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Sustainability in bio-metallic orthopedic implants

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ABSTRACT
An orthopedic implant is surgically introduced into the body as a replacement of a missing or affected biological structure. As these are stationed inside the body hence the material chosen should be bio-acceptable so that it does not cause rejection or gangrene. In this work, Ti-6Al-4V has been chosen for the implant. In actual practice the implant, after design approval is cast and machined to the required dimension and surface smoothness followed by heat treatment to remove stresses induced while machining. The product needs to be cooled before surgical fitment. The present work proposes film cooling technique for the same. The primary deciding factor for the effectiveness and longevity of the orthopedic implants primarily concentrates on the cooling effectiveness. The simulation study has been done using Fluid Flow Simulator Analysis software i.e. FLUENT and results were found to be in good agreement with the experimental results available in the relevant literature. The present work was aimed at a critical situation where an orthopedic implant of titanium alloy (Ti-6Al-4V) is to be manufactured ensuring that it not only resists loosening or migration but also is thermally stable and does not damage surrounding tissues or organs. The results indicate that although forward injection of coolant is a more economically viable but backward injection of coolant should be preferred while working with an orthopedic implant as it provides more area under cooling. Hence it can be inferred that with a backward injected cooling system the implant would be cooled better and would surely ensure a better component with respect to strength and longevity.
Keywords: *Orthopedic Implant, Bio-Metal, Magnetic Resonance Imaging, Titanium Alloy, FLUENT, Orientation of Coolant Jet, Blowing Ratio, Density Ratio, K-ϵ Turbulence Model, ICEM CFD, Reynolds number, Centreline Cooling Effectiveness, Weighted Area Cooling Effectiveness*

1. INTRODUCTION

An orthopedic implant is a component or product manufactured and introduced into the body as a replacement of an absent, damaged or undeveloped skeletal structure [1]. Orthopedic implants also help in wear and tear issues with the bones and joints due to the aging of the body. They are provided as an augmentation towards failures and diseases e.g. bone fractures, spinal stenosis, scoliosis, osteoarthritis, and chronic pain etc. in the process of healing of fractured bone, supports are provided in the form of screws, pins, plates and rods. Orthopedic implants, in contrast to a transplant which are biological products, are human-made products. The surface of implants which comes in contact with the live tissues, cells or blood should be essentially made of a biomedical metal such as titanium or titanium alloy for eradication of rejection or infection [2, 21, 22]. Titanium has acceptable mechanical properties and has been used for orthopedic implants, yet for still better performance titanium is alloyed with small amounts of aluminium and vanadium (Ti-6Al-4V), typically 6% and 4% respectively, by weight [3, 23, 24]. To make this high-strength alloy more stable heat treatment process is carried out after machining and before it is implanted [25, 26].

Patient with orthopadic implants is periodically put under Magnetic Resonance Imaging (MRI) machine for estimation of the progress and extent of healing. This poses two major concern to the researchers while working with design and manufacturing of implants. First being loosening and migration of implant and secondly thermal stability due to heating of the implant and damage to surrounding tissues. Solution to the first problem can be proper fixation and effective cooling of the components after manufacturing would solve the next problem.

In this work both the above problems are being handled in an innovative manner which would not only ensure a proper fixation but also would provide a longer service life of the component. The work concentrates on the effective cooling of the component after all machining operations ensuring eradication of residual thermal stresses and also at a faster rate so that the surgical fitment can be undertaken at the earliest without causing any further damage to the affected patient.

The manufacturing of implants is usually tailor made as the size, fitment and requirements vary from patient to patient. Yet an outline of the process can be summarized as provided in the flow chart (Figure 1).

As discussed earlier and also depicted in the flow chart, a solid model of the implant is created on the basis of the X-ray photograph and MRI data. The implant, after design approval, is cast and machined to the required dimension and surface smoothness. Machining is usually by shearing and in this process it gets lot of thermal stresses due to localized heat generation. Heat treatment is hence very much required to removed / normalize the developed stresses. The product requires cooling after heat treatment. Cooling can be carried out by either putting it in still air or putting it in a coolant. The former takes a lot of time whereas in second case the product becomes brittle. The present work proposes a third option wherein demerits of both the earlier methods can be eradicated. It is using the concept of film cooling. Film cooling is a proven cooling method wherein coolant forms a thin envelope over the surface of the implant and a jet of cool air with certain parameters are injected from the lower to upper surface through a hole [27, 28].

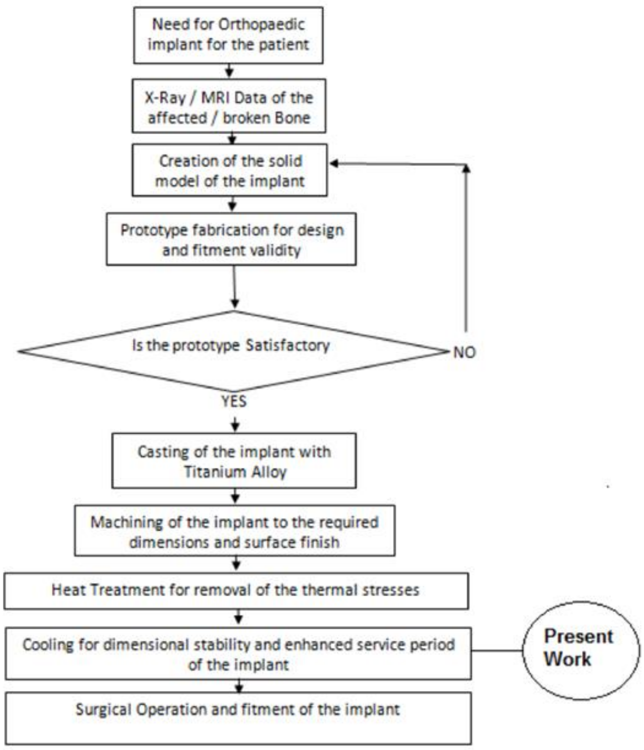


Figure 1. Flow Chart for Manufacturing of Metallic Orthopedic Implants.

The effectiveness of cooling [29, 30, 31], an essential parameter for such a delicate product, depends on various parameters such as:

i. Orientation of coolant jet (α) [32]
ii. Blowing ratio (M)
iii. Density ratio
iv. Surface profile to be cooled
v. Free stream turbulence
vi. Effect of near wall transport and interfacial mixing.

Mathematically, the cooling effectiveness can be expressed in a dimensionless form as:

$$\eta = \frac{T_\infty - T_W}{T_\infty - T_C} \quad (1)$$

Where, T_∞ is temperature of mainstream, T_W is for wall temperature (adiabatic), T_C is temperature of coolant.

The blowing ratio (M) can be expressed as

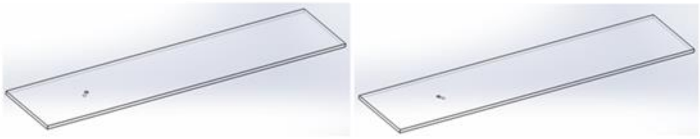
$$M = \frac{\rho_C U_C}{\rho_\infty U_\infty} \quad (2)$$

where ρ denotes density, U denotes velocity, subscript c and ∞ denotes coolant and mainstream respectively.

Lot of research has taken place for cooling effectiveness, orientation of coolant jet, blowing ratio, density ratio etc. Bunker [4] concentrated on shaped holes in his review work on film cooling whereas effectiveness obtained with a single cylindrical hole and row of holes was subsequently given by Goldstein et al. [5-6]. They found that maximum effectiveness was with blowing ratio (M) 0.5 and density ratio (DR) 1.0. Bergeles et al. [7-8] studied the behavioural pattern of a single discrete jet injected normally and at an angle of 30^0 to the cross-flow and phenomena of jet lift-off and cross-flow penetration was established. Andreopoulus and Rodi [9] found a vortex pair with counter rotation in the downstream of jet injection when they introduced an isolated normal jet in cross-flow. Yuen and Martinez [10] investigated film cooling effectiveness using a cylindrical hole positioned at 30°, 60° and 90° to cross-flow. They inferred that in downstream region of the hole, maximum effectiveness occurred at a blowing ratio < 0.5 and that also using single 30° hole. Their other literature [11-12] was on the study of heat transfer coefficients and film cooling effectiveness for a series of circular holes with a different angle of injections. T. Wang and X. Li [13] used FLUENT to investigate film cooling performance by introducing water into the cooling air. Lange et al. [14] used imperfect or distorted hole on cooling effectiveness. The calculations were done for the cooling effectiveness, in presence of imperfection at a different position. G.Li et al. [15] worked on effects of different hole shapes on film cooling using CO2. Becchi et al. [16] studied adiabatic effectiveness distributions on three trailing edge cooling system. The effect of sister holes on a circular shaped hole's performance was carried out by Khajehhasani and Jubran [17] using K-ϵ turbulence model. They could able to capture the effectiveness with good accuracy. Using Large Eddy Simulation (LES) the effect of density ratio of film coolant and mainstream hot gas was investigated by Oda et al. [18]. They found that the density ratio of film coolant and hot mainstream has a remarkable impact on the film cooling effectiveness distribution on the cooled surface, and therefore it should be considered in the design process of cooling. Singh et al. [19] carried out experimental and numerical study to find an effect of reverse coolant injection on cooling effectiveness at Reynolds number 3.75 x 10^5 based on main flow for a circular hole at a various angle of injection. They concluded that among all angle of coolant injection, 30^0injection showed the best cooling effectiveness. They also found that reverse coolant injection showed better cooling effectiveness than forward coolant injection for their range of experimentation. Mishra et al. [20] found that in reverse injection of coolant, weighted area average of cooling effectiveness found is more than that for forward coolant injection at higher velocities due to better spreading of the cold fluid. They concluded that more uniform cooling effectiveness is possible using backward coolant injection.

2. MATERIALS AND METHODS

For analysis of the proposed methodology, a rectangular model with a hole is created in solid modeling software. Hole has been provided at an angle of 30^0 (forward) and -30^0 or 30^0 (backward) with horizontal (Figure 2 (a & b)). The model resembles the implant and the hole is for fixing the implant with the affect bone. The same hole would be used for the cooling purpose. In present work, cooling effectiveness for selected blowing ratios (M = 0.3, 0.50, 0.8, 1.0, 1.3, 1.6 and 2.0) were computationally investigated. The velocity and the temperature of the main free-stream were taken as 5m/s and 600K respectively. The injected coolant temperature was 300K.



a) b)

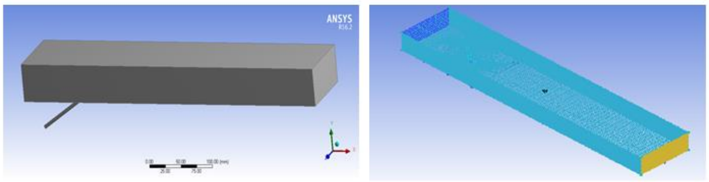
Figure 2.3D model of the implant with hole.
a) 30^0 (forward); b) 30^0 (backward) with horizontal.
b)

Coolant injection velocities were calculated based on Equation 2 which is shown in Table 1. The computational mesh for analysis was created using ICEM CFD. Optimized mesh consists of 490000 hexahedral cells.

The model has been imported into ANSYS as shown in Figure 3.

Table 1. Blowing ratio and coolant inlet velocity.

Sl. No	Blowing ratio (M)	Coolant velocity (U_C) m/s
1	0.3	0.75
2	0.50	1.25
3	0.8	2.0
4	1.0	2.5
5	1.3	3.25
6	1.6	4.0
7	2.0	5.0



a) b)

Figure 3: Imported Model.
a) Computational model b) Meshed model for the analysis.

3. RESULTS

As stated earlier, the primary deciding factor for the effectiveness and longevity of the orthopedic implants primarily concentrates on the cooling effectiveness.

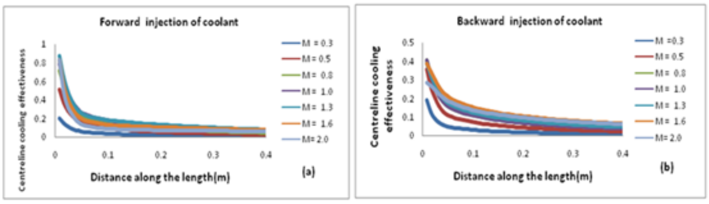
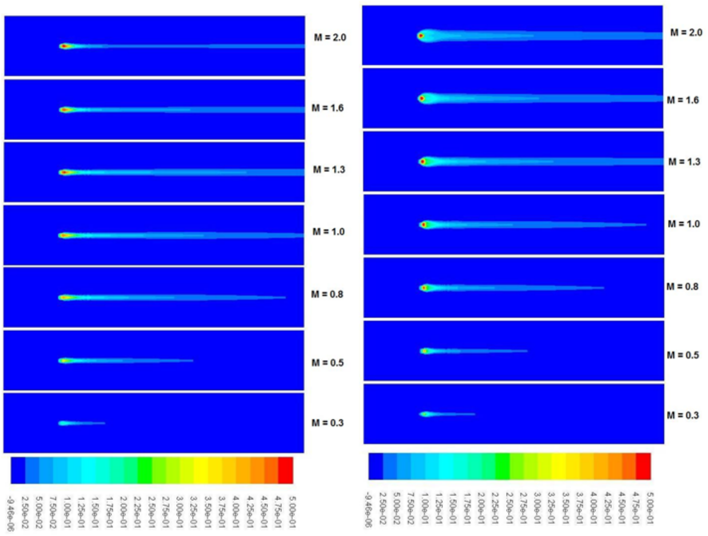


Figure 4. Centreline effectiveness; (a) Forward coolant injection, (b) Backward coolant injection.



a) b)

Figure 5. Contours of cooling effectiveness on the plate surface downstream of the coolant hole (a) forward injection(b) backward injection of the coolant.

The simulation study has been done using Fluid Flow Simulator Analysis software i.e. FLUENT. The developed model was validated with experimental values available in literature of Yuen and Botas [11] using standard k-Ɛ turbulence model to determine the cooling effectiveness and found to be in excellent agreement between experimental data and present computation. Hence, the same methodology has been adopted for further computational studies. For the entire computational work, 30^0 coolant injection has been chosen (Singh et al.[19]).

The variation of centreline cooling effectiveness downstream of the hole has been plotted at different blowing ratio for 30^0 forward and backward coolant injection and are shown in figures 4 (a-b) respectively.

From figure 4(a) it is observed that centreline cooling effectiveness increases with the blowing ratio up to M=1.3 then starts to decrease. This is because after a certain blowing ratio, jet lift takes place and hence reduces the effectiveness. From figure 4(b) for the case of backward coolant injection, the same trend of centreline cooling effectiveness has been observed as observed in case of forward coolant injection, but the maximum cooling effectiveness has been observed for blowing ratio M=1.6. This is because to the fact that after a certain blowing ratio, jet lift takes place which reduces the effectiveness due to mixing of hot and coolant fluids. Figure 5(a-b) show contours of cooling effectiveness on the plate surface downstream of the coolant hole at different blowing ratios for forward injection and backward injection of the coolant. From figure 5(a) it is observed that weighted area cooling effectiveness increases with increase in blowing ratio upto 1.3 and then it decreases with further increase in blowing ratio. This trend of weighted area cooling effectiveness is also observed in the case of backward injection of coolant, with only difference is that the maximum weighted area coolant effectiveness for backward injection is at blowing ratio 1.6. Comparing figures 5(a) and 5(b) it is observed that the backward injected coolant spreads more on the plate surface as compared to forward injection, hence more uniform cooling effectiveness is possible using backward injection of coolant.

4. CONCLUSIONS

The present work was aimed at a critical situation where an orthopedic implant of titanium alloy (Ti-6Al-4V) is to be manufactured ensuring that it not only resists loosening or migration but also is thermally stable and does not damage surrounding tissues or organs. The proposed methodology offers solution to both of the above. Fluid Flow Simulator Analysis software i.e. FLUENT has been employed for the simulation study. The developed model was validated with experimental values available in literature and was found to agree with them. The circular hole produced at 30^0 forward and 30^0 backward as indicated in the literature were used for the work. Atmospheric air, used as coolant, was injected at different blowing ratios and the cooling effectiveness was evaluated. It was observed that:

i. In the case of forward injection centreline cooling effectiveness increases with the blowing ratio up to 1.3 then starts to decrease whereas in case of backward injection the same happens at a higher blowing ratio i.e. at 1.6. This indicates that centreline cooling effectiveness at a particular blowing rate is more for forward injection than the backward injection.

ii. The weighted area cooling effectiveness also follows the same trend for both but it is observed that the backward injected coolant spreads more on the plate surface as compared to forward injection, hence more uniform cooling effectiveness is possible using backward injection of coolant.

The results indicate that although forward injection is more economically viable but backward injection should be preferred while working with an orthopedic implant as it provides more area under cooling. Hence it can be inferred that with backward injected cooling system the implant would be cooled better and would surely ensure a better component with respect to strength and longevity.

5. REFERENCES

1. Wong, J.Y.; Bronzino,J.D.;Peterson, D.R., *Biomaterials: Principles and Practices*, Boca Raton, Florida: CRC Press,2012; pp. 281.
2. McLatchie,G.;Borley,N.; ChikweJ. *Oxford Handbook of Clinical Surgery*, Oxford, UK: OUP Oxford,2013; pp. 794, https://doi.org/10.1093/med/9780199699476.001.0001.
3. Bărbînţă,A.C.; Chelariu, R.; Crimu, C.I.; Istrate, B.;Nazarie, S.;Earar,K.;Munteanu, C. Metallographic Characterization of a New Biomedical Titanium-Based Alloy For Orthopedic Applications.*Bulletin of the Transilvania University of Braşov*, Series I: Engineering Sciences, **2013**, *6*, 83 – 88,
4. Bunker,R.S.A review of shaped hole turbine film-cooling technology.*ASME Journal of Heat Transfer* **2005**,*127*,441-45, https://dx.doi.org/10.1115/1.1860562.
5. Goldstein, R.J.; Eckert, E.R.G.; Ramsey, J.W. Film Cooling with Injection through Holes: Adiabatic Wall Temperatures Downstream of a Circular Hole. *Journal of Engg for Power***1968**,*90*, 384-395.
6. Goldstein, R.J. Film Cooling, In *Advances in Heat Transfer*,Academic Press,New York, 1971, https://doi.org/10.1016/S0065-2717(08)70020-0.
7. Bergeles, G.; Gosman, A.D.; Launder, B.E. The Near Field Character of a Jet Discharged Normal to a Main Stream.*Journal of Heat Transfer***1976**,*98*, 373-378,https://dx.doi.org/10.1115/1.3450563.
8. Bergeles, G.;Gosman, A.D.; Launder, B.E. Near-Field Character of a Jet Discharged through a Wall at 30 Degrees to a Mainstream. *AIAA Journal***1977**, *15*, 499-504, https://doi.org/10.2514/3.7343.
9. Andreopoulos, J.;Rodi, W. Experimental Investigation of Jets in a Crossflow.*Journal of Fluid Mechanics***1984**, *138*, 92- 127,.
10. Yuen, C.H.N.; Martinez-Botas, R. Film Cooling Characteristics of a Single Round Hole at Various Streamwise Angles in a Crossflow: Part I Effectiveness.*International Journal of Heat and Mass Transfer***2003**, *46*, 221-235, https://doi.org/10.1016/S0017-9310(02)00274-0.
11. Yuen, C.H.N.; Martinez-Botas, R. Film Cooling Characteristics of Rows of Round Holes at Various Streamwise Angles in a Crossflow: Part I. Effectiveness.*International Journal of Heat and Mass Transfer***2005**, *48*, 4995-5016, https://doi.org/10.1016/j.ijheatmasstransfer.2005.05.019.
12. Yuen, C.H.N.;Martinez-Botas, R. Film Cooling Characteristics of Rows of Round Holes at Various Streamwise Angles in a Crossflow: Part II. Heat Transfer Coefficient. International. *Journal of Heat and Mass Transfer***2005**, *48*, 5017-5035,https://doi.org/10.1016/j.ijheatmasstransfer.2005.05.020.
13. Wang, T.; Li, X. Mist Film Cooling Simulation at Gas Turbine Operating Conditions.*International Journal of Heat and Mass Transfer***2008**,*51*, 5305-5317, https://doi.org/10.1016/j.ijheatmasstransfer.2008.04.040.
14. Jovanovic,M.B.; Lange,H.C.;Van-Steenhoven, A.A. Effect of Hole Imperfection on Adiabatic Film Cooling Effectiveness.*International Journal of Heatand Fluid Flow***2008**, *29*, 377-386, https://doi.org/10.1016/j.ijheatfluidflow.2007.11.008.
15. Li, G.; Zhu, H.; Fan, H. Influence of Hole Shapes on Film Cooling Characteristics with CO_2 Injection.*Chinese Journal of Aeronautics***2008**, *21*, 393-401, https://doi.org/10.1016/S1000-9361(08)60051-5.
16. Becchi, R.; Facchini, B.; Picchi, A.; Tarchi, L.;Coutandin D.; Zecchi, S. Film Cooling Adiabatic Effectiveness Measurements of Pressure Side Trailing Edge Cooling Configurations.*Propulsion and Power Research***2015**, *4*, 190-201, https://doi.org/10.1016/j.jppr.2015.10.001.
17. Khajehhasani, S.; Jubran, B.A. A Numerical Evaluation of the Performance of Film Cooling from a Circular Exit Shaped Hole with Sister Holes Influence.*Heat Transfer Engineering***2016**, *37*, 183–197, https://doi.org/10.1080/01457632.2015.1044415.
18. Oda, Y.;Kiyozumi, H.; Takeishi, K. Effect of Density Ratio on The Film Cooling with Shaped Cooling Hole And Swirled Coolant. Proceedings of The Asian Conference On Thermal Sciences, Jeju Island, Korea,1st ACTS, March 26-30, 2017, 1-5.
19. Singh, K.; PremachandranB.; Ravi, M.R. Experimental and Numerical Studies On Film Cooling with Reverse/Backward Coolant Injection.*International Journal ofThermal Sciences***2017**, *111*, 390-408, https://doi.org/10.1016/j.ijthermalsci.2016.09.027.
20. Mishra, M.P.; Chandel, S.; SahaniA.K.; Negi, B. Enhancement of Full Coverage Film Cooling Performance with Opposite Injection Holes.*Materials Today: Proceedings* **2018**, *5*, 19517–19528,https://doi.org/10.1016/j.matpr.2018.06.313.
21. Bertolini, R.; Bruschi, S.; Bordin, A.; Ghiotti, A.; Pezzato, L.; Dabal, M. Fretting corrosion behavior of additive manufactured and cryogenic-machined Ti6Al4V for biomedical

applications. *Adv. Eng. Mater*. **2016,** *19*, 1-9, https://doi.org/10.1002/adem.201500629.
22. Bruschi, S.; Bertolini, R.; Bordin, A.; Medea, F.; Ghiotti, A. Influence of the machining parameters and cooling strategies on the wear behavior of wrought and additive manufactured Ti-6Al-4V for biomedical applications. *Tribology International* **2016**, *102*, 133-142, https://doi.org/10.1016/j.triboint.2016.05.036.
23. Banerjee, N.; Sharma, A. Development of a friction model and its application in finite element analysis of minimum quantity lubrication machining of Ti-6Al-4V. *Journal of Materials Processing Technology* **2016**, *238*, 181-194, https://doi.org/10.1016/j.jmatprotec.2016.07.017.
24. Shokrani, A.; Dhokia, V.; Newman, S.T. Investigation of the effects of cryogenic machining on surface integrity in cnc end milling of Ti-6Al-4V titanium alloy. *Journal of Manufacturing Processes* **2016**, *21*, 172-179, https://doi.org/10.1016/j.jmapro.2015.12.002.
25. Sartori, S.; Ghiotti, A.; Bruschi, S. Temperature effects on the Ti-6Al-4V machinability using cooled gaseous nitrogen in semi -finishing turning. *Journal of Manufacturing Processes* **2017**, *30*, 187-194.
26. Bruschi, S.; Bertolini, R.; Ghiotti, A. Coupling machining and heat treatment to enhance the wear behaviour of an Additive Manufactured Ti-6Al-4V titanium alloy. *Tribol. Int.* **2017**, *116*, 58 – 68, https://doi.org/10.1016/j.triboint.2017.07.004.
27. Nikpatro, A.; Schobeiri, M.T.; Numerical and experimental investigation of aerodynamics on flow around a highly loaded low-pressure turbine blade with flow separation under steady and periodic unsteady inlet flow condition. Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition, Paper No. GT2016-56699, V05AT13A010; 17 pages, http://dx.doi.org/10.1115/GT2016-56699.
28. Hammami, Z.; Dellil, Z.A.; Nemdili, F. Improving Adiabatic Film-Cooling Effectiveness By Using An Upstream Pyramid. *Computational Thermal Sciences* **2016**, *8*, 135-146, http://dx.doi.org/10.1615/ComputThermalScien.2016016302.
29. Abdala A.M.M.; Elwekeel, F.N.M. CFD Simulations of Film Cooling Effectiveness and Heat Transfer for Annular Film Hole. *Arabian Journal for Science and Engineering* **2016**, *41*, 4247-4262, http://dx.doi.org/10.1007/s13369-016-2028-3.
30. Wong, T.H.; Ireland, P.T.; Self, K.P. Film Cooling Effectiveness Downstream of Trailing Edge Slots Including Cutback Surface Protuberances. *Int. J. Turbomach. Propuls. Power* **2016**, *1*, 1-15, https://doi.org/10.3390/ijtpp1010004
31. Krishna Anand, V.G.; Parammasivam, K.M. Investigations of Trenched Film Hole Orientation Angle on Film Cooling Effectiveness. *Int J Turbo Jet Eng*. **2017**, 1-10, https://doi.org/10.1515/tjj-2017-0049.
32. An, B.T.; Liu J.J.; Zhou, S.J. Effects of Inclination Angle, Orientation Angle, and Hole Length on Film Cooling Effectiveness of Rectangular Diffusion Holes. *J. Turbomach* **2018**, *140*, http://dx.doi.org/10.1115/1.4040101.

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