

# Computational Investigation of Tangential Convective Cooling of Hypersonic Cowl Leading Edge

T.Tirupati<sup>1</sup>, Dr. B.Subash Chandran<sup>2</sup>Associate Professor, Dept of Mechanical Engineering, Bharath Institute of Engineering and Technology, Hyderabad,  
Telangana, India<sup>1</sup>Director of Propulsion, DRDL, Hyderabad, Telangana, India<sup>2</sup>

**ABSTRACT:** Hypersonic air breathing vehicles are subjected aerodynamic heating. Engine cowl of the vehicle is subjected to shock-shock interaction. This creates localized intense heating leading to thermo structural failure of the system. Thermal management of hypersonic structures is necessary to protect from structural failure. Investigation of tangential convective cooling, actively cooled concept applicability for a cowl leading edge is carried using CFD. Computational models of idealized geometry (straight) and curved cowl leading edge of hypersonic vehicle are evaluated and compared. The parameters considered for the computational investigations are flow conditions, laminar or turbulent and coolant type, liquid sodium, liquid water or cryogenic Hydrogen. The simulations are carried with ANSYS CFX, CFD software. The results indicate that temperature variation pattern near the localized heat flux region for both cases, straight and curved geometry are same, but there is a magnification of temperature range for curved geometry. The three coolants for Laminar flow condition yield the maximum temperature for range of velocities investigated, which is above the limiting temperature of copper alloy, cowl leading edge material for both cases. All the three coolants with turbulent flow condition with a suitable velocity yield the temperature below the desired. The liquid sodium coolant in all velocity range investigated and water coolant for nominal condition of velocity yield the desired temperature. The liquid sodium coolant is less sensitive to velocity variation.

**KEYWORDS:** Tangential Convective Cooling, Localized Heat Flux, Shock-Shock Interaction, CFD Analysis.

## I. INTRODUCTION

Thermal management of hypersonic air breathing vehicle is necessary to protect the vehicle from localised heating aroused due to shock-shock interaction, which causes intense thermal stresses in vehicle structure. As an example, the National Aero-Space Plane (NASP) is expected to operate at flight conditions that produce severe aero thermal heating of the engine cowl leading edge because of shock-shock interactions [1]. A schematic of this situation and the heat flux distribution on the engine cowl leading edge is given in figure1 [2]. The estimated localized heat flux is 567447 kW/m<sup>2</sup> [3].

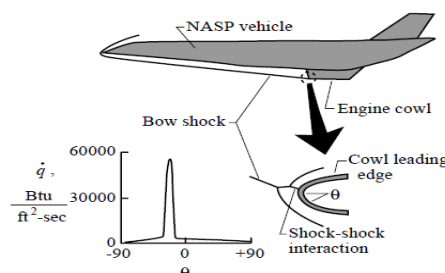


Figure1. Heat flux distribution on engine cowl subjected to shock-shock interaction [2]

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Passive and active cooling techniques are used for thermal management of hypersonic vehicle cowl leading edge. Schematic of active cooling systems are shown in figure 2. These are heat pipe with liquid metal convectively cooled, transpiration cooling in which cooling gas is injected through porous surface, impingement convective cooling in which the coolant is impinged at the location of applied heat flux and tangential convective cooling in which the coolant pass through the channel situated below the surface to be cooled.

Transpiration and heat pipe cooling

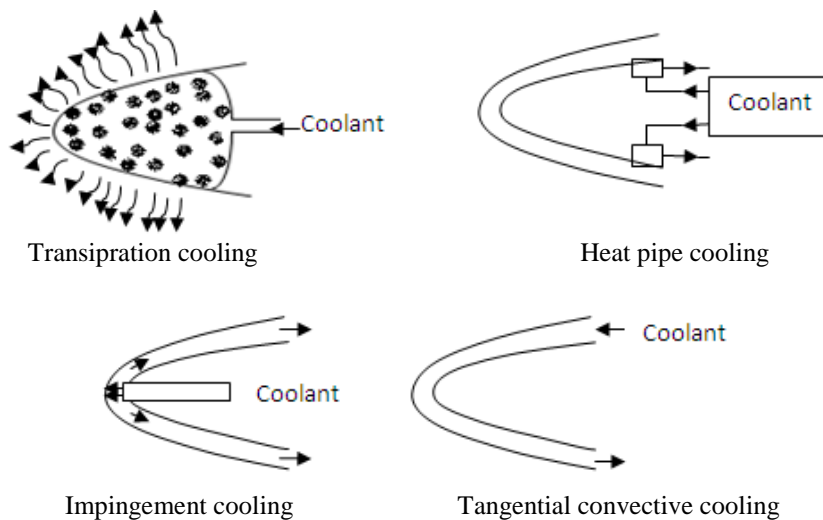


Figure2. Actively cooling concepts applicable to hypersonic cowl leading edge

In this research paper, tangential convectively cooling concept is investigated computationally for the two cases, neglecting curvature of leading edge i.e. idealizing the geometry and considering curvature of the cowl and comparison of computed results.

## II. LITERATURE REVIEW

McConarthy et.al. [4] conducted experiments on indirect convective cooling system analysis with heat sink as fuel for a wing with different leading edge radii. The transport fluid used for the analysis are water-ethylene glycol solution for operating temperatures below 200°F and silicone fluid for the temperature range of 200°F to 400°F. They concluded that leading edge radius variation effect on cooling system is insignificant. In their preliminary investigations, it is found that with increase in sink temperature, hydrogen flow rate required is decreased and transport fluid cooling rate is required. It is concluded that leading edge radius is not a significant factor in the design of convective systems. They conducted experiments separately for the components of wing included top surface, leading edge and bottom surface. They showed that bottom surface required more mass flow rate of coolant in comparison to top surface. They suggested further investigation with a parameter as transport fluid rate.

Stephen J. Scotti [2] carried out the numerical study to evaluate the capability of tangential convective cooling of locally heated skins. He performed numerical simulations of two-dimensional coolant flow bounded by the heated skin. The study case considered in his analysis is an engine cowl leading edge subjected to localized thermal load due to shock-shock interaction heating. The assumptions made in the analyses are uniform coolant and skin properties, further the analysis is simplified with neglecting model curvature and channel side wall conduction. The parameters investigated are flow regime (laminar or turbulent), type of liquid coolant (cryogenic hydrogen, water and liquid metal sodium), mass flow rate of coolant, width of heated region, thickness of skin and coolant bulk properties. In his studies,

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he concluded that liquid metal sodium is least sensitive to parametric variations and all the coolants are able to bring down the temperature of skin below the maximum operating temperature.

Tobias Schwanekamp *et al.*[5] investigated to evaluate the design of potential active thermal protection systems for space liner reference vehicle. Thermal protection systems included for the analysis of mass balance and total cost are transpiration, convective and spray cooling systems. They conducted the simulations of convectively cooled system with water, gaseous hydrogen and lithium liquid as coolants. They found that mass savings are very high with hydrogen coolant in comparison to other coolants as it is readily available on board as propellant. Lithium is not suitable for direct cooling method but it can be considered for hybrid cooling methods.

The present research paper is focused on the assumptions and simplifications made in Stephen J. Scotti numerical simulations. The computational investigation is carried out to assess the impact of the idealized conditions. The results are showed for idealised and curved cowl leading edge on the effectiveness of tangential convective cooling system for hypersonic cowl leading edge.

### III. DESCRIPTION OF THE PROBLEM

The idealized geometry for the case1 in which curvature of cowl leading edge is neglected and geometry of the case 2 are shown in Figure 3. The liquid coolant flows through the channel of height,  $H_c$  which is situated below the copper alloy skin of cowl leading edge of thickness  $H_s$ , the length of the channel is  $X$  and localized heat flux due to shock-shock interaction is located at a length  $L$  and the width of location is  $W$ . The cowl leading edge is representative of prototype of NASP leading edge [6] is considered for non-idealized geometry simulations. The radius of cowl leading edge,  $R$  is 1.397mm and it is swept back at angle,  $\alpha$  is  $5^\circ$ . The other geometrical parameters are same as idealized geometry for the comparison purpose.

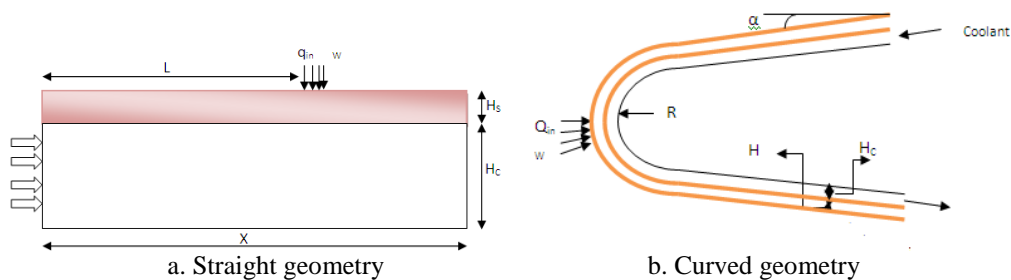
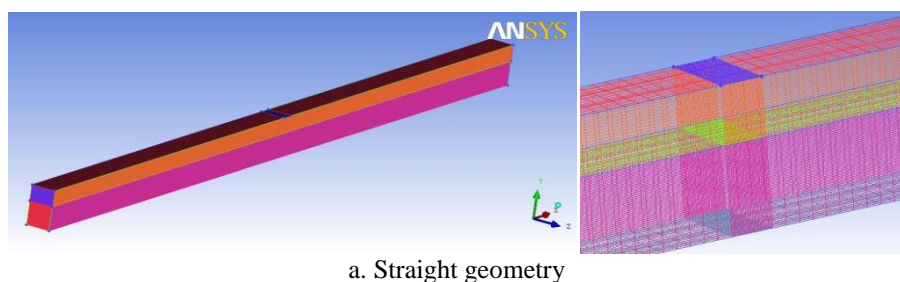


Figure 3. Geometry of cowl leading edge considered for the analysis.

### IV. COMPUTATIONAL METHODOLOGY

Geometry creation and structured mesh generation is done using ICFM CFD, advanced meshing software. Geometry and mesh for the two cases shown in Figure 4.

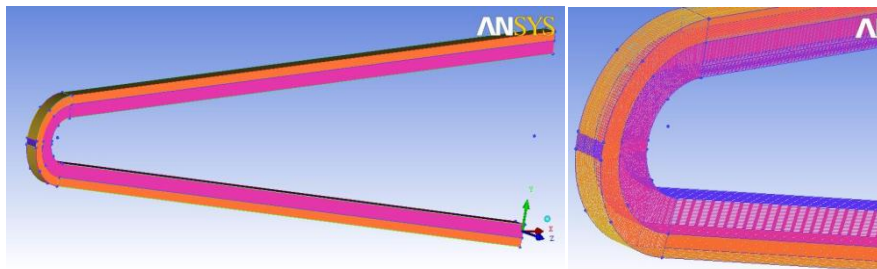


a. Straight geometry

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b. Curved geometry

Figure 4. Geometry and Mesh generated of cowl leading edge

All the computational simulations are carried with ANSYS CFX, CFD software. The turbulence model considered for the analysis is Shear Stress Turbulence with percentage of turbulence 1 approximating to Laminar and 10 with high turbulence case. The boundary conditions are based upon Scott et al [2]. The local heat flux, value of  $567447 \text{ kW/m}^2$  is applied in a small region downstream the coolant and this location is based on the flow regime laminar or turbulent. In this present paper, the computational simulations are carried with fixed geometry of coolant channel height, cowl skin thickness and area of applied localized heat flux. The effect of flow regime and velocity are investigated computationally for three different coolants namely liquid water, cryogenic hydrogen and liquid sodium. The inlet nominal velocities considered for the different cooling fluids are shown in Table 1. The properties of the fluid are assumed constant with variation of temperature and their values are taken at nominal bulk temperature, shown in Table 2. The properties of liquid coolants are based upon Scott et al. [2] and are represented in the Table 3.

Table 1. Dimensions of the geometry considered

Geometry parameter	Laminar flow regime, mm	Turbulent flow regime, mm
$H_c$	0.762	0.762
$H_s$	0.508	0.508
$W$	0.381	0.381
$L$	25.4	12.7
$X$	50.8	25.4

Table 2. Liquid coolant parameters

Liquid coolant	Bulk Temperature, K	Inlet Temperature, K	Inlet velocity, m/s
Hydrogen	222	55.4	182.88
Water	450	291.48	60.96
sodium	478	394.26	60.96

Table 3. Liquid coolant properties at bulk temperature

Liquid coolant	Density, $\text{kg/m}^3$	Sp.Heat, J/kg K	Thermal conductivity, W/Km	Viscosity, $\text{cp} \times 10^{-5}$
Hydrogen	16.63	16378.7	0.201	79
Water	839.19	4379.4	0.679	0.1532
sodium	905.20	1339.77	82.62	0.4577

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The schematic of boundary conditions for two cases are shown in Figure 5 and red region indicates the applied heat flux location.

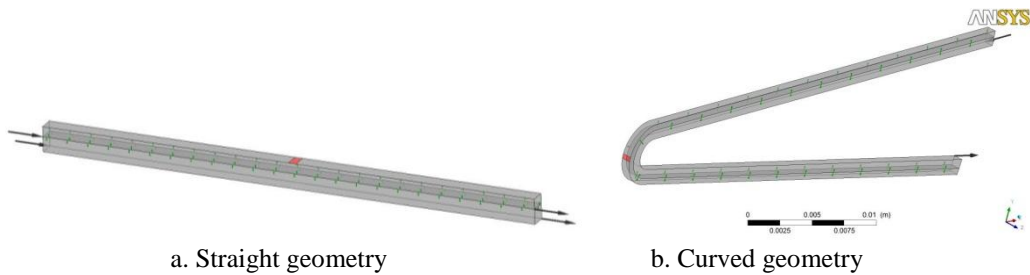


Figure 5. Boundary conditions applied for CFD simulations

## V. RESULTS AND DISCUSSION

### Water coolant under Laminar flow conditions (nominal):

Temperature contour on central plane for the nominal case of laminar flow regime with liquid water as coolant are shown in Figure 6. The maximum temperature calculated by simulations for the case of straight geometry is 1616K and for that of curved is 2038K. The minimum skin temperature calculated is 1270K for the case of idealized geometry and for that of curved geometry is 1616K. The maximum temperature obtained for curved geometry is higher as compared to straight one. The reason assigned to this is velocity loss in downstream of coolant flow due to curvature.

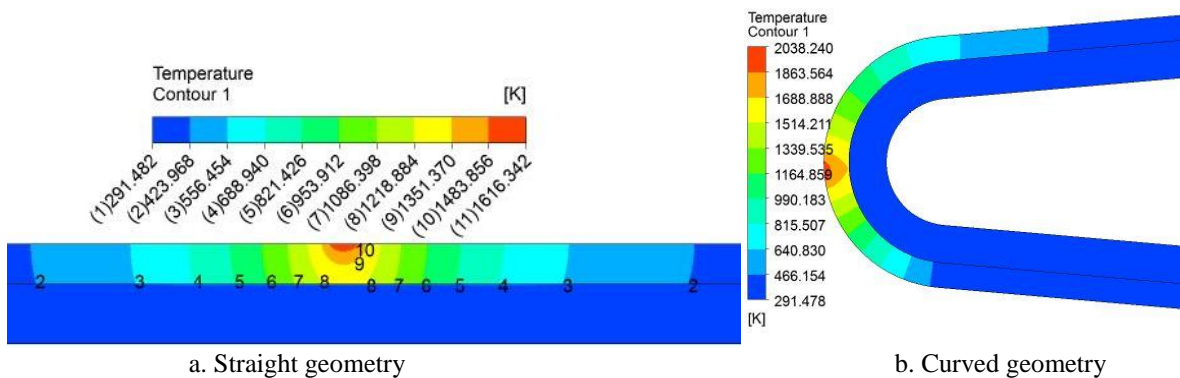
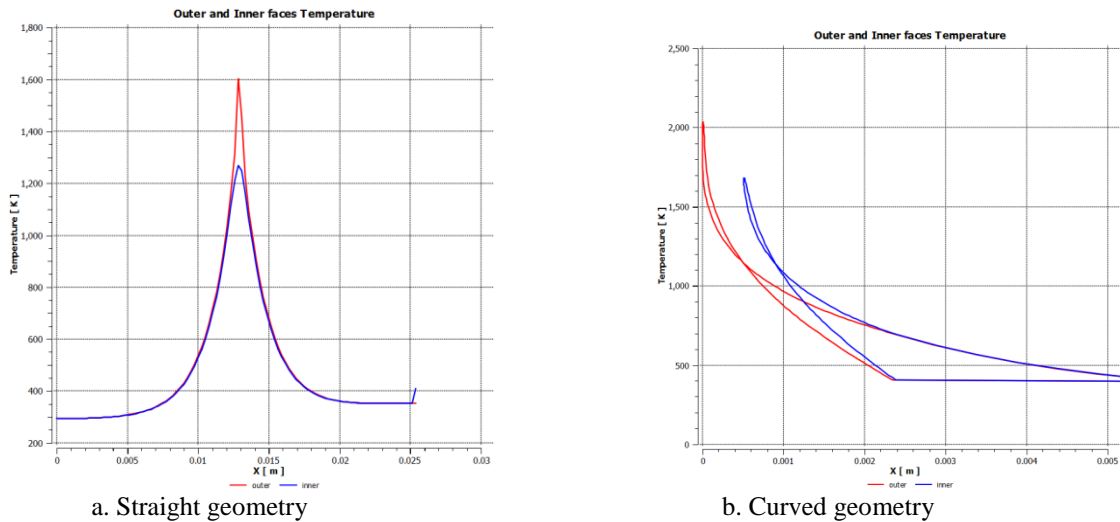


Figure 6. Temperature contours of nominal case (water coolant) under Laminar flow regime

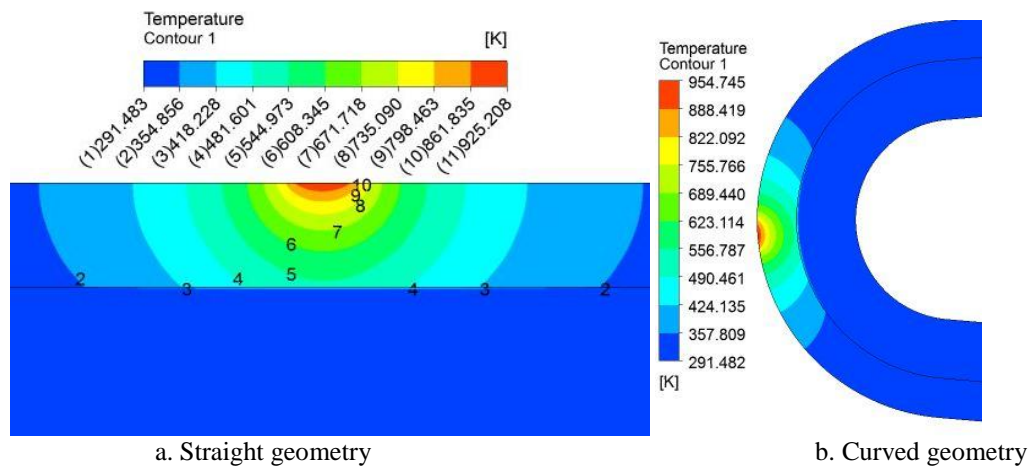
The variation of temperature along stream wise direction i.e X-axis is shown in Figure 7. The peak temperatures calculated for the both cases are beyond the limit of usage temperature of skin alloy. Although the velocity numerically same for both laminar and turbulent i.e. only length has been changed to consider the flow regime, the turbulence percentage effected the heat transfer rate.



**Figure 7. Temperature variation along X-axis for laminar nominal case (water coolant)**

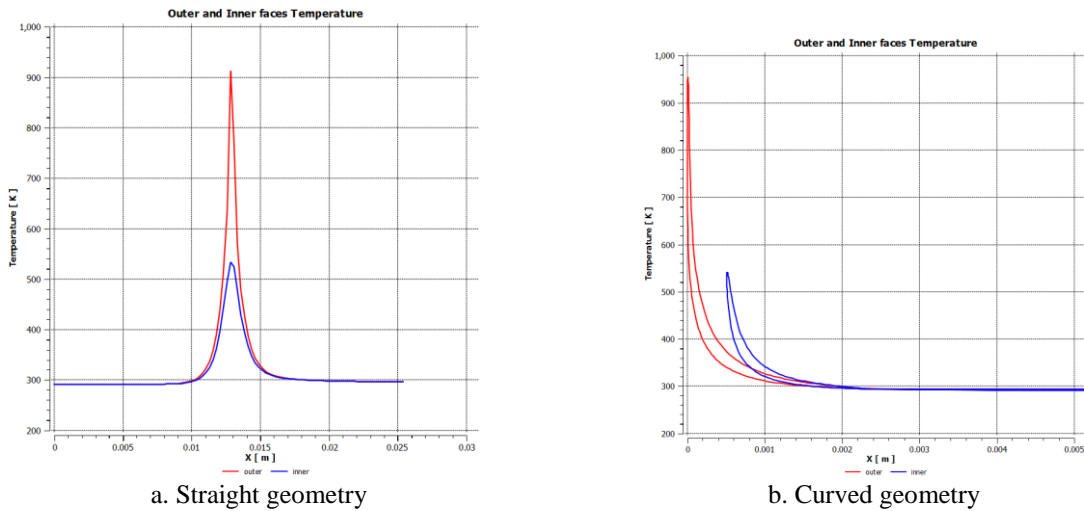
**Water coolant under Turbulent flow conditions (nominal):**

Temperature contours on central plane near localized thermal load beginning at  $x = 12.7\text{mm}$  are given in figure 8. A large temperature variation is observed from outer skin to inner skin. It is observed from the contour that the bulk temperature of the coolant is at lower temperature, around 300K. The temperature difference decreases rapidly along the downstream and upstream direction. For the straight and curve cowl leading edges, the contour patterns are same, differs in the maximum outer and inner skin temperatures. The temperature started rising from 5mm and normalized after 20mm along the flow direction.



**Figure 8. Temperature contours for turbulent nominal case (water coolant)**

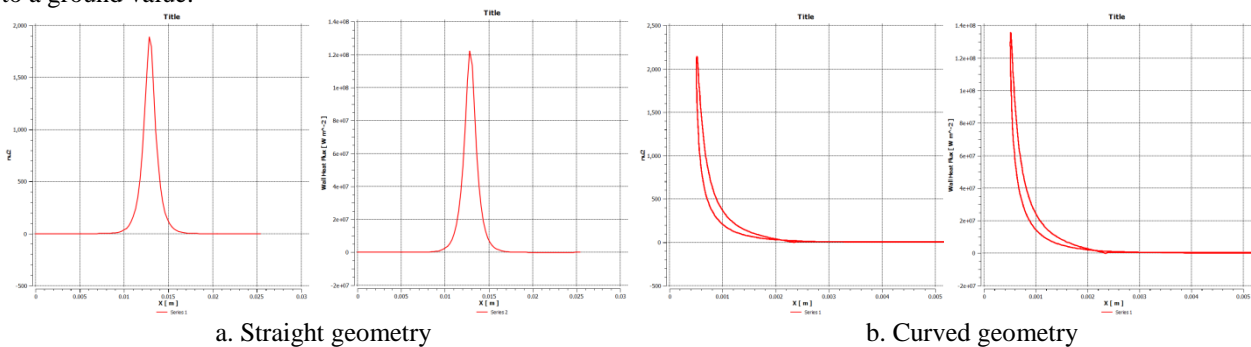
Variation of temperatures along the stream wise direction on both the outer (heated) and inner (cooled) surfaces of the skin represented in figure 9. The temperature difference between heated skin and coolant is observed along stream wise direction, which starts at 9mm and vanishes at 17mm in the presence of localized thermal load, which starts at 12.7mm and ends at 13.08mm for the case of straight geometry. The influence of localized thermal load observed from 2.2mm upstream to 2.2 downstream the thermal load.



**Figure 9. Temperature variation along X-axis for turbulent nominal case (water coolant)**

The maximum temperature of outer surface of leading edge for straight case reached is 913.30 K and that of the inner skin (near to coolant) is 534 K. for the curved cowl leading edge the values are 954.70 K and 542.30 K. The velocity in downstream ahead of thermal load decreased due to curvature of cowl. This caused increase in temperature of inner skin lead to increase in outer skin.

The Nusselt number and wall- heat flux variation in the stream wise direction are represented in figure 10. Most of the heat enters the coolant in the narrow region that surrounds the localized thermal load. The maximum heat flux entering the coolant is 135686 kW/m<sup>2</sup> where as the applied heat flux is 567447 kW/m<sup>2</sup>, the heat flux reduction is due to stream wise conduction in skin. It indicates that spreading of thermal load in the skin. The Nusselt number variation in a parabolic manner, in upstream of heat input low ground value, reaches to a peak at heat input and in downstream of it to a ground value.



**Figure 10. Nusselt number and heat flux variation along stream wise direction for turbulent nominal case (water coolant)**

**Effect of coolant type:**

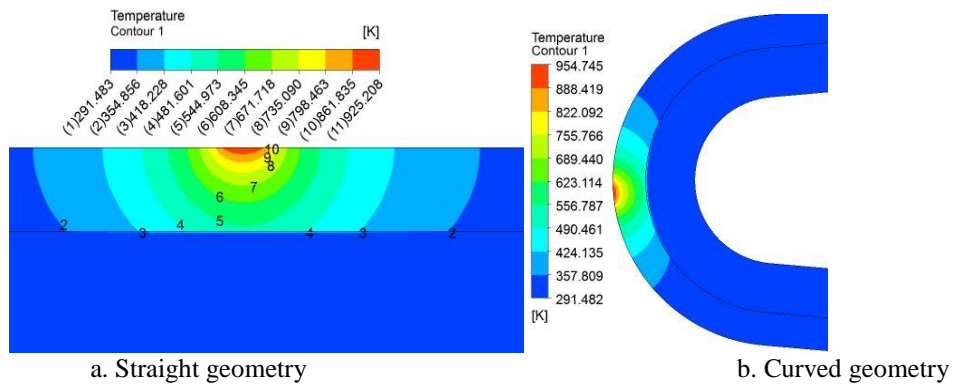
The three liquid coolants namely water, liquid sodium and cryogenic hydrogen effectiveness under nominal turbulent flow conditions are presented inform of contours and charts as shown in figures 10 and 11. The maximum skin temperature obtained for the idealized geometry cooled with Water is 925K, with liquid sodium is 899K and Cryogenic Hydrogen is 1043K. The peak temperature is brought to lowest with Liquid Sodium coolant. The maximum skin temperature calculated for the curved geometry with water coolant is 955K, with liquid Sodium coolant is 936K and with cryogenic hydrogen is 1071K. The difference observed in maximum temperatures calculated for the two cases,

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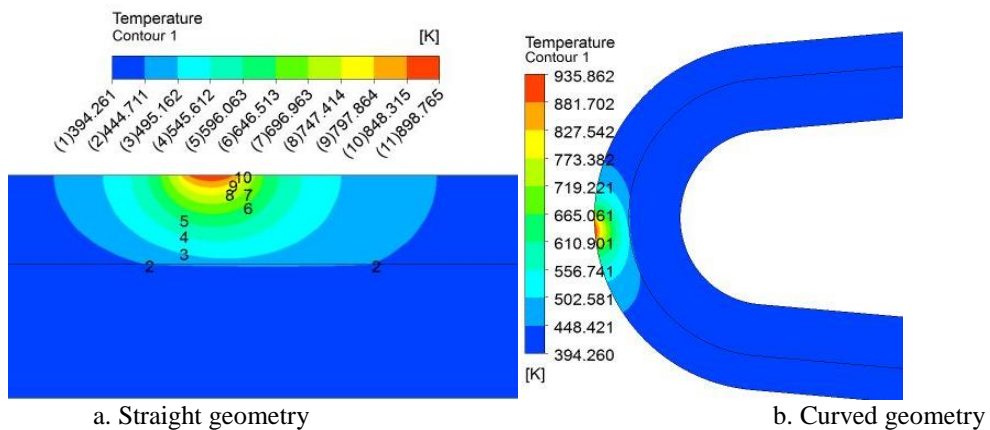
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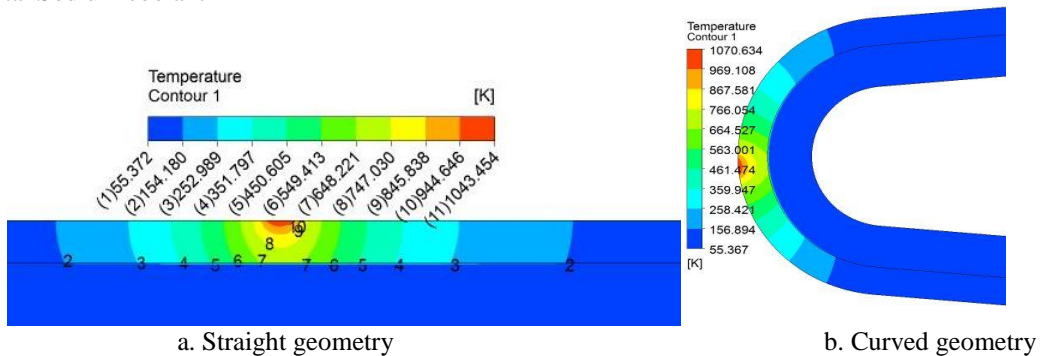
idealized and curved geometries are 30K with water, 37K with liquid sodium and 28K with hydrogen. The local heat flux applied is spread over for idealized geometry approximately is 9mm with water, 10mm with Sodium and 18mm with hydrogen. For the case of curved geometry, the heat flux spread is maximum with Hydrogen and minimum with water.



i) Water coolant



ii) Liquid metal Sodium coolant



**Figure 10: temperature contours in central plane for different coolants under nominal turbulent conditions**



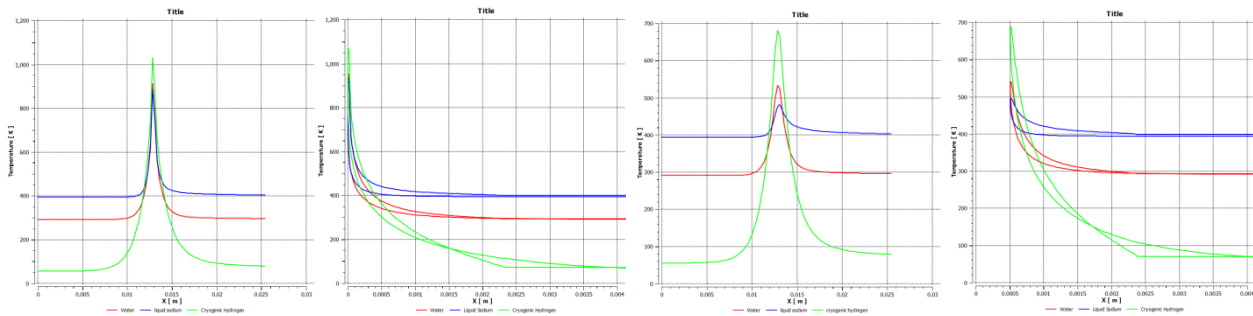
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### iii) Cryogenic Hydrogen coolant

Temperature variation along the central line on inner and outer surface is represented below for three coolants. From the charts it can be concluded that liquid sodium is efficient in cooling in comparison to other two coolants.



### Effect of coolant velocity variation (turbulent flow):

Maximum surface temperature of idealized geometry cowl leading edge and curved edge variation with the velocity of coolant for three coolants in turbulent flow regime is represented in figure 12. Maximum skin temperature decreases with increase in coolant velocity for all the three coolants. The variation pattern is almost same but with magnified values of temperatures calculated. For the case of liquid sodium, the temperature is almost invariant with velocity. The maximum temperature is 939.10 K at 15.24 m/s and minimum of 880.50 K at 60.96m/s. The optimum coolant velocity is 60.96m/s, above of this value i.e. at 76.2m/s, temperature slightly increases to 886.2 K. Temperatures obtained with hydrogen coolant showed great variation with coolant velocity. The maximum skin temperature is 2017 K at a velocity of 30.48m/s and minimum of 949.40K at 76.2m/s; it is still higher in comparison with maximum temperature obtained by liquid sodium coolant. The temperatures obtained with water coolant are the maximum of 1165K at a velocity of 15.24m/s and the minimum of 887.10K at 76.2 m/s. The maximum temperature obtained at nominal conditions with cryogenic hydrogen coolant, 1031K, exceeds the maximum usage temperature of copper alloy 920 K; almost the same of 913.3K obtained with water coolant and liquid sodium, 880.5K surface temperature, is below the usage value. From the above results, it is concluded that the optimum coolant is liquid sodium with minimum variation of temperatures calculated at different coolant velocities.

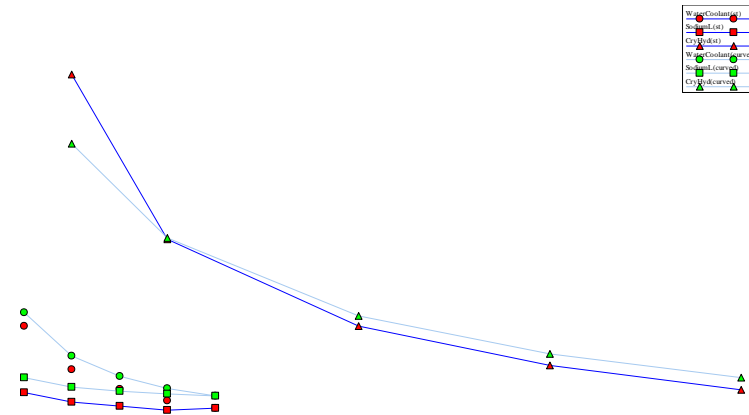
The same pattern of variation is observed as that of idealized cowl leading edge geometry with little magnification of values with respective coolants. The least value in maximum temperature of the skin is with liquid sodium coolant, value of 929.60K at a velocity of 76.2m/s and the greatest is with cryogenic liquid hydrogen, 990.50K at 76.2m/s. The greatest value in maximum temperature of the copper skin is with cryogenic liquid hydrogen, value of 1783K at a velocity of 30.48m/s and the least with liquid sodium coolant, 989.30K at 15.24m/s. The Maximum and minimum skin temperatures calculated are with water coolant are 1211K at a coolant velocity of 15.24m/s and 927.40K at 76.2m/s. The minimum temperatures obtained are almost same for liquid sodium and water coolant, but the optimum coolant employable is liquid sodium which shows less variation with the velocity and skin temperature calculated is near with the maximum usage value 920K with coolant velocities ranging from 45.72m/s to 76.2m/s.

All the coolants with curved geometry showed higher temperature than idealized geometry. The optimum coolant concluded from the results is liquid sodium.

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**Figure 11: Effect of velocity variation on maximum temperature of skin in turbulent flow regime for the three coolants**

## VI. CONCLUSION

Investigation of tangential convective cooling, active cooling method applicability to cowl leading edge is carried out. The effect of curve leading edge on the effectiveness of cooling edge with three different coolants namely Water, Liquid metal Sodium and Cryogenic Hydrogen is evaluated in comparison to idealized geometry. In addition, the investigation is done varying the laminar and turbulent flow with variation in velocity of coolant. The liquid sodium is the suitable coolant for the application as it is insensitive to velocity variation. The temperature calculated for the idealized geometry is 880.5K and that for curved leading edge is 935.9K, which is below the working temperature of Copper alloy.

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