

A SURVEY OF NUSSELT NUMBER CORRELATIONS FOR AIRCRAFT THERMAL ANTI-ICING DESIGN

Rosiane Cristina de Lima, rosiane@ita.br
João Batista do Porto Neves Júnior, portojr@ita.br
Edson Luiz Zaparoli, zaparoli@ita.br
Cláudia Regina Andrade, claudia@ita.br
Instituto Tecnológico de Aeronáutica, Departamento de Engenharia Aeronáutica e Mecânica, Área de Aerodinâmica, Propulsão e Energia – Grupo de Simulação de Escoamento e Transferência de Calor – Praça Marechal Eduardo Gomes, 50, Vila das Acácias, CEP 12228-900, São José dos Campos, SP.

Abstract. *Impingement jets have been widely used in several engineering applications to heat and/or cool surfaces. Some practical examples include: paper drying, cooling of electrical equipments, tempering and shaping of glass, annealing of metal and plastic sheets, cooling of high-temperature gas turbine blades. In aviation, impingement jets are used in anti-icing systems on leading edge of aircraft wing. Such anti-icing systems use hot air educed from the motor compressor (bleed air). In this work, the important parameters to build a correlation that represents the compressible flow with heat transfer in internal concave curved surfaces of the aircraft wing leading edge were identified using a dimensional analysis. In the literature survey were found many correlations used to evaluate the heat transfer rate of impingement jet flow in aircraft thermal anti-icing systems, thereby the correlations proposed in the revised works were developed for heat transfer problems geometrically not similar to the anti-icing system and only one carried on the compressibility effect (Mach number).*

Keywords*: anti-icing system, impingement jet, curved surface, Nusselt number, CFD.*

1. INTRODUCTION

Aircraft anti-icing systems are important to guarantee the crew and passengers safety during flight under adverse icing forming weather conditions. Thermal anti-icing methods are used to prevent or minimize the ice buildup on airplane critical surfaces, which alter the aerodynamic performance and impairing the aircraft flight safety. There are regulations that define the required performance level of anti-icing systems used in large civil jet aircraft. These regulations are contained in Federal Aviation Regulations (FAR) and Joint Airworthiness Requirements (JAR). According to Brown et al. (2002) one of the biggest challenges of the aerospace industry is to design a cost-effective anti-icing system that attends these requirements.

There are several types of anti-icing systems, as: electrical, freezing point depressant fluids, surface deformation (inflatable boots), vibration mechanism and hot bleed air. In this last system, it is used compressed air extracted from the propulsion turbine motor (bleed air) to heat the aircraft wing leading edge, (Fig. 1 esquematically represents this system). Thermal anti-icing is accomplished by flowing through a spanwise duct in the wing leading edge. Air leakages through a row of small holes (“piccolo tube”) and impinges in the inner surface of the wing leading edge.

The energy source available as compressed hot (bleed) air and high and controlled heat flux are some factors that contribute with the usage of impingement jets in thermal icing protection systems. So, it is necessary to evaluate the convection coefficient to calculate the necessary heat transfer rate to avoid the ice buildup in the wing outside surface. In the thermal system design is important to obtain the convection coefficient, but when this is not impossible, an average Nusselt number provided by numerical or experimental correlations can be used.

In the literature there are many works concerning heat transfer correlations for impingement jets in flat plates, concave or convex surfaces. However, the heat transfer correlations specifically applied to a “piccolo” tube anti-icing system was not found in the literature surveyed. Besides, there is not a unique correlation that takes account all the parameters that affect the heat transfer problem. The main dimensionless parameters that often appear in the correlations are: Mach number, Reynolds number, Prandtl number, impinging surface distance-to-jet diameter ratio (H/d) and jet spacing-to-diameter ratio (W/d).

A difficulty in the usage of impingement jet to heat and/or cool is the inequality of the heat flux distribution; crossflow and adjacent jet interaction that cause variations in the heat transfer mechanisms, complicating the determination of the local heat transfer coefficient.

A literature search was performed by Wright (2004) which yielded several candidate correlations that could be applicable to “piccolo” tube anti-icing. His work showed that some correlations overpredict surface temperature, which resulted in different ice residual patterns from the experimental shapes. However, the author didn’t analyze what the parameters set must be taken account to evaluate accurately the convective heat transfer coefficient. Besides, the different experimental setup features used to develop the heat transfer correlations analyzed aren’t rightly considered.

Goldstein and Timmers (1982) utilized a visualization technique (liquid crystal) to measure the heat transfer coefficient distribution on a flat plate on which three different jets arrays were used: a single jet, array of 3 co-linear jets and an array of 7 jets. They used experimental setup with H/d=2 and 6. A minimum local Nusselt number was observed near the impingement center for small jet-to-wall spacing (H/d) when a single impingement jet arrangement is used. They encountered higher heat transfer coefficients with larger jet-to-plate spacing. Cornaro et al (1999) also presented flow visualizations of a round single impingement jet on flat plate and on convex and concave cylindrical surfaces. According to authors the jet-to-surface spacing also strongly influences the flow dynamic of jet impinging on a concave surface. However, these above last two works didn't present correlations for the Nusselt number.

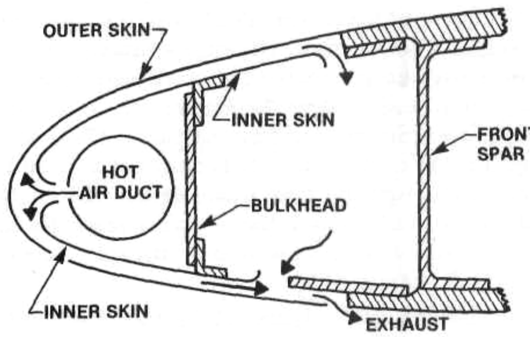


Figure 1 - Thermal anti-icing system using hot bleed air in the leading edge of the wing (Garret, 1991).

Goldstein and Behbahani (1982) experimentally studied a circular jet varying the jet-to-plate spacing with and without cross flow. They concluded that for jets impinging normally to the surface, for H/d=12 the maximum Nusselt number decreases when cross flow increases and for H/d=6 it increases with moderate cross flow (for Mach number > 9). The peak Nusselt number moves downstream as the blowing rate decreases at both spacing.

Goldstein et al (1986) developed an experimental study to determine the recovery factor and the local heat transfer coefficient to an impinging circular air jet for the following nozzle-to-impingement plate spacing H/d=6, 8 and 12. The maximum stagnation Nusselt number occurs at about H/d=8. According to the authors the heat transfer is best correlated by $Nu/Re^{0.76}$ for any H/d. The Nusselt number has a maximum point at r/d~2 (radial distance to jet diameter ratio) and for jet-to-plate spacing up to H/d=5.

Gau and Chung (1991) studying the surface curvature effect on slot-air-jet on concave cylindrical surface concluded that the local Nusselt number increases with surface curvature. They compared their small curvature results with the published results for jet impinging on a flat plate and they obtained good agreement.

Tawfek (2002) studied the effects of jet inclination in the local heat transfer under an obliquely impinging round air jet on isothermal convex circular cylinder. They concluded that higher jet inclination causes increasing asymmetry around the point of maximum heat transfer; besides the heat transfer coefficient drops more rapidly upstream of the jet stagnation point than the downstream.

Brown et al. (2002) experimentally studied the convective heat transfer in the gas turbine inlet lip anti-icing system. In this study they used the smallest hole diameter sufficient to pass the required mass flow aiming to optimize the heat transfer. According to authors this will not only result in increased heat transfer, due to the effect from hole diameter, but will also ensure that a reduction in heat transfer performance for a H/d greater than 5 will not occur. They analyzed the parameters included in several correlations and concluded that the usage of a Reynolds number for the flow that is based solely on hole diameter and does not take into account the area of the impingement surface will not lead to a single correlation relating heat transfer. However these authors didn't present a correlation based on their results.

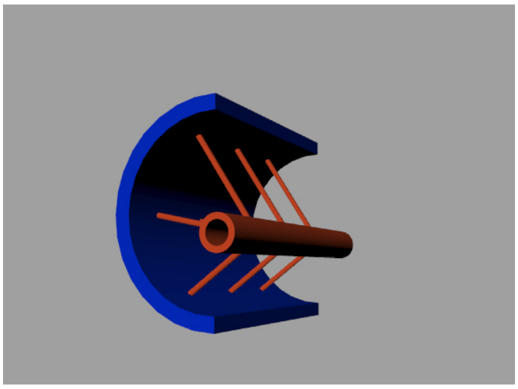
All above cited works experimentally investigated the impingement jet problem. Recently, Fregeau et al (2005) present a numerical study about a generic single array of round hot-air jets impinging on a concave circular surface. They compared their numerical results for flat plate impinging surface with experimental results and obtained a good agreement. Correlations were presented for average Nusselt number as function of the Reynolds number and maximum Nusselt number variation with Mach number.

In the following sections of this work, it will be done a dimensional analysis of the round impingement jet on concave cylindrical surface which will be used to review some Nusselt number correlations proposed to aircraft anti-icing system design.

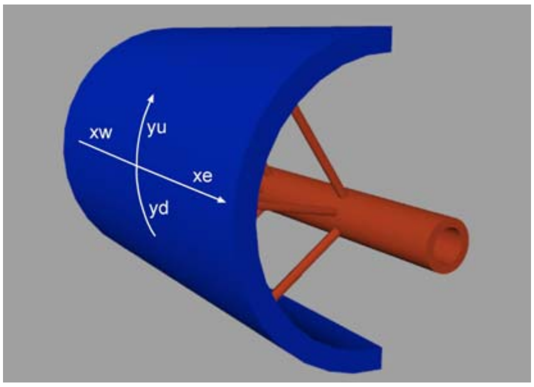
2. PROBLEM ANALYSIS

In the thermal anti-icing system, the compressed hot air extracted from the propulsion bleed air system impinges in the aircraft wing leading edge inner surface to prevent or minimize the ice build up on airplane critical surfaces, Fig. 1. Air leakages through a row of small holes ("piccolo tube") and impinges in the inner surface of the wing leading edge.

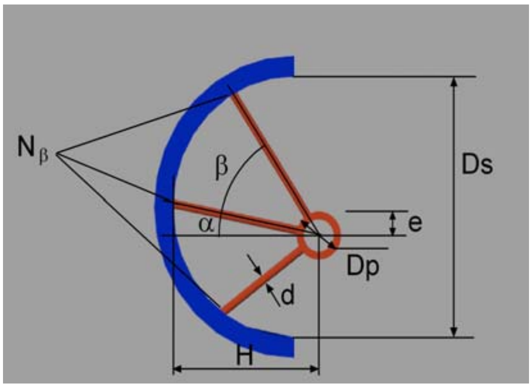
The wing leading edge near stagnation point can be suitably represented by a circular surface. Figure 2 shows the sketch of the thermal anti-icing protection: a) three array of jets emerging from the “piccolo” tube - represented by red circular rods; b) coordinate system over the circular surface; c) and d) geometrical parameters that influences the heat transfer coefficient in the impingement jet on inner surface of aircraft wing leading edge.



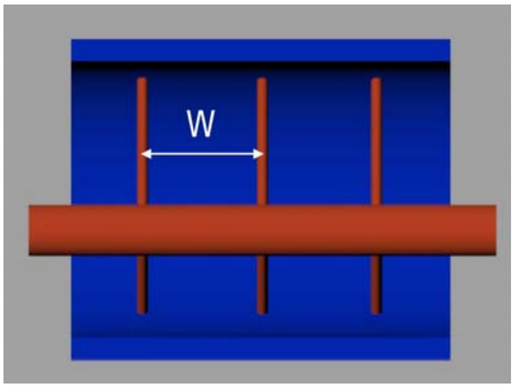
a) Inner surface of the leading edge, “piccolo” tube with array of holes.



b) Outer surface of the leading edge, “piccolo” tube with array of holes.



c) Geometrical parameters involved in the impingent jet study.



d) Inner surface of the leading edge, “piccolo” tube and hole-to-hole spanwise distance (W).

Figure 2 – Geometrical parameters of impingement jet in a curved surface.

Some non-dimensional parameters also influences in the accurate prediction of the heat transfer coefficients, as: Reynolds, Mach, Prandtl and Eckert numbers.

According to a dimensional analysis, the parameters for a full Nusselt number correlation were found, Eq. (1), which carry on all effects on impingement jet flow. Table 1 presents the parameters that affect the convection coefficient of impingement jet flow.

$$Nu = \frac{h\,l}{k} = f\left(\text{arrangement}, \frac{x}{l}, \frac{y}{l}, \alpha, \beta, \gamma, N_\beta, \frac{W}{l}, \frac{D_S}{l}, \frac{D_p}{l}, \frac{H}{l}, \frac{e}{l}, Re, Ma, \frac{P_{jet}}{P_{atm}}, Pr, Ec, bc, S\right) \quad (1)$$

In the revised literature, a lot of researches analyzed the heat transfer in impingement jet flow considering simplified phenomena as: incompressible single round jet impinging on flat plate, but none presents relationship that includes all the parameters cited in Eq. (1) and described in Tab. 1 necessary to do accurate anti-icing design.

However, due to complexity of this flow, it is generally accepted that the prediction of the heat transfer in anti-icing systems be done by the usage of correlations developed for simplified phenomena, although these predictions can be not so accurate, (Wright, 2004).

Hole arrangements which is one of the parameters considered in above Nusselt number correlation is related with the hole relative positions in the “piccolo” tube. The encountered arrangement types were: single jet, single row, two rows (two arrays), three rows (three lines of holes, see Fig. 2) and staggered rows. Some researchers have dedicated its studies to a fixed arrangement, focusing at the hole-to-impingement wall distance (H) and hole-to-hole spanwise distance (W), Fregeau et al (2003); Tawfek (2002); Huber and Viskanta (1994); Godstein and Timmers (1982); Goldstein and Behbahani (1982).

Table 1 - Parameters that affect the convection coefficient of impingement jet flow.

arrangement:	holes relative position: single one; array of holes; staggered rows;	P_{jet}/P_{atm}	jet exit to atmospheric pressure ratio;
bc:	boundary condition on impingement wall;	$Pr=\mu cp/k$	Prandtl number;
c:	sound velocity;	$Re=\rho Vl/\mu$	Reynolds number;
c_p:	air specific heat;	S:	= cx (for convex impingement surface);
D_p:	“piccolo” tube diameter;		= cv (for concave impingement surface);
D_S:	impingement surface diameter;		= ∞ (for flat plate impingement surface);
e:	“piccolo” tube eccentricity;	V:	jet velocity at exit of the “piccolo” tube;
$Ec=V^2/cp\Delta T$	Eckert number;	x:	spanwise coordinate;
H:	hole-to-impingement wall distance;	y:	wrap (chordwise) coordinate;
h:	convective heat transfer coefficient;	W:	hole-to-hole spanwise distance;
k:	air thermal conductivity;	α:	angle between jet row and an horizontal plane;
l:	= d, hole diameter (for round circular jet);	β:	angle between two successive jet rows;
	= w, slot width (for slot jet);	γ:	impingement jet angle;
$Ma=V/c$	Mach number;	μ:	air viscosity;
N_β:	number of jet rows;	ρ:	air density;
$Nu=hl/k$	Nusselt number;	ΔT:	temperature difference based on boundary conditions;

The parameter Pjet/Patm is important only for supersonic gas flow (Ma > 1), as the revised literature correlations are suitable for incompressible and subsonic compressible flow, then it isn’t appear any analyzed correlation.

3. ASSESSMENT OF THE NUSSELT NUMBER CORRELATIONS

In this section it will be presented an assessment of the convection coefficient correlations derived from experimental and numerical setups based on Eq. (1) and Tab. 1. Table 2 shows in first four columns information about Nusselt number type (average, maximum and stagnation), jet hole arrangements (inline array, staggered array, slot and single oblique nozzle), the kind of impingement surface (flat plate, concave and convex circular surface) and thermal boundary conditions (prescribed temperature or heat flux). The other columns identify if the catalogued correlations carrying on the effects of following parameters: Dp/l, Ds/l, e/l, H/l, x/l, y/l, W/l, α, β, γ (impingement angle), Ma, Nβ, P_{jet}/P_{atm}, Pr and Re.

Some correlation parameters as impingement surface area and thermal boundary conditions weren’t clearly defined in the surveyed papers, because the correlations had not been gotten from the original research of them.

To design an anti-icing system it is necessary to define a local Nusselt number correlation for a compressible air flow (carrying on Mach number effects). However, the revised literature correlations foresaw average, maximum or stagnation Nusselt numbers. Solely the correlation proposed by Fregeau et al (2003, 2005) considered the Mach effects, the remaining ones are suitable for incompressible air flows.

The majority of the proposed correlations depends on Reynolds number and H/l ratio (jet-to-impingement surface distance)/(jet diameter or slot width). Some parameters had not been considered by any of the authors, as: Dp/l, e/l, α and β.

Table 2 – Nusselt number correlations.

Authors	Nu	Arrangement (array)	S	bc	Dp/l	Ds/l	e/l	H/l
Behbahani and Goldstein (1982)	Ave	staggered						X
Florshuetz et al, 1981	Ave	inline/ staggered						X
Fregeau et al, 2005	Ave	inline	cv			X		X
	Max		cv					X
Gau and Chung, 1991	Ave	slot	(cv,cx)	Flux		X		X
	Stag		cv					
Goldstein and Behbahani, 1982	Ave	inline		Flux				
Goldstein and Seol, 1991	Ave	inline	∞					X
Goldstein et al, 1986	Ave	inline		Flux				X
Hrycak, 1981	Stag	inline	∞					X
			(cv)			X		
Huang and El-Genk, 1994	Ave	inline	∞					X
Huber and Viskanta, 1994	Ave	inline	∞					X
Martin, 1992	Ave	inline	∞					X
Tawfek, 1996	Ave	inline	∞					X
Tawfek, 2002	Max	single oblique nozzle				X		X
	Stag		cx					

Table 2 – Nusselt number correlations (continued).

Authors	x/l	y/l	W/l	α	β	γ (imp. ang.)	Ma	N_β	P_{jet}/P_{atm}	Pr	Re
Behbahani and Goldstein (1982)								X			X
Florshuetz et al, 1981										X	X
Fregeau et al, 2005			X								X
			X				X				
Gau and Chung, 1991											X
Goldstein and Behbahani, 1982	X										X
Goldstein and Seol, 1991		X									X
Goldstein et al, 1986											X
Hrycak, 1981										X	X
Huang and El-Genk, 1994										X	X
Huber and Viskanta, 1994										X	X
Martin, 1992			X								X
Tawfek, 1996			X							X	X
Tawfek, 2002						X					X

4. EXAMPLES OF NUSSELT NUMBER CORRELATIONS

This section aims to present a support to the user involved in design of thermal equipment which utilizes the jet impingement heat transfer. Thus, correlations proposed by the revised authors who are cited in Tab. 2 are below presented. The validity range (when available) is also shown.

Behbahani and Goldstein (1982) – In this work the authors presented an average Nusselt number correlation studying staggered jet arrays. It has not been encountered the validation range, Eq. (2).

$\overline{Nu} = 0.0954(4J / N_{\beta}\pi\mu d)^{0.78}(H/d)^{-0.7}$	no information	(2)

where, J is the jet mass flow rate.

Florshuetz et al (1981) – The authors compared the spanwise effects in staggered jet arrays versus inline arrays with crossflow. An average Nusselt number correlation was presented as function of the Prandtl and Reynolds numbers, hole-to-impingement wall distance and ratio between the crossflow and jet mass flux, Eq. (3).

$\overline{Nu} = C\,Pr^{1/3}\,Re^{m}\left[1 - B\left[\frac{H}{d}\frac{G_c}{G_j}\right]\right]$	$2{,}500 \le Re \le 70{,}000$ $5 \le L/d \le 1.5$ (inline) ; $5 \le L/d \le 10$ (staggered) $4 \le W/d \le 8$; $1 \le H/d \le 3$ C, m and B are constants	(3)

where:
L = chordwise distance between holes.
G_j = mass flux of the jet.
G_c = mass flux of the crossflow.

Fregeau et al (2005) – According to authors for a generic single array of round hot-air jets impinging on a curved surface a local Nusselt number correlation can be expressed as function jet Mach number, hole-to-impingement wall distance and hole-to-hole spanwise distance, but they not presented the equation of this correlation. In this study the authors numerically analyzed the influence of some parameters in jets impinging on concave surfaces and presented average and maximum Nusselt number correlations, Eq. (4).

$\overline{Nu} = 10^{-10}\,Re_G^{\,1.1131}$ $Nu_{max} = 0.282Ma^{0.49}(H/d)^{-1.69}(W/d)^{-0.856}\exp\left[9.14(H/d)^{0.034}(W/d)^{0.074}\right] - 3$	$M_{jet} = 0.4, 0.6, 0.8$; $H/d = 5, 10, 15$; $W/d = 7.5, 15, 22.5$; $Re_G = (G/d\mu)HW$ $G = \dot{m}/Z$ $Z = (HW)\left(\frac{\pi}{2}\right)\left(\frac{H}{d}\right)\left(\frac{W}{d}\right)^{3/2}$	(4)

where $\dot{m}$ is the mass flow rate of air.

Gau and Chung (1991) – In this work the authors shown that a local Nusselt number should be expressed as function of Reynolds and Prandtl numbers, circumferential distance from the stagnation point, slot-to-impingement surface spacing and diameter of the curved surface, but they not exposed the correlation expression. They presented different correlations for average Nusselt number to concave and convex surface and with variations of the slot-to-impingement surface distance. The correlations of the stagnation point Nusselt number presented are only to jet impinging on convex surfaces. Equation (5) also shows the validation range of this study.

Concave surface $\overline{Nu} = 0.251Re^{0.68}\left(\frac{D_S}{w}\right)^{-0.38}\left(\frac{H}{w}\right)^{0.15}$	$2 \le H/w \le 8$	$6{,}000 \le Re \le 35{,}000$ $8 \le D_S/w \le 45.7$	(5)
$\overline{Nu} = 0.394Re^{0.68}\left(\frac{D_S}{w}\right)^{-0.38}\left(\frac{H}{w}\right)^{-0.32}$	$8 \le H/w \le 16$		

Convex surface $\overline{Nu} = 0.221\,Re^{0.65}\left(\frac{D_v}{w}\right)^{-0.33}\left(\frac{H}{w}\right)^{0.1}$	$2 \le H/w \le 8$		
$\overline{Nu} = 0.308\,Re^{0.65}\left(\frac{D_v}{w}\right)^{-0.38}\left(\frac{H}{w}\right)^{0.2}$	$8 \le H/w \le 16$		
Convex surface $Nu_o = 0.729\,Re^{0.5}\left(\frac{D_v}{w}\right)^{-0.14}\left(\frac{H}{w}\right)^{0.16}$	$2 \le H/w \le 8$		
$Nu_o = 1.76\,Re^{0.54}\left(\frac{D_v}{w}\right)^{-0.15}\left(\frac{H}{w}\right)^{-0.38}$	$8 \le H/w \le 16$		

Goldstein and Behbahani (1982) - In this work was studied an impingement circular jet with and without cross flow varying the jet-to-impingement wall distance. The authors presented an average Nusselt number correlation as function of the jet Reynolds number in the absence of cross flow, Eq. (6).

$\frac{\overline{Nu}}{Re_j^{0.6}} = \frac{1}{A + B(x/d)^n}$	$A = 3.329; B = 0.273; n = 1.3 \rightarrow W/d = 6$ $A = 4.577; B = 0.4357; n = 1.14 \rightarrow W/d = 12$ $33{,}400 \le Re_j \le 121{,}300$	(6)

Goldstein and Seol (1991) – A row of circular air jets impinging on curved surface and effects of entrainment on heat transfer that can occur near the leading edge were studied by the authors. Thus, an average Nusselt number correlation was presented considering some important parameters as shown by Eq. (7).

$\overline{Nu} = \frac{2.9\,Re^{0.7}\exp\left(-0.09\left(\frac{y}{d}\right)^{1.4}\right)}{22.8 + \left(\frac{W}{d}\right)\left(\frac{H}{d}\right)^{0.5}}$	$10{,}000 \le Re \le 40{,}000$ $2 \le H/d \le 8;\ 4 \le W/d \le 8;\ 0 \le y/d \le 6$	(7)

Goldstein et al (1986) – They studied a circular air jet impinging on flat plate and presented an average Nusselt number correlation based upon the assumption of constant temperature difference and taking account the distance to the jet stagnation point, as shown by Eq. (8). According to authors with this correlation it is possible to evaluate the local Nusselt number as the average values between two successive radial distances.

$\overline{Nu} = Re^{0.76}\,\frac{24 - \left\|\left(\frac{H}{d} - 7.75\right)\right\|}{533 + 44\left(\frac{r}{d}\right)^{1.285}}$	$61{,}000 \le Re \le 124{,}000$ $0.5 \le r/d \le 32;\ 6 \le H/d \le 12$ $r = \sqrt{x^2 + y^2}$	(8)

Hrycak (1981) – A row of jets impinging on flat and concave cylindrical surface were studied and stagnation Nusselt number was reported as function of non-dimensional Prandtl and Reynolds numbers, Eq. (9).

Flat Plate $Nu_o = 0.763\,Pr^{0.39}\,Re^{0.5}\left(\frac{H}{d}\right)^{0.16}$	$14{,}000 \le Re \le 67{,}000$ $1.5 \le H/d \le 7\quad D_S = 127\,mm$	(9)
Semi-Cylinder (Concave) $Nu_o = 1.85\,Pr^{1/3}\,Re^{0.695}\left(\frac{d}{D_S}\right)^{1.05}$		

Huang and El-Genk (1994) – Experimental study on impinging jet on a flat surface was performed and an average Nusselt number correlation for a circular region with **r** radius, Eq. (10).

$\overline{Nu} = Re^{0.76}\, Pr^{0.42}\left[a + b\left(\frac{H}{d}\right) + c\left(\frac{H}{d}\right)^2\right]$	$a = 10^{-4}\left[506 + 13.3\left(\frac{r}{d}\right) - 19.6\left(\frac{r}{d}\right)^2 + 2.41\left(\frac{r}{d}\right)^3 - 0.0904\left(\frac{r}{d}\right)^4\right]$ $b = 10^{-4}\left[32 + 24.3\left(\frac{r}{d}\right) - 6.53\left(\frac{r}{d}\right)^2 + 0.694\left(\frac{r}{d}\right)^3 - 0.0257\left(\frac{r}{d}\right)^4\right]$ $c = -3.85*10^{-4}\left[1.147 + \left(\frac{r}{d}\right)\right]^{-0.0904}$ $6{,}000 \le Re \le 60{,}000$; $0 \le r/d \le 10$; $1 \le H/d \le 12$ $r = \sqrt{x^2 + y^2}$	(10)

Huber and Viskanta (1994) – The authors studied effects of jet-to-jet spacing (W/d) and nozzle-plate distance (H/d) in confined 3x3 square arrays of round jets impinging on flat surfaces, Eq. (11).

$\overline{Nu} = 0.285\, Re^{0.71}\, Pr^{1/3}\left(\frac{H}{d}\right)^{-0.123}\left(\frac{W}{d}\right)^{-0.725}$	$3{,}400 \le Re \le 20{,}500$ $0.25 \le H/d \le 6$; $4 \le W/d \le 8$	(11)

Martin (1992) – Equation (12) presents an average Nusselt number correlation as function of the nozzle-to-nozzle spacing, nozzle-to-impingement surface distance and Reynolds number. This correlation was obtained by the study of square and triangular arrays of round nozzles impinging on flat plate.

$\overline{Nu} = \left[1 + \left(\frac{H/d}{0.6/\sqrt{A}}\right)^6\right]^{-0.05} \sqrt{A}\, \frac{1 - 2.2\sqrt{A}}{1 + 0.2(H/d - 6)\sqrt{A}}\, Re^{2/3}$	$A = \frac{\pi}{4}\left(\frac{d}{W}\right)^2$; $2{,}000 \le Re \le 100{,}000$ $0.004 \le A \le 0.04$; $2 \le H/d \le 12$	(12)

Tawfek (1996, 2002) – Studied heat transfer in round jets impinging on solid surfaces: normal on flat plate and oblique on convex surface. Equation (13) presents an average Nusselt number correlation on flat surface. The stagnation and maximum Nusselt number correlations (Eq. 14) for inclined impingement jet on cylindrical convex surface considering the γ angle effect.

$\overline{Nu} = 0.453\, Pr^{1/3}\, Re^{0.691}\left(\frac{H}{d}\right)^{-0.22}\left(\frac{W}{d}\right)^{-0.38}$	$3{,}400 \le Re \le 41{,}000$ $6 \le H/d \le 58$; $2 \le W/d \le 30$	(13)

$Nu_0 = 0.16\, Re^{0.71}\left(\frac{H}{d}\right)^{-0.14}\left(\frac{d}{D_S}\right)^{-0.35}$ $Nu_{max} = 0.142\, Re^{0.71}\, \gamma^{0.194}\left(\frac{H}{d}\right)^{-0.14}\left(\frac{d}{D_S}\right)^{-0.35}$	$\frac{y_{max}}{d} = Re^{0.611}\left(\frac{H}{d}\right)^{-0.14}\left[0.005 - 0.0016\gamma - 0.0012\gamma^2\right]$ $3{,}800 \le Re \le 40{,}000$ $20^\circ \le \gamma \le 90^\circ$; $7 \le H/d \le 30$; $0.06 \le d/D_S \le 0.14$	(14)

5. FINAL COMMENTS

In order to support the design of an aircraft thermal anti-icing system an assessment of available Nusselt number correlations was done. To design this system it is necessary to evaluate the local heat transfer coefficient on compressible impingement jets on concave curved surfaces. A functional relation like Eq. (1) should be used to carry on all parameters that influence the heat transfer in impingement jets on inner surface of the aircraft wing leading edge.

Solely the correlations proposed by Fregeau et al (2003, 2005) considered the Reynolds and Mach number effects on concave cylindrical surface (compressible flow). The others correlations were obtained using experimental results for incompressible flow. Furthermore, the remaining majority are suitable to evaluate heat transfer coefficients for impingement jet on flat surfaces. Those correlations have been used to design the aircraft thermal anti-icing, but their results for heat transfer rate may not have the desired accuracy.

6. ACKNOWLEDGMENTS

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