CFD ANALYSIS OF IMPINGEMENT CONVECTIVE COOLING FOR A LOCALLY HEATED SKIN

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ABSTRACT

A computational study of the potentiality of impingement convective cooling for a locally heated skin is carried using CFD package ANSYS-CFX. The simulations are carried for an idealized cooling problem for a thermal load representative of a shock-shock interaction on the engine cowl leading edge of a hypersonic study vehicle (NASP). The parameters investigated are Prandtl number by varying coolant type (liquid sodium, liquid water, or supercritical cryogenic hydrogen), Reynolds number by variation with inlet Jet velocities), jet diameter and coolant channel height (jet to target spacing) with single jets in the absence of phase change. The results indicate that for specific combinations of parameters, all three coolants may yield temperatures within the temperature limits of a copper-alloy, engine cowl leading edge. However, a liquid sodium coolant is the least sensitive of the three coolants to the assumed flow conditions and to the other parameters investigated in the study.

Keywords: *Heat Transfer, Impingement Cooling, Hypersonic Cowl.*

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INTRODUCTION

Choice of cooling system for aero space structures subjected to intense, localized thermal load can be difficult. Such a condition is expected in National Aero-Space plane, a hyper sonic vehicle, where the engine cowl is subjected to severe aero thermal heating as a result of shock-shock interaction.[1] Distribution of heat flux on the engine cowl leading edge is presented schematically in “fig.1”. Maximum heating rate is predicted over 567826 kW/m^2[2]. Schematic representations of active cooling concepts are shown in “fig.2”, they are heat pipe, transpiration, tangential and impingement cooling. Heat pipe cooling concept involved with liquid metal heat pipe. Transpiration cooling is based on transpiration of coolant through a porous metal surface. Impingement and tangential cooling methods are similar in concept except impingement of coolant flow in former one.

Jet impingement is an attractive cooling mechanism due to the capability of achieving high heat transfer rates for and it has been employed effectively for annealing of metals, cooling of gas turbine blades, cooling in grinding processes [3], thermal management of high-powered electronic and photonic applications. A fluid jet issuing into a region containing the same fluid is characterized as a submerged jet while a fluid jet issuing into a different, less dense, fluid is characterized as a free-surface jet. Womac et al. [4, 5] have shown that higher heat transfer coefficients result from submerged jet conditions than from free-surface jet conditions for $Re \geq 4000$. An impinging jet is said to be confined or semi-confined if the radial spread is confined in a narrow channel, usually between the impingement surface and the orifice plate. The presence of a confining top wall in jet impingement causes lower heat transfer coefficients, thought to be caused by the recirculation of fluid heated by the target plate. Huang et al. [6] suggest that confinement promotes a more uniform heat transfer distribution for the area enclosed by a non-dimensional radial distance from the stagnation point (r/d) of 5. The key parameters determining the heat transfer characteristics of a single impinging jet are the Reynolds number, Prandtl number, jet diameter and jet-to-target spacing. Numerous studies have been conducted to investigate the influence of each of these parameters.

The present research paper is focused on effectiveness of impingement convectively cooling for engine cowl leading edge of National Aero-Space Plane, a representative of intense, localized thermal loads due to shock-shock interaction. A parametric analysis is carried through CFD simulations using ANSYS-CFX, CFD software. The parameters considered for the analysis are Jet diameters (d) of 0.254mm, 0.381mm, 0.762mm and 1.524 are investigated for impinging jets with jet velocities 15.24 m/s, 30.48 m/s and 61.96 m/s (Reynolds number variation) and non-dimensional jet-to-target spacing (H/d) from 1 to 4.Analysis is performed on three dimensional simplified model and conditions are taken in such a way that analysis becomes two dimensional one. The jet considered for the analysis is axisymmetric, normally impinging, confined and submerged. The results of temperature distribution and flow field analysis are presented for water cooled skin.

DESCRIPTION OF PROBLEM

Idealized geometry of a cowl leading edge is schematically presented in "fig.4". Analysis of heat transfer involves convection-conduction problem aroused due to shock-shock interaction. Curvature of cowl leading edge is neglected to idealize the geometry of cowl. The investigation is concentrated on localized heat flux due to shock-shock interaction and other effects are ignored to simplify the solution of the problem. The coolant flows in a channel of height hc, which is bounded above by the heated metallic skin with a thickness of hs, and below by an insulated wall. A single axisymmetric jet is made to impinge at the central location of heated skin. The flow is both eds open flow and confined in a channel. A steady, uniform heat flux (q. = Q) is applied at the beginning of location $x = l$ on the external face of the skin and extending for a length w. All other surfaces except side surfaces bounding the channel skin system are subjected to zero heat flux. The skin side surfaces are considered as symmetry wall.

Mesh Generation

Geometry is created and mesh generation is done in ICEM CFD, commercial software. Mesh generated is unstructured mesh with tetrahedral elements. The mesh is shown in "Fig.1"

Analysis Conditions

Geometry parameters are presented in table 1. The values of stream wise lengths are less important in case of turbulent as the hydrodynamic flow is fully developed. Values of l and *xmax* are of 0.0254m and 0.0508m, respectively. The nominal thermal and flow conditions for the three coolants are given in table2. *Tb'* is the bulk temperature at which the thermodynamic and transport properties of coolants are evaluated. These properties are assumed to be constant in the present study. Nominal values of inlet temperature *Tin*, bulk temperature *Tb'* and average coolant velocity u are given in table 2.

Table 1. Geometry parameters

Parameter	Linear dimension, mm
hc	0.762
hs	0.508
l	25.4
xmax	50.8
w	0.381

Table2. Analyses conditions

Coolant	*Tb'*,ºK	*Tin*, ºK	*u*,m/sec
Hydrogen	222	55.4	182.88
Water	450	291.48	60.96
Sodium	478	394.26	60.96

Coolant properties for supercritical, cryogenic hydrogen, liquid water and liquid sodium are given in table 3. The properties are taken from [19].

Table 3: Coolant properties

Coolant	*Tb'*,ºK	ρ, kg/m^3	Cp, J/kgK	k J/m-k-sec	μ, cp	Pr
Hydrogen	222.04	16.63	16378.7	0.201	79	0.645
Water	449.82	893.19	4379.4	0.679	0.1532	0.987
sodium	477.59	905.20	1339.77	82.62	0.4577	7.4

The copper alloy has a thermal conductivity, ks of 346.2W/mK. As the investigation carried is Steady state time step and thermal diffusivity are not considered for analysis. In all cases, the magnitude of heat flux,

q. = Q, is 567826 kW/m^2.

The parameters considered for the analysis are Jet diameters (d) of 0.254mm, 0.381mm, 0.762mm and 1.524mm with jet velocities 15.24 m/s, 30.48 m/s and 61.96 m/s (Reynolds number variation) and non-dimensional jet-to-target spacing (H/d) from 1 to 4. The jet considered for the analysis is axisymmetric, normally impinging, confined and submerged.

RESULTS AND DISCUSSION

Some detailed results are given for the nominal case of water impinged cooled skin. Detailed results shows the structure of the temperature & flow field in the vicinity of the localized thermal load, improve understanding of the maximum skin temperature results.

The simulations for a constant jet diameter with variation in jet velocity are presented in fig.5. The results plotted are of temperature contour, velocity vector & streamline for the better view of flow & temperature distribution. The lower maximum temperature obtained is 1009°K for 61.96m/s and higher maximum temperature is 1222°K for 15.24 m/s. The decrease in maximum temperature is due to increased in heat transfer rate as it is proportional to Nusselt number, which in turn proportional to Reynolds number.

The CFD simulations for a constant Reynolds number (constant jet velocity) with variation in jet diameter are presented in fig.6. The decrease in jet diameter results in decrease in Maximum temperature attained for skin. The expected factor is due to localized concentration of jet at heat source.

It has been shown that the jet-to-target spacing has little change in maximum temperature for $H/d < 4$. The relative consistency of heat transfer for $H/d < 4$ in the above studies can be explained by the jet impingement taking place within the potential core with its nearly uniform velocity, while the decrease in heat transfer at higher H/d values is attributed to complete degradation of the potential core prior to impingement.

CONCLUDING REMARKS

A computational study of the impingement convective cooling of locally heated skins has been performed to evaluate the capability of impingement convective cooling. Uniform coolant and skin properties have been assumed in all the analyses. As a study case, a localized thermal load representative of shock-shock interaction heating of an engine cowl leading edge has been assumed. The effects due to model curvature and channel sidewalls have been ignored. Detailed thermal results are given for a single jet of water at the nominal analysis conditions. Detailed thermal results are given for a water coolant at parametric analysis conditions. With a 1400°K temperature limit for a copper-alloy, cowl leading edge, it appears that impingent convective cooling with single jet of 1% turbulence yields near-feasible temperatures for some values of coolant velocity in the ranges investigated.

From the analysis performed it has been shown that, for a constant jet diameter, heat transfer increases with increasing Reynolds number, increase in jet velocity, results in lowered skin temperature. It has also been shown that, for a constant Reynolds number, decreasing the jet diameter yields higher in Maximum temperature attained for skin. It has also been shown that the jet-to-target spacing has little change in maximum temperature for H/d < 4. The relative consistency of heat transfer for H/d < 4 in the above studies can be explained by the jet impingement taking place within the potential core with its nearly uniform velocity, while the decrease in heat transfer at higher H/d values is attributed to complete degradation of the potential core prior to impingement.

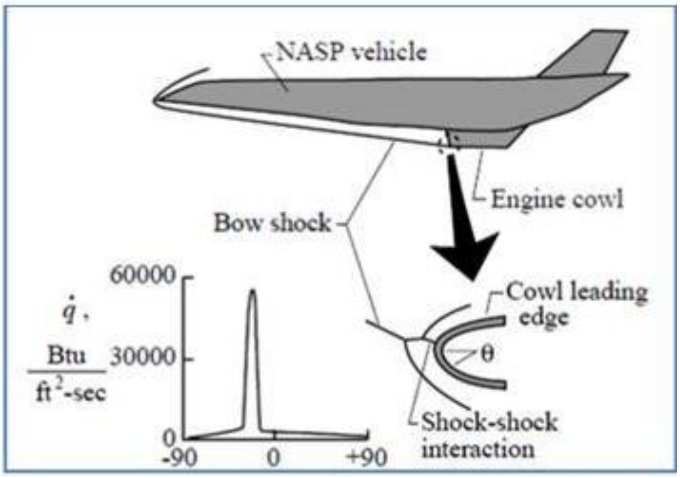

Figure 1. Schematic of a NASP vehicle and the heat flux distribution on engine cowl leading edge.

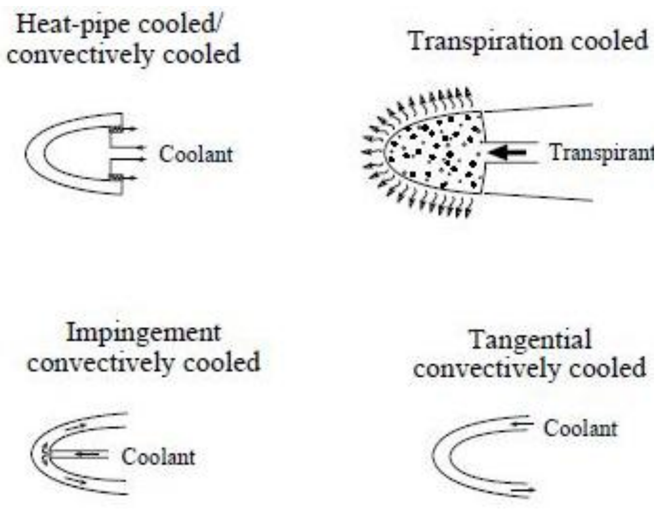

Figure 2. Several cooling concepts for a cowl leading edge.

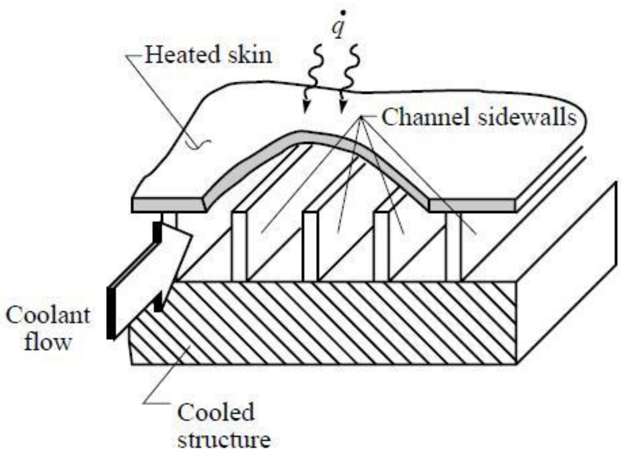

Figure 3. Channel flow geometry for tangential convective cooling.

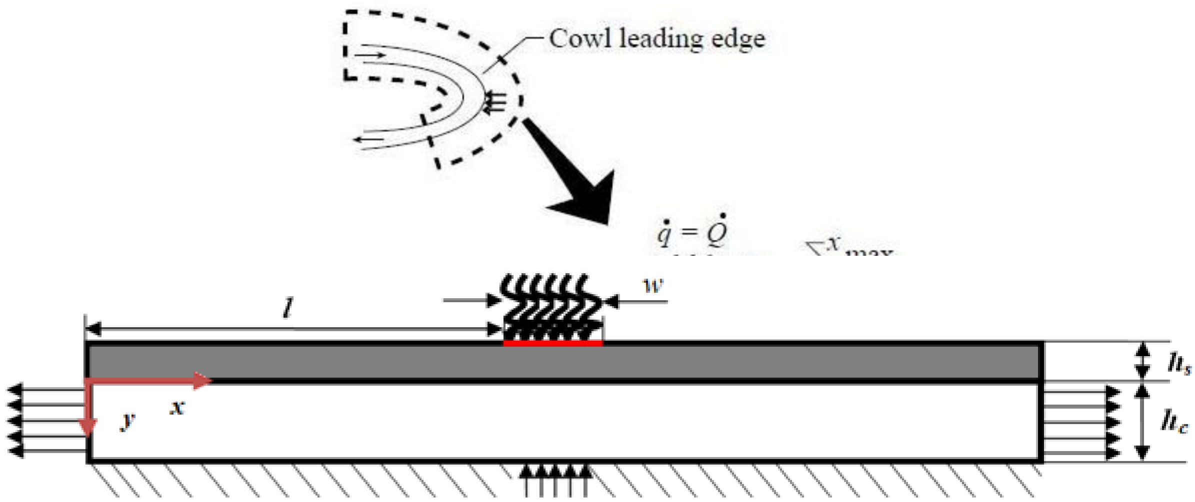

Figure 4. Schematic of geometry for convective cooling problem.

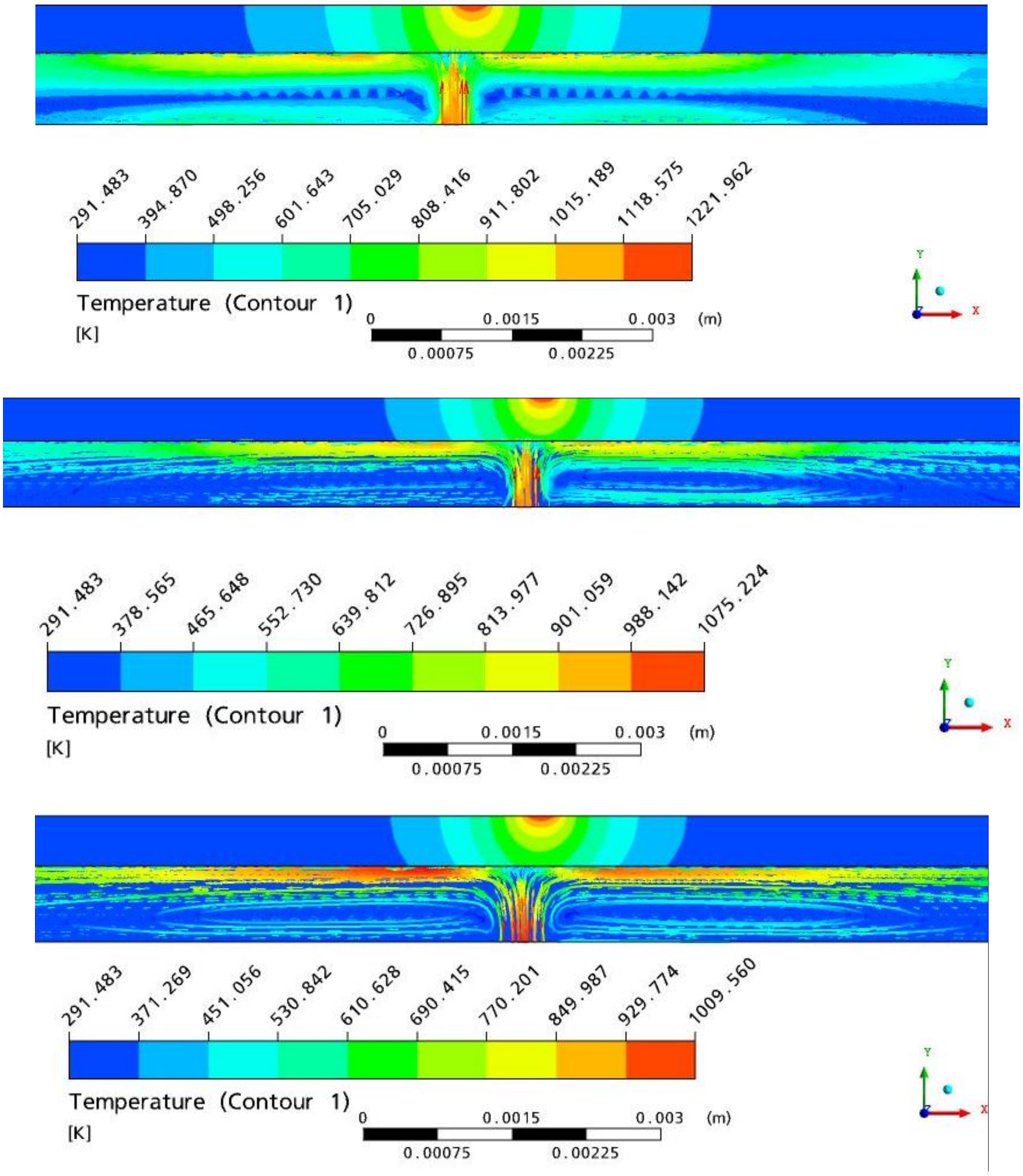

Figure 5. Temperature contours in skin and coolant flow near localized thermal load for 15.24 m/s, 30.48 m/s and 61.96 m/s for a constant jet diameter.

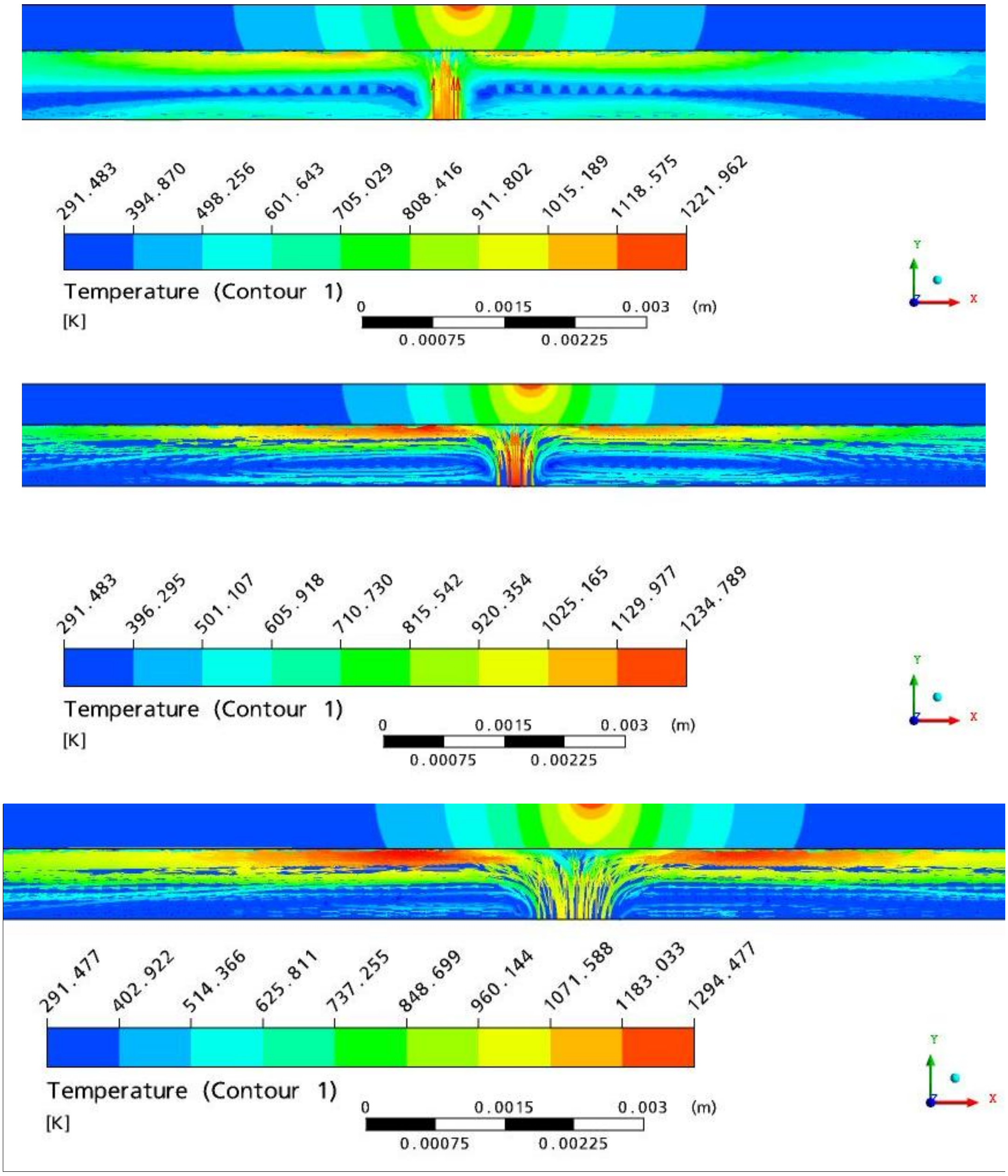

Figure 6. Temperature contours in skin and coolant flow near localized thermal load for Jet diameters (d) of 0.254mm, 0.381mm, 0.762mm for a constant jet velocity 15.24 m/s.

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