The Impingement Flow Study on the Temperature Profile Perforated Plate

BY:
WONG WEI CONG

Supervisor:
Dr. Mohd Azmi bin Ismail

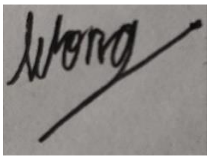
Jun 2021

This dissertation is submitted to
Universiti Sains Malaysia
As partial fulfillment of the requirement to graduate with honors degree in
BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering
Engineering Campus
Universiti Sains Malaysia

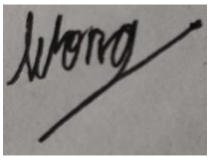
DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed……..………………………………………. (Wong Wei Cong)
Date…………09/07/2021……………………………………………………….

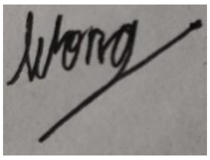
Statement 1:

This journal is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/ references are appended.

Signed…………………………………………… (Wong Wei Cong)
Date…………09/07/2021……………………………………………………….

Statement 2:

I hereby give consent for my journal, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available outside organizations.

Signed…………  ………………………………. (Wong Wei Cong)
Date…………09/07/2021……………………………………………………….

ACKNOWLEDGEMENT

The completion of this paper could not be possible without the support and the assistances of so many people. First and foremost, I would like to express my sincere gratitude to my supervisor, Dr. Mohd Azmi bin Ismail for giving me opportunities to do this research and providing his unvaluable guidance throughout the research. He has taught me the methodology to carry out the simulation and always ready to answer my question which help me a lot in completing this paper. I am also grateful for his consideration throughout the Covid-19 pandemic.

I would also like to thank my friends. Their suggestion helps me solve the problems especially the area I not familiar with. They also willing to helps and give supports to me when I faced problems.

I am also grateful to my family who support me morally. Their encouragement, understanding, and love play an important role in helping me completing this research.

Last but not least, I would like to thank to all people who directly or indirectly helping me in completing this research.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

A	Surface area of aluminum plate (m^2)
C_P	Specific heat capacity at constant pressure (J /K kg)
D	Nozzle diameter (m)
h	Heat transfer coefficient (W/m^2 K)
H	Nozzle to plate distance
$\dot{m}$	Mass flow rate of fluid (kg/s)
Nu	Nusselt number
$\dot{Q}$	Heat transfer rate (W)
q	Heat flux (W/m^2)
Re	Reynolds number
r	Radial distance
ΔT	Change in Temperature
u	Velocity of fluid
μ	Viscosity of fluid (Ns/m^2)
ρ	Density of fluid (kg/m^3)
θ	Dimensionless Temperature

LIST OF APPENDICES

ABSTRAK

Sistem pendarah udara merupakan salah satu sistem perlindungan ais yang membekalkan udara berdarah dan memanaskan permukaan pesawat untuk mencegah ais terbentuk. Udara berdarah yang terangkap dalam bibir nasel pesawat akan menyebabkan suhu terlalu tinggi dan akan merosakkan Liner bias dalam bibir nasel pesawat. Oleh itu, profil suhu pada plat aluminium merupakan aspek yang sangat penting. Kertas ini menerangkan pengaruh nombor Reynolds dan susunan lubang pada plat kepada profil suhu pada plat aluminium. Component model yang terdiri daripada nozel , domain udara dan plat aluminium yang mempunyai pelbagai jenis susuan lubang telah direka bentuk dan jet panas akan menghentam ke permukaan plat melalui nozel. Suhu plat aluminium akan meningkat apabila nombor Reynolds meningkat. Apabila nombor Reynolds meningkat secara berterusan, kenaikan suhu tanpa dimensi akan meningkat dari 0.02 ke 0.04. Bagi kesan susunan lubang, susunan yang tiada lubang di tengah akan mempunyai suhu tanpa dimensi yang lebih tinggi berbanding dengan susunan yang mempunyai lubang di tengah semasa aliran angka Reynolds tinggi. Dari segi pola susunan lubang, suhu tanpa dimensi untuk 3cm susunan lubang tandem lebih tinggi berbanding dengan 4cm susuan lubang stagak semasa aliran angka Reynolds tinggi. Susunan lubang tandem tanpa lubang di tengah merupakan pilihan yang lebih baik untuk Liner bias kerana lapisan suhu tinggi yang lebih tebal akan terbentuk di permukaan luar dan susunan ini mempunyai suhu tanpa dimensi yang lebih tinggi.

ABSTRACT

Thermal anti-ice system is one type of anti-icing system that provided sufficient heat energy to cause the supercooled water that impinge on the aircraft surface to evaporate. The hotspot temperature profile on the perforated plate is concerned as the hot air temperature might destroy the Bias Acoustic Liner that applied on the nacelle lip, since Bias Acoustic Liner surface is fabricated by thin aluminium plate. In this paper, the effect of Reynolds number and the hole arrangement to the temperature distribution of the perforated plate are studied for a hot impingement jet. Geometrical models that consist of a nozzle inlet, air domain and different hole arrangement of perforated plate are created and 70°C hot air jet is impinged on the perforated plate through the nozzle inlet. It can be observed that the dimensionless temperature will be increased when the Reynolds number of the flow increased. The increment of the dimensionless temperature increased from 0.02 to 0.04 when the flow increased from low Reynolds number to high Reynolds number. For the effect of hole arrangement on the temperature distribution of perforated plate, the dimensionless temperature of hole arrangement without centre hole is 0.25 higher than the hole arrangement with centre hole under high Reynolds number flow. In terms of the pattern of hole arrangement, it has been shown that dimensionless temperature for the 3 cm tandem hole arrangement is 0.04 higher than the 4cm staggered hole arrangement under high Reynolds number flow. Tandem arrangement without centre hole is recommended for Bias acoustic Liner as a thicker high temperature layer will be developed at the outer surface and the dimensionless temperature for the plate is considerably high.

CHAPTER 1

INTRODUCTION

Icing is one of the most hazardous threats in aviation. The built up of ice on the aircraft will cause an unsafe flight condition. The formation of ice on wing and tails of the aircraft changes the shape of these parts which will significantly alter the aircraft flight characteristic. Ice may also break away ingested into engine which can damage the fan and the compressor blade of the aircraft.

Anti-Icing system is introduced to prevent the formation of ice. Thermal anti-ice system is one type of anti-icing system that provided sufficient heat energy to cause the supercooled water that impinge on the aircraft surface to evaporate.

1.1 Project Background

When an aircraft flies through clouds or precipitations, supercooled water droplets at temperature below freezing point, which is usually -20°C, comes in contact with the aircraft surface, and a portion of the water droplets are freeze into ice immediately. The formation of ice usually occurs at the frontal area of the aircraft, which is the leading edge of the wings and nacelle lip-skin.

Ice accretion on the aircraft surface has an adverse aerodynamic effect as ice reshapes the surface feature of those parts of the aircraft. The ice alters the shape of the aircraft which will disturb the air flow, and lead to lift loss. The formation of ice also increases the drag force and thrust must added to compensate for the reduced performance of the aircraft. Ice also decreases the stall angle of attack (AOA). Basically, the AOA of wing is increased to increase the lift force, at certain angle, the air does not flow over the upper surface due to the formation of ice, which results in aerodynamic stall.

Hence, anti-icing equipment is designed to prevent the formation of ice. The most common anti-icing system is use heat to prevent the accumulation of ice on the aircraft surface. The hot air is directed from the engine to the inner surface of the leading edges. Heat is transfer through conduction form the inner surface to the outer surface of leading edge. The heat from the hot air evaporates the liquid water when the liquid water in contact with the surface of the aircraft. However, if the heat provided is insufficient, the water droplets will not evaporate, and it will run back until it reached the unheated section of aircraft and freeze at that section.

Other than icing formation on aircraft, the noise generated by the engine of aircraft is becoming a major concern due to the strict noise control regulation. Hence, the noise reduction for aircraft engine becomes one of the important fields of research. A successful method of reducing noise is by using noise abatement system, for example acoustic liner. The Acoustic Liner consists of solid face sheet, honeycomb, and perforated back sheet. It is installed on the inner wall surface of the nacelle inlet section to absorb the radiated acoustic energy and to reduce the noise from engine and compressor.

A suggestion has been introduced by the researchers that the noise abatement is applied on the nacelle inlet lip surface to increase noise reduction from the engine. At the same time, the ice protection system is employed on the nacelle lip, by directing the hot engine bleed air from the engine to D-chamber. However, the solid face sheet of the acoustic liner behaves like an insulation barrier to conduct the necessary heat for anti-ice formation purpose. Hence, Bias Acoustic Liner is chosen for this paper. Different from Acoustic Liner, Bias Acoustic Liner have perforated face sheet instead of solid face sheet which make Bias Acoustic Liner have higher heat transfer rate compared to the Acoustic Liner. Bias Acoustic Liner is usually placed in the nacelle D-chamber to enable the hot air to exit to the ambient through Bias Acoustic Liner.

In the present study, the effect of impingement flow on the perforated plate temperature profile is investigated. The aim of proposed study is to understand the temperature distribution profile at different holes arrangements. Various Reynolds number impingement flows are also investigated in the present study.

1.2 Problem Statement

Anti-Icing System is used on aircraft to prevent the ice accretion on the surface. At the same time, the Bias Acoustic Liner need to be installed in the nacelle lip. The hotspot temperature of anti-icing might destroy Bias Acoustic Liner surface, since Bias Acoustic Liner is fabricated by thin aluminium plate. Thus, the hotspot temperature profile on the perforated plate needs to be studied. However, there are limited research on the hotspot temperature profile of the impingement hot air on the perforated plate at various holes arrangement. Therefore, the present work compared the hotspot temperature profile of impingement hot air flow on the perforated plate at different holes arrangements and Reynolds number.

1.3 Objectives

1. To study the impingement hot air flow on perforated plate using simulation.

2. To study effect of Reynolds number impingement flow to dimensionless temperature distribution on perforated plate.

3. To investigate the effect of holes arrangement (tandem and staggered) on the dimensionless temperature distribution of perforated plate in impingement flow study.

CHAPTER 2

LITERATURE REVIEW

2.1 Aircraft Anti-Icing System

Ice accretion on the aircraft surface happens because of the supercooled water droplets strike on the aircraft critical surface including wing and nacelle leading edge. A portion of supercooled water will freeze immediately and adhere to the surface or run back and refreeze downstream depends on the size and temperature of the supercooled water. The ice that forms on the aircraft can be divided into rime ice, glaze ice and mixed ice. Rime ice formed at temperature cooler than 10 ^{o}C and rime ice usually freeze instantly upon impact. Rime ice is the least dense and most brittle type of ice that can be removed easily. Glare ice is formed when the droplets are large and have relatively warm temperature. The supercooled liquid does not freeze upon impact and will run back on the surface and freeze. Glare ice with higher liquid water content have higher accretion rate and consider more serious when comparing with rime rice. Mixed ice is the ice that most often formed. Mixed ice possesses the characteristic of rime ice and glaze ice (Vukits, 2002).

The ice forms on the aircraft gives negative effect on the flying characteristic of the aircraft, as it alters the aerodynamic shape of the aircraft. This leads to the decrease in lift force and increase in drag force (Hassaani et al., 2020). The formation of icing on aircraft also may result in aerodynamic stall. Since the maximum coefficient of lift is significantly reduced by ice, the aircraft will stall at a lower angle of attack with the presence of ice. The formation of icing on wings of aircraft may affect roll control. Since the tips of the wing are usually thinning than the other parts of wing, more ice is formed at the tips of the wing which can lead to partial stall of the wings at the tips and affect the roll control (John Steuernagle, Kathleen Roy, 2008) .

Cao et al. (2020) study the effect of ice accretion on the longitudinal aerodynamic characteristics of an aircraft. An engineering prediction of the longitudinal aerodynamic derivatives established based on the individual component CFD calculation and narrow strip theory. Based on the flight test data, the longitudinal aerodynamic parameters of clean aircraft and icing aircraft is calculated. Based on their research, icing reduce the lift, increase drag and reduce elevator effectiveness of an aircraft. The main wing icing contributes a lot in the change of aircraft lift and drag characteristics under icing conditions.

Chengxue Liu et al. (2011) study the ice accretion effects at super large droplet conditions on aircraft aerodynamics using ANSYS fluent. Based on their studies, the lift coefficient loss is significant when the angle of attack is larger than 2^o. When the angle of attack reached 3^o, the lift coefficient remains unchanged for iced aircraft surface although the angle of attack increased.

Therefore, anti-icing system or de-icing system is used. Anti-icing system is used to avoid the formation of ice while de-icing system is used to break up the ice that formed on the aircraft.

The most common method of de-icing method is electro-thermal de-icing which develops heat in the transmission line. Huge amount of current is passed through the transmission line and heat is generated to melt off the ice (Verma et al., 2018). Other electro-thermal de-icing methods are the microwave de-icing system and laser de-icing system. Microwave de-icing system increase the temperature of the droplets so that they do not freeze on contact with the aircraft surface. For laser de-icing system, a beam of radiant energy is generated and directed towards the critical surfaces of aircraft. The laser beams have wavelengths that reflected by the aircraft surface and absorb by the ice. The beam will generate heat and removes the ice (Shinkafi et al., 2014).

Shu Jun et al. (2020) study the hybrid de-icing system which is the combination of the traditional electrothermal deicing system and electro impulse deicing system. Icing wind tunnel deicing test is used to verify the principle of hybrid deicing system. From their experimental study, the hybrid deicing system shows good deicing effect and consumes lesser energy.

For anti-icing system, hot lubricating oil anti-icing system is one type of anti-icing system that utilizes hot lubricating oil of engine to heat the inlet components of aircraft. Hot oil anti icing system supply heat for anti-icing system which decrease the required anti-icing hot air and cools the lubrication oil by supplying the heat. (Dong et al., 2014)

Another type of anti-icing system is use hot air as heat source. Hot bleed air from the engine compressor is ducted to the parts where ice is most likely to form such as the wing leading edges. A study has been conducted by Mathioudakis et al. (2016) with title, the effect of anti-icing system operation on gas turbine performance. According to the result, the operating line of compressors on its map is shifted when anti-icing system is activated. When anti-icing system is activated, the hot air is extracted from the compressor to the parts of aircraft that ice is likely to form. This indicates that the air flow into the combustion chamber and turbine is reduced, which lead to performance loss (Singh et al., 2016).

High temperature bleed air anti-icing system is commonly known as piccolo tube. Piccolo tube has staggered holes around the tube which can eject high velocity hot air from the engine compressor to the inner surface of wing. The hot air is distributed via piccolo tube that running along the length of slat of aircraft within the

D chamber. The heat is transfer through conduction from the inner surface to outer surface and achieve the anti-icing effect. The waste air is then ejected from the aft bay of the slats through the vents (Labuhn et al., 2012).

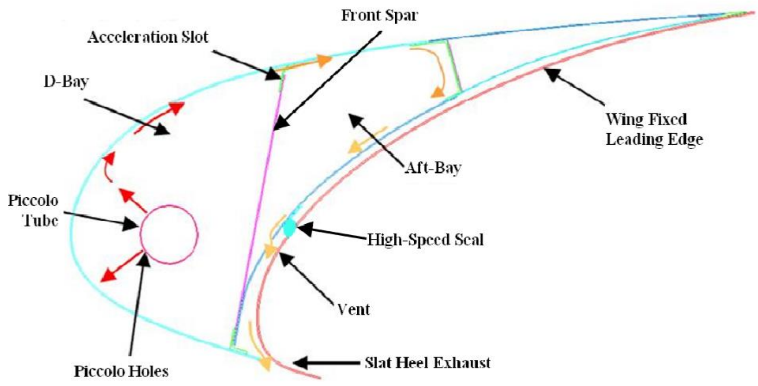


Figure 2.1 Cross Section of Slat with internal flow field

Essam E. Khalil et al. (2020) study the effect of hot air arrangement from a piccolo tube by using ANSYS software. In his studies, three different arrangements are used, inclined shape which comprised one row of jets, staggered shape that comprised two row of jet and the third shape is comprised three rows of jet. Based on the results, the third shape covers larger surface area on the leading edge compared to other shapes.

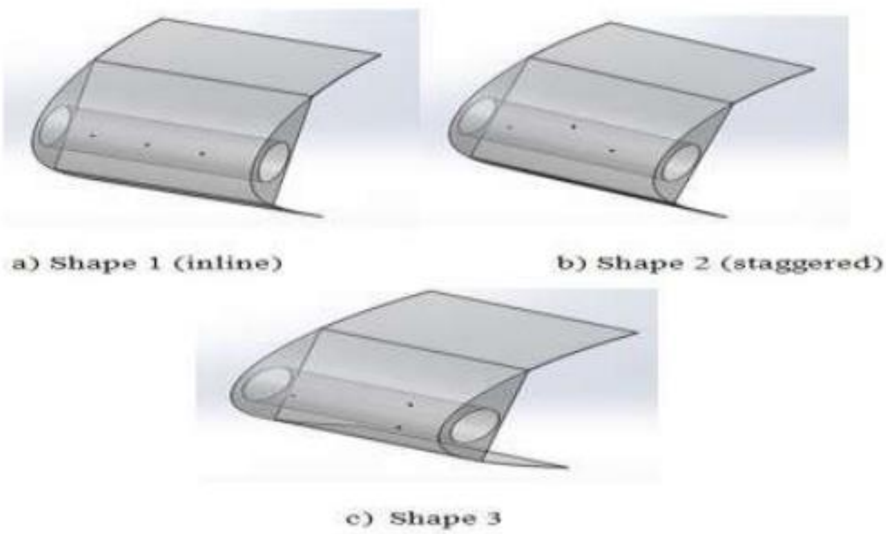


Figure 2.2 Three different hole arrangement for piccolo tube

Research was done by Rohini et al. (2019) to compare the performance of rotating piccolo tube with the piccolo tube using CFD. Two models are built to compare the results with anti-icing piccolo tube concept with the rotation piccolo tube concept for performance improvement. Based on the results, piccolo model tube gives better temperature distribution and higher surface temperature compared to the rotational piccolo tube model. A higher, but concentrated temperature zone is obtained for fixed piccolo tube model.

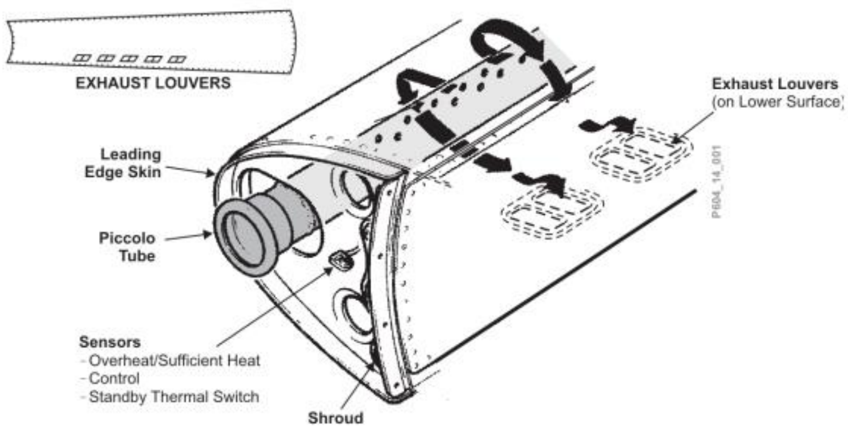


Figure 2.3 Piccolo Tube Anti-Icing System

2.2 Bias Acoustic Liner (BAL)

Due to the strict noise control regulation issue, noise reduction of aircraft engine had become an important issue. A successful method to reduce the noise generated by engine is by using noise abatement tool. Acoustic Liner (AL) is a type of noise abatement tool that placed at the inlet section of engine of an aircraft. AL is a honeycomb structure with perforated face sheet and solid back-face sheet while BAL is a honeycomb structure sandwiched between two perforated plates. BAL has a better thermal and acoustic properties compared to AL. BAL has wider and tunable sound absorption due to various bias flow velocities through the perforated face plate. BAL also give higher average absorption than AL which makes BAL has higher heat transfer rate and longer life cycle (Ma et al., 2020).

According to the research done by Ives et al. (2011),the heat transfer coefficient of BAL is higher than AL as the fluid can passed through two porous plates for BAL compared to AL which is only one porous plate. Hence, the active area for the heat transfer between the fluid and solid surface to take place for BAL is approximately double compared to AL.

Ibrahim et al. (2018) had studied the effect of perforation shape or geometry on the heat transfer of perforated fin. They claimed that perforation to the fin will help in transferring the heat by creating higher turbulence intensity at the perforation area. The increased in turbulence intensity is related to the shape or geometry of the perforations. In others word, the BAL with perforated back-face sheet will have higher heat transfer rate compared to AL as perforation creates higher turbulence intensity at the perforation area causes heat dissipated more rapidly.

The performance of BAL for noise reduction is also an important issue. BAL behave like Helmholtz resonators that enable reduction of noise within an optimized frequency range. Therefore, BAL is suitable for fan noise which is basically a tonal noise. Normally, superimposed layers of BAL which called 2 degree of freedom, or 3 degree of freedom acoustic liner are used so that the absorption range can be broaden. (Leylekian et al., 2014)

Figure 2.4 A superimposed layers of acoustic liner sample

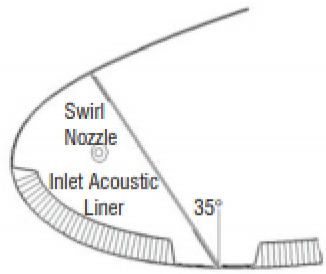


Figure 2.5 Sketch of extended nacelle lip treatment

Thanapal et al. (2019) have studied the effect of porosity of perforated liners in the presence of grazing flow. Based on their results, the acoustic amplification will occur instead of damping when the perforated liner is at very low porosity. Increasing porosity will increase the acoustic damping capability of perforated liner until optimal porosity is reached. Further increased in porosity will affect the performance of liners.

Legendre et al. (2014) have conducted a research on sound absorption by an acoustic liner with bias flow. Based on their research, BAL with bias flow with small Mach number can change the acoustic pressure in the boundary layer which improve the acoustic properties. This is done by broadening the range of propagation into the silence zone and change the ratio of pressure amplitudes in free stream.

2.3 Impingement Jet Study

In thermal anti-icing System, the hot bleed air from engine compressor is passed through a piccolo tube and impinges on the inner surface of wing or nacelle leading edge. When the hot air impinged on the inner surface, thermal energy transfers efficiently from the fluid to the surface. When the hot air strike on a surface, a very thin stagnation region will form. As the jet approaches the wall, the axial velocity component will decrease and transformed into accelerated horizontal component (S et al., 2018) .

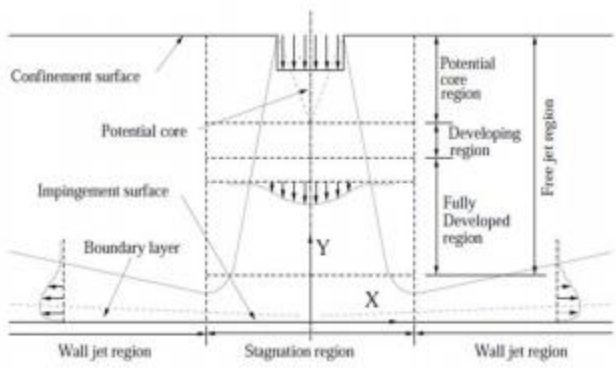


Figure 2.6 Schematic diagram of an impingement jet

Sagot et al. (2008) has investigated the jet impingement heat transfer on a flat plate at a constant wall temperature. An average Nusselt Number correlation was derived using the experimental measurements. A general correlation is proposed for jet impingement heat transfer calculations at a uniform wall temperature for condition: $10000 \leq \mathrm{Re} \leq 30000, \quad 3 \leq \text{plate radius over injection diameter ratio} \leq 10$ and $2 \leq \text{jet distance to nozzle diameter ratio} \leq 6$. Their results show that the Nusselt number increases as the Reynolds number increases, and the distance between nozzle and plate only has a minor effect on the Nusselt number.

Sreedharan et al. (2014) investigated the effect of distance between the piccolo tube and the inner surface of wing leading edge in Aircraft Wing Anti-Icing unit. The results show that a higher, but more concentrated temperature is obtained when the jet impingement distance is small. However, when the jet impingement distance is large, the impingement is not effective. Hence, the jet impingement distance chosen must provide sufficient temperature to avoid ice formation and gives a favorable temperature distribution.

Numerical investigation of jet impingement heat transfer on a flat plate is carried out by Nabadavis et al. (2016) to study the heat characteristic when a high velocity air jet impinges upon a flat plate. From their studies, the effect of jet distance