (CMSX-10) alloy casting material is a third generation of Crystal (SX) which is used under challenging applications bleedings the turbine engines. Certified aircraft engine alloy is characterized by its 6% weight rhenium content and a high level of the thermal element added as well as chrome content is relatively low.

Based on published data and thought of slug top view power creep and fatigue resistance of any production of Base superalloy (SX), and throws provides single crystal superalloys CMSX 10 rough slug 30°C with the relative creep strength to second generation is about 3% by weight [23].

Superalloy (SX) can base on Single crystal superalloys (CMSX-4) and Nickel base single crystal alloy (PWA 1484). Moreover, it is obtained low cycle high cycle fatigue (LCF and HCF) strength as much as 2-3 times better than best alternatives [24]. On the other hand, as an attraction for the alloy and evolution tension strength, perform treatability foundry, heat, and environmental characteristics.

Most notably, theses alloys offers surprisingly good hot corrosion resistance, although relatively novel and low chromium content (2-3% weight). Also, slug performs exceptionally well in all of the aluminizing PT-aluminise coated circumstances [23]. The Tables 1 and 2 shows nominal compositions for CMSX cast 10 [25].

Table 1. Nominal compositions of cast CMSX-10 [25].														
Alloy	Description	Composition (WT %)												
		Ni	Cr	Co	Mo	Re	Al	Ti	Ta	W	Zr	c	В	Others
CMSX 10	- Nickel-base single crystal, known for strength and cast ability. Contains Re	bal.	2	3	0.4	6	5.7	0.2	8	5				0.1 Nb, 0.03 Hf, 6 Re

Table 2. Material properties table of CMSX-10 [25].						
Property	Value	Units				
Elastic Modulus	1.15e+011	N/m <sup>2</sup>				
Poisson's Ratio	0.33	N/A				
Shear Modulus	4.9e+010	N/m <sup>2</sup>				
Mass Density	4730	kg/m <sup>3</sup>				
Tensile Strength	90000000	N/m <sup>2</sup>				
Compressive Strength	875000000	N/m <sup>2</sup>				
Yield Strength	81000000	N/m <sup>2</sup>				
Thermal Expansion Coefficient	8.6e-006	1/K				
Thermal Conductivity	10.9	W/m·K				
Specific Heat	495	J/kg·K				
Material Damping Ratio	1.15e+011	N/A				

#### 3. Mathematical model

A mathematical model has been createdtoanalyse fluid flow and heat transfer prepared for this work to discretized control volume domain, the simulation includes the application of conservation laws of the mass, momentum and energy. The conservation equations were solved at every finite volume iteratively until achieved the desirable convergence in flow parameters. Due to the high computing demand, the modelling process was done by considering three-dimension domains that simulate an infinite length configuration.

The model fluid flow and heat transfer governing equations eq.(1)-(3) need to solve in discretized form. In this work assumed that temperature is a passive scalar and have no influence on the air flow. The governing equations: continuity, momentum and heat transfer equations can write in the following form:

$$\nabla \cdot \vec{U} = 0 \tag{1}$$

$$\frac{\partial \vec{U}}{\partial t} + \left(\nabla \vec{U}\right) \cdot \vec{U} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \vec{U}$$
<sup>(2)</sup>

$$\frac{\partial T}{\partial t} = -\nabla \left( \vec{U} \cdot T \right) + \alpha \nabla^2 T \tag{3}$$

where U,P and T are velocity vector, pressure and temperature; v,  $\alpha$  are fluid viscosity and thermal diffusivity. When air velocity increases flow become turbulent for this reason the turbulence Realizable k- $\varepsilon$  model has been used:

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \left( \vec{U} \cdot \nabla \right) k = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\mu_k} \right) \nabla k \right] + P_k - \rho \varepsilon$$
(4)

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \left( \vec{U} \cdot \nabla \right) \varepsilon = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\mu_\varepsilon} \right) \nabla \varepsilon \right] + \rho C_1 S_s - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{vs}} + C_{e1} \frac{s}{k} C_{e3} G_b + S_s \tag{5}$$

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

$$P_{k} = \mu_{T} \left[ \nabla \vec{U} : \left( \nabla \vec{U} + \left( \nabla \vec{U} \right)^{T} \right) \right]$$
(7)

where  $\kappa$  and  $\varepsilon$  are turbulence kinetic energy and dissipation,  $\mu_T$  is turbulent viscosity. The turbulent model constants are as follows:

$$C_{1} = \max\left[0.43, \frac{n}{n+s}\right]; \ \eta = S\frac{k}{s}; \ S = \sqrt{2S_{ij}S_{ij}}; \ C_{\mu} = \frac{1}{k\sqrt{S_{ij}S_{ij}} + \Omega_{ij}\Omega_{ij}}; \ S_{ij} = \frac{1}{2}\left(\frac{\partial u_{j}}{\partial x_{i}} + \frac{\partial u_{i}}{\partial x_{j}}\right)$$
$$\Omega_{ij} = \Omega_{ij} - 2\varepsilon_{ijk}\omega_{k}; \ \Omega_{ij} = \overline{\Omega}_{ij} - 2\varepsilon_{ijk}\omega_{k}; \ A_{o} = 4.04; \ A_{s} = \sqrt{6\cos\phi} \quad ;\phi = \frac{1}{3}\cos^{-1}\left(\sqrt{6w}\right)$$
$$C_{e1} = 1.44; \ C_{2} = 1.9; \ \sigma_{k} = 1.0; \ \sigma_{\varepsilon} = 1.2; \ W = \frac{S_{ij}S_{jk}S_{ki}}{\tilde{s}^{3}}$$

For the radiative heat transfer Surface-to-Surface radiation model has been used:

$$q_{out,k} = \varepsilon_k \sigma T_k^4 + \rho_k q_{in,k} \tag{8}$$

$$A_{k}q_{in,k} = \sum_{i=1}^{N} A_{j}q_{out,k}F_{jk}$$
(9)

where  $q_{out,k}$  and  $q_{in,k}$  are energy flux leaving the surface and energy flux incident on the surface from surroundings;  $A_k$  is an area of k-surface,  $F_{jk}$  is view factor between k-surface and j-surface.

#### 3.1 Boundary Conditions and mesh

The simulation for the geometry presented in Figure 2 is done. To solve the problem, an appropriate boundary condition for flow, temperature and pressure are required. The simulation started with initial conditions. The system under consideration was designed and solved using finite volume approach. A mesh used was a structural mesh consist of multiple blocks. The variables u, v, p,  $\rho$  and T were subjected to solved iteratively. The numerical analysis performed based on the principle of finite

volume on the formulas has presented as a mathematical model for mass, energy and momentum. Second order scheme were used for convective and diffusive terms discretisation.

Table 3. Mesh sensitivity.								
Mesh Distribution	Elements no.	Temp. relative error %	Nu. relative error %					
Baseline	34,663	0.61	2.9					
Coarse	17,542	0.86	9.44					
Independent	233,000	-	-					

## 4. Results and discussion

The sketch of the analyzed geometry is presented in Figure 2. The blade span is 20.0 mm while thickness is 8.0 mm. The size of the computational domain considered in this work is  $0.5 \times 0.45 \times 0.5$  m and an unstructured hex-dominant mesh has been generated for the domain. Before a set of final simulation were performed several different test analysis with different mesh resolution were performed to obtain mesh independent solution. Results of analysisare presented in Table 3.



Figure 2. Designed turbine blade dimensions.

In this work, a blade for the micro jet engine is investigated for possibilities to maintain the blade surface temperature below a threshold. The blade dimension considered 20 mm span and the maximum thickness of 8 mm with the designing specifications (mass= 0.22 kg, volume =2.4 m<sup>3</sup>, density =2710 kg/m<sup>3</sup> and weight =2.16 N). The internal passages in the blade are designed in circled small holes with 2 mm diameter - Figure 3(a)or internal passages are designed in an elliptical shape as shown in Figure 3(b). The flow speed inside cooling is equal to 56 m/s with mass flow rate 0.0431 kg/s for Design I form Figure 3(a) and 0.172 kg/s for Design II from Figure 3(b) and with the inlet temperature equal to 10°C. Including combustion temperature out the blade is about 1200°C with the blade external wind speed 73m/s. The nominal values of the air property considered here are: density  $\rho$ = 1.225 kg/m<sup>3</sup>, specific heat at constant pressure  $C_p$ =1006.44 J/(kgK) ,thermal conductivity k =0.0243 W/(mK), Prandtl Number Pr=0.745 and the viscosity  $\mu$  = 1.029\*10<sup>-4</sup> kg/ms.



Figure 3. Schematic with evaluated temperature for cooling turbine blade: Desgin I (a), Desgin II (b).

Operating at high temperatures reduces the lifespan of micro-jet engine and increases operating costs. In contrast overcooling, the blade is incompatible with the objectives and thus requires the blade design decisions of the which considered as exchanges between targets. Figure 4 shows the blade

temperature which is stabilized at a level about 888°C for Design I after 11.6 minutes from initial start conditions while for Design II the temperature stabilizes at a level about 843°C the after 16.6 minutes. For design companies both results are satisfactory. Compared to results Rolls-Royce results for jet engines which turbine blades recorded as high as 1050°C temperature [26].



## 5. Conclusions

Turbine blades impingement cooling for the micro-jet engine was analyzed numerically subjected to a constant heat flux applied to the surface. The prepared model based on steady Navier-Stoke equations coupled with energy condition. A comparison of two configurations turbine blade made at the same Re number and same boundary conditions were done. The results revealed that the average temperature along the blade surface is lower than leading and trailing edges. The optimizing the cooling of turbine blades can significantly improve efficiency by reducing average blade surface temperature. The numerical simulations performed for both designs got a very promising result comparing with Rolls-Royce results that temperature in the turbine propulsion jet engines to 1050°C [26].

# 6. Future work

Using the similar designs and taking into consideration the stresses on the blade.

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