NUMERICAL SIMULATION OF JET IMPINGEMENT COOLING ON A SMOOTH CONCAVE SURFACE

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Dedicated to my beloved daughter, Nurul Iman Nabihah...

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ABSTRACT

Jet impingement has been widely used as a means of heat removal because of its advantages in effective removal of locally concentrated heat and easy adjustment to the location where cooling is needed. Typical applications are paper drying, cooling of electronic chips, annealing of glass and elimination of excessive thermal load near the leading edge of gas turbine blade inner surface. More studies of jet impingement cooling are reported on flat surfaces than on concave and convex surfaces. For the flows on concave surface, the centripetal force due to the curvature makes the flow unstable and produces Taylor-Görtler vortices. Such vortices are known to enhance momentum and energy transfer and thereby heat transfer rate on the surface. The present study involves a 2-dimensional simulation of homogeneous air jet impinging normally onto a smooth concave surface from a single slot nozzle by means of the Computational Fluid Dynamics software FLUENT.

The effect of Reynolds number and nozzle-to-target spacing on the velocity profile and the local Nusselt number are studied by means of the Reynolds stress model. The predicted results are validated against the experimental data of Choi et al. (2000). The optimum conditions of operation correspond to the ratio of heat transferred to the pumping power. The value of the optimum nozzle-to-target distance has been identified. It is observed that the optimum parameter is dependent on the flow Reynolds number. Correlations of mean Nusselt number, non-dimensional pressure drop and mean temperature are obtained as they can assist in the design of equipment for relevant applications with relative ease, especially in view of the enhanced heat transfer encountered in the concave surface jet impingement. The performance of the k-ε turbulence model is also evaluated and compared with the Reynolds stress model used.

ABSTRAK

Pensantakan jet telah digunakan secara meluas dalam proses penyingkiran haba kerana kelebihannya menyingkir haba tumpu setempat dan mudah untuk pelarasan ke lokasi yang perlu penyejukan. Contoh applikasi adalah seperti pengeringan kertas, penyingkiran haba component elektronik, penyepuhlindapan kaca dan penyingkiran beban haba berlebihan di pinggir depan permukaan dalam bilah turbin. Lebih banyak kajian pensantakan jet atas permukaan rata telah dilaporkan berbanding kajian atas permukaan cekung dan permukaan cembung. Berkenaan aliran atas permukaan cekung, daya setempat yang terjadi akibat dari kehadiran permukaan cekung mengakibatkan terjadinya vorteks Taylor-Görtler. Vorteks seumpamanya dapat meningkatkan pemindahan momentum dan haba pada satu-satu permukaan. Kajian kini melibatkan simulasi dua dimensi pensantakan homogen jet udara secara menegak atas permukaan cekung dari satu muncung dengan menggunakan perisian FLUENT.

Kesan nombor Reynolds dan jarak dari muncung ke permukaan terhadap susuk halaju dan nombor Nusselt setempat dikaji dengan mengaplikasikan model tegasan Reynolds. Keputusan ramal disahkan secara membandingkan dengan data ujkaji oleh Choi *et al.* (2000). Keadaan pengendalian yang optimum adalah berhubung kait dengan nisbah pemindahan haba dan kuasa pam. Nilai jarak antara muncung dan permukaan yang optimum telah dikenalpasti. Didapati bahawa parameter yang optimum adalah bergantung kepada nombor Reynolds aliran. Sekaitan nombor Nusselt min, susutan tekanan tanpa dimensi dan suhu min telah dihasilkan dan ia dapat membantu dalam merekabentuk kelengkapan bagi penggunaan yang berkaitan, terutama dalam proses penyingkiran haba dari permukaan cekung dengan menggunakan pensantakan jet. Prestasi model gelora k-ε telah dinilai dan dibandingkan dengan model tegasan Reynolds yang digunakan.

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NOMENCLATURE

A - Heating surface area (m^2)

a - Coordinate perpendicular to the concave surface (m)

B - Two-dimensional slot jet width (m)

c_p - Specific heat capacity (kJ/kg·K)

Eu - Euler number (dimensionless)

h - Convection heat transfer coefficient ($W/m^2.K$)

H - Distance between nozzle exit and stagnation point of target Surface (m)

k - Thermal conductivity (W/m.K)

Nu_{2B} - Nusselt number ($Nu_{2B} = \frac{h2B}{k}$; dimensionless)

$Nu_{2B,0}$ - Nusselt number at stagnation point ($Nu_{2B} = \frac{h2B}{k}$; dimensionless)

Nu_{mean} - Mean Nusselt number ($Nu_{2B} = \frac{h2B}{k}$; dimensionless)

p - Static pressure (N/m^2)

R_{CW} - Radius of target surface (m)

$RMSD$ - Root mean square of difference (dimensionless)

$RMSDP$ - Root mean square of difference percentage (dimensionless)

R_{OUT} - Radius of pressure outlet (m)

Re_{2B} - Jet Reynolds number at nozzle exit ($\mathrm{Re}_{2B} = \frac{\rho U_{avg} 2B}{\mu}$; dimensionless)

RSM - Reynolds stress model

q - Heat transfer rate (W/m^2)

q_w - Heat flux on the heating surface (W/m^2)

s - Circumferential distance from stagnation point (m)

T - Temperature (K)

T_j - Jet temperature (K)

T_w - Wall temperature (K)

T_{mean} - Mean target surface temperature (K)

Tu (%) - Turbulence intensity ($\frac{\sqrt{\mathrm{u}^2}}{U_j}\times 100$; %)

U - Jet axial mean velocity (m/s)

U_j - Jet velocity at the center of the nozzle exit (m/s)

U_{avg} - Area averaged jet velocity at the nozzle exit (m/s)

t - Time (s)

u - Velocity fluctuation (m/s)

u - Velocity (m/s)

x, y - Coordinates

z - Distance from the nozzle exit (m)

Greek symbols

ρ - Density of air (kg/m^3)

μ - Dynamic viscosity of air (kg/ms)

τ - Shear stress (m^2/s)

ϕ - Scalar property (unit according to property)

Γ_ϕ - Diffusion coefficient for ϕ

Subscripts

i, j - Indices for coordinate notation

CHAPTER I

INTRODUCTION

1.1 Research Background

Jet impingement cooling is used widely to cool the elements exposed to high temperature and heat flux conditions because of its compactness and its ability to remove locally concentrated heat loads. In engineering applications the jets are turbulent and arranged in arrays to produce high heat transfer coefficients over a large area. A single jet is used when localized heating or cooling is required.

Heat transfer rates obtainable with impinging air jets are an order of magnitude higher than those usually associated with gaseous heat transfer media. Applications of impinging air jets include drying of paper, film and textiles, annealing of metal, glass and plastic sheets, cooling of electronic equipment etc. In particular, air-jet-impingement has been effectively used to eliminate excessive thermal load near the leading edge of gas turbine blade inner surface. Jet impingement allows for short paths, relatively high heat transfer rates, low cost and simplicity. It permits a fine degree of control. Also, easy adjustment to the location where cooling is needed is possible.

1.1.1 Flow Characteristics of Impinging Jets

A jet is a rapid stream of fluid forced out of a small opening. It is called a submerged jet when it emerges into the same fluid as the jet. The flow pattern of impinging jets can be divided into three characteristic regions namely the free jet region, the impingement region and the wall jet region. The free jet is the region that is not influenced by the impingement surface. The impingement region or the stagnation region is characterized by an increased static pressure as a result of the sharp decrease of mean axial velocity. Upon impingement the flow deflects and starts to accelerate along the impingement surface. The end of the impingement region is the location where the pressure gradient at impingement surface becomes negligible. The wall jet region is characterized by higher velocities surrounded by lower velocities on the either side, one due to the presence of the wall and the other due to the stagnant fluid. The boundary layer grows along the impingement surface.

The free jet region also may show three characteristic regions namely the potential core region, developing flow region and developed flow region depending on the nozzle-to-target spacing. In the potential core region, the axial velocity remains almost equal to that at the jet entry. The end of the potential core is determined by the rate of growth of two mixing layers originating at the edges of the nozzle. In the developing flow region, the axial velocity starts to decay and the jet spreads to the surrounding. Eventually lateral profiles of the axial velocity approach a bell shape. In the developed flow region, similar axial profiles exist at different jet lengths. Depending on the nozzle-to-target spacing, the free jet region may display one or more of the above regions. Initially laminar jets could turn turbulent due to mixing at the outer jet boundaries. How quickly an initially-laminar jet transforms into a turbulent one depends on many factors like confinement, the inlet Reynolds number, the velocity profile at the nozzle exit etc.

1.1.2 Jet Impinging on Curved Surfaces

When jet impingement cooling is applied to curved surfaces such as a turbine blade surface, the curvature effect should be taken into consideration. For flows on a surface with concave curvature, for sufficiently high flow speeds, the centripetal force due to the curvature usually makes the flow unstable and a Taylor-Görtler type vortex is produced. The velocities are low near the wall and are large away from the wall. This means that the centrifugal forces on the faster moving fluid particles are higher and there is a tendency for these fast moving particles to be pushed outward near the surface. This causes the instability. This vortex has its axis parallel to the flow direction and is known to enhance momentum and energy transfer.

1.2 Problem Statement

In the design of an impinging-jet system for a given thermal application, a large number of geometric and flow parameters like jet type (round/slot), nozzle to target spacing, angle of impingement, nozzle design, jet-inlet Reynolds number etc are involved. So a purely experimental approach to the problem is unlikely to lead to a satisfactory solution at reasonable cost and time. The advent of high-speed computers and robust numerical techniques for solving transport equations have made it possible to supplement experimental data with numerical studies so as to permit interpolation and extrapolation of impingement transport phenomena for design purposes. Also, properly validated numerical simulations can enhance our understanding of the jet impingement flow and heat transfer phenomena with much less cost and time.

1.3 Objectives

To produce properly validated numerical simulations which are able to predict:-

a) The mean velocity distribution of the impinging jet and along the concave surface in order to understand the hydrodynamics characteristics.

b) The local Nusselt numbers along a concave surface in order to understand the heat transfer characteristics.

1.4 Scope

The scope chosen based on Choi et. al. (2000) work.

a) Reynolds numbers investigated, Re_{2B}, are: 1780, 2960 and 4740, with

$$Re_{2B} = \frac{U_{avg} 2B}{\nu}$$

where

$2B$ = hydraulic diameter of the nozzle exit studied in the present work.

B = nozzle-exit width.

U_{avg} = averaged velocity at the nozzle exit.

ν = kinematic viscosity

b) Nozzle-to-Surface-Distance ranges from $H/B = 2$ to $H/B = 14$. H is the distance between the nozzle exit and stagnation point of target surface.

c) Nozzle with 2D-contraction shape used by Choi et. al. (2000).

d) Submerged jet flow.

1.5 Research Significance

The developed approach yields low-cost and accurate predictions of heat transfer processes on a concave surface via impinging jet, which may assist the design of relevant applications, with relative ease.

1.6 Outcome

a) Validated numerical approach, which is able to predict the thermal and dynamic aspects of jet impingement on a concave surface.
b) Useful correlations from the simulation that able are to assist in designing a relevant system.
c) Possible optimum operating conditions.

1.7 Limitation

The obtained numerical predictions and correlations are limited to the range of scope involved.

CHAPTER II

LITERATURE STUDY: FLOW AND HEAT TRANSFER IN JET IMPINGEMENT

2.1 Overview

Impinging jets have been the interest of many researchers due to their common use in industrial heat and mass transfer applications. In improving the design of these systems, knowledge of parameters affecting the heat transfer rate is required. Among of those parameters are such as the Reynolds number, the nozzle-to-surface spacing, the nozzle type and geometry, orientation, the number of jets and the impingement surface shape.

2.1.1 Jet Flow Characteristics

An impinging jet is consisting of three characteristics regions namely free jet region, impingement region and wall region (Martin, 1977) as illustrated in Figure 2.1. The free region is the region where the velocity profile is not influenced by the impingement. The impingement or the stagnation region is the region where adverse pressure gradient attenuates the mean axial velocity, subsequently deflecting the fluid flow into the wall jet region. In wall jet region, the fluid flow velocity is low at the wall due to the viscous friction. Laterally from the wall the shear strain rate reduces gradually but increases again as the higher velocity fluid mix with the surrounding fluid.

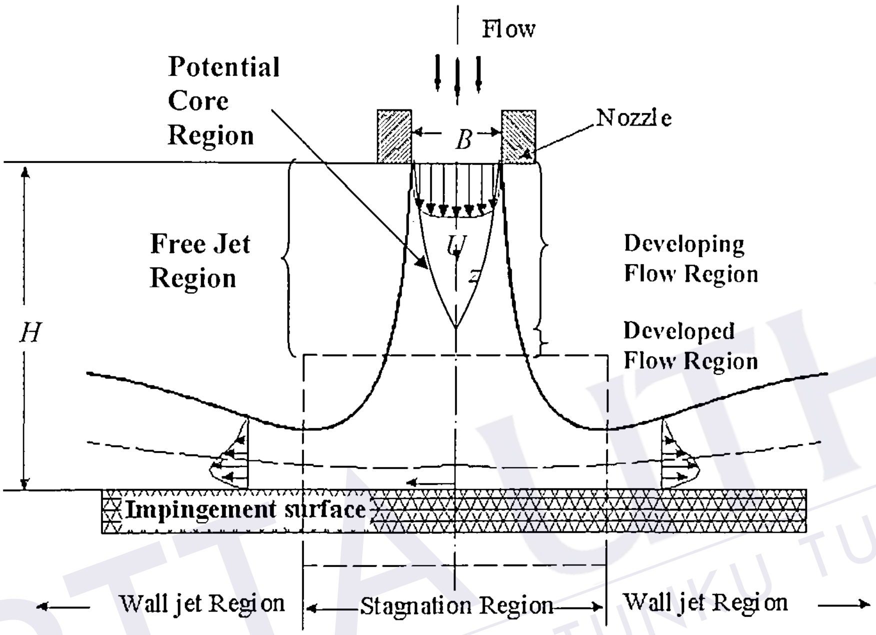

Figure 2.1: The jet impingement regions (Martin, 1977)

The free jet region is further separated into three characteristics region; the developing flow region, the potential core region and the developed flow region. The developing flow region is where the surrounding fluid entrains into the jet starting from the nozzle edge. This mixing or shear zone causing the jet to spread and reduces the flow velocity. The potential core region is a part of the developing flow region and is the region where the velocity is not less than 95 % of the velocity at the nozzle exit (Jambunathan *et al.*, 1992). Beyond the potential core region, the lateral profiles of the axial velocity is a bell shape (Martin, 1977). In the developed flow region, similar axial velocity profiles exist at different jet lengths.

2.2 Previous Studies

Comprehensive literature reviews on jet impingement studies are available. Martin (1977) reviewed the earlier works on impingement that included single round jets and slot jets as well as arrays of round jets and slot jets. Empirical equations were presented for prediction of heat and mass transfer coefficients. The equations presented however did not take into account the radial variation in the effect of Reynolds number, which is expected to occur as the thermal and flow boundary layers develop. Jambunathan *et al.* (1992) on the other hand produced local Nusselt number correlations from reviewed experimental heat transfer data of single circular jet impinging on a flat plate. The produced correlation was a function of nozzle-exit Reynolds number and nozzle-to-plate spacing.

Huang *et al.* (1994) studied experimentally a single round jet for the distribution of local Nusselt numbers for a Re at the range of 6000 to 60000 and a wide range of nozzle-to-plate distances. Lee *et al.* (1995) investigated an impinging round air jet onto a flat plate with constant heat flux for Reynolds numbers of 4000 to 14400. Relation between stagnation Nusselt number and Reynolds number was observed for specific jet spacing of 2, 4, 6 and 10 times of jet width. The relation was also true for local Nusselt number within impinging region of radius equivalent or less than twice the jet width. Beyond the radius, transition of laminar to turbulent boundary layer was connected to the relation failure. The work concluded that for a fully developed jet impinging at a spacing less than 6 jet width and at Reynolds number less than 8000, the stagnation Nusselt number is independent of the jet spacing. Chen and Modi (1999) investigated numerically the mass transfer coefficients of a turbulent slot jet impinging normally on a flat plate. They studied a wide range of Reynolds number from 450 to 20000 with nozzle-to-target spacing of 2 to 8 jet width. The fluid flow was modeled using the k-ε model.

Despite the fact that a number of engineering applications, such as turbine blade cooling, deal with impingement on curved surfaces, the majority of previous study have focused on flat-surface impingement. In general, works dealing with jets impinging on curved surfaces are limited, compared to the flat-plate investigations.

2.3 Jet Impingement on Curved Surface

When jet impingement cooling is applied to a curved surface, the curvature effect should be taken into consideration. A concave surface for instance induces centripetal force by which the flow becomes unstable and a so-called Taylor Gortler type vortex is produced (Mayle *et al.,* 1979).

Gau and Chung (1991) studied the effect of face curvature on the two-dimensional slot jet impinging heat transfer along semi-cylindrical concave and covex surfaces. Visualizations of the impinging jets on both surface curvatures were presented. Secondary maxima have been reported at radius of 2 jet width for jet spacing of 2 jet width and for high Reynolds number of larger than 23000. They observed that at the stagnation point region on a convex surface, the momentum transport in the flow is increased due to a series of three dimensional counter-rotating vortices initiated near the wall, and subsequently the heat transfer rate on and around the stagnation point increases with increasing surface curvature. On the other hand, the vortices were not observed in a concave surface. However the local Nusselt number was found to be increasing with increasing surface curvature due to the vigorous vortex motion in the jet mixing region.

Lee *et al.* (1999) investigated the effect of hemispherical-concave surface curvature on the local heat transfer of a developed round impinging jet. Like Gau and Chung (1991) finding, the Nusselt number increases with increasing surface curvature. It was concluded that it was attributed to a thinning of boundary layer

REFERENCES

Chen, Q. and Modi, V. (1999). "Mass transfer in Turbulent Impinging Slot Jets." *Int. J. Heat Mass Transfer.* **Vol. 42.** 873 - 887.

Choi, M., Yoo, H. S., Yang, G., Lee, J. S and Sohn, D. K. (2000). "Measurements of Impinging Jet Flow and Heat Transfer on a Semi-circular Concave Surface." *Int J. Heat Mass Transfer.* **Vol.43.** 1811 - 1822.

Colucci, D. W. and Viskanta, R. (1996). "Effect of Nozzle Geometry on Local Convective Heat Transfer to a Confined Impinging Air Jet." *Exp. Therm. Fluid Sci.* **Vol. 13.** 71 - 80

Cooper, D., Jackson, D. C., Launder, B. E. and Liao, G. X. (1993). "Impinging Jet Studies for Turbulence Model Assessment-I; Flow- field Experiments." *Int. J. Heat Mass Transfer.* **Vol. 36.** 2675 - 2684.

Craft, T. J., Graham, L. J. W. and Launder, B. E. (1993). "Impinging Jet Studies for Turbulence Model Assessment-II. An Examination of the Performance of Four Turbulence Models." *Int. J. Heat Mass Transfer.* **Vol. 36.** 2685 - 2697.

Garimella, S. V. and Nenaydykh, B. (1996). "Nozzle-geometry Effects in Liquid Jet Impingement Heat Transfer." *Int. J. Heat Mass Transfer.* **Vol. 39.** 2915 – 2923.

Gau, C. and Chung, C. M. (1991). "Surface Curvature Effect on Slot-Air-Jet Impingement Cooling Flow and Heat Transfer Process." *ASME Journal of Heat Transfer.* **Vol. 113.** 858 – 864.

Gilard, V. and Brizzi, L. E. (2005). "Slot Jet Impinging on a Concave Curved Wall." *ASME Journal of Fluids Engineering.* **Vol. 127.** 595 – 603.

Huang, L and El-Genk, M. S. (1994). "Heat Transfer of an Impinging Jet on a Flat Surface." *Int. J. Heat Mass Transfer.* **Vol. 36.** 1915 - 1923.

Issa, R. I. (1986). "Solution of the Implicitly Discretised Fluid Flow Equations by Operator-Splitting." *J. Comput. Phys.* **Vol. 62.** 40-65.

Jambunathan, K., Lai, E., Moss, M., A., and Button, B. L. (1992). "A Review of Heat Transfer Data for Single Circular Jet Impingement." *Int. J. Heat and Fluid Flow.* **Vol. 13.** 106 – 115.

King, A. J. C. and Chandratilleke, T. T. (2007). "Heat Transfer Enhancement in Single Impinging Jets Due to Surface Cavities." *HEFAT2007 5th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics.* KA3.

Launder, B. E., Spalding, D. B. (1974). "The Numerical Computation of Turbulent Flows." *Computer Methods in Applied Mechanics and Engineering.* **Vol. 3.** 269 – 289.

Lee, D., Greif, R., Lee, S. J. and Le, J. H. (1995). "Heat Transfer from a Flat Plate to a Fully Developed Axisymmetric Impinging Jet." *Trans. ASME Journal of Heat Transfer.* **Vol. 117.** 772 - 776.

Lee, D. H., Chung, Y. S. and Won, S. Y. (1999). " Technical Note: The Effect of Concave Surface Curvature on Heat Transfer from a Fully Developed Round Impinging Jet." *Int. J. Heat Mass Transfer.* **Vol. 42.** 2489 – 2497.

Leonard, B. P. and Mokhtari, S. (1990). "ULTRA-SHARP Nonoscillatory Convection Schemes for High-Speed Steady Multidimensional Flow." NASA TM 1-2568 (ICOMP-90-12). NASA Lewis Research Center.

Martin, H. (1977). "Heat and Mass Transfer between Impinging Gas Jets and Solid Surface." *Advances in Heat Transfer.* **Vol. 13.** 1 - 60.

Mayle, R. E., Blair, M. F. and Kopper, F. C. (1979). "Turbulent Boundary Layer Heat Transfer on Curved Surfaces." *ASME Journal of Heat Transfer.* **Vol. 101.** 521 – 525.

Nawaf H. Saeid. (2007). "Jet Impingement Interaction with Cross Flow in Horizontal Porous Layer Under Thermal Non-equilibrium Conditions." *Int. J. Heat Mass Transfer.* **Vol. 50.** 4265 - 4274.

Nawaf H. Saeid and Abdulmajeed A. Mohamad. (2006). "Jet Impingement Cooling of a Horizontal Surface in a Confined Porous Medium: Mixed Convection Regime." *Int. J. Heat Mass Transfer.* **Vol. 49.** 3906 - 3913.

Patankar, S. V. and Spaldind, D. B. (1972). "A Calculation Procedure for Heat, Mass and Momentum Transfer in Three-dimensional Parabolic Flows." *Int. J. Heat Mass Transfer.* **Vol. 15.** 1787.

Van Doormal, J. P. and Raithby, G. D. (1984). "Enhancements of the SIMPLE Method for Predicting Incompressible Fluid Flows." *Numer. Heat Transfer.* **Vol. 7.** 147 - 163.

Xu, C. X., Choi, J. I. and Sung, H. J. (2003). "Identification and Control of Taylor-Gortler Vortices in Turbulent Curved Channel Flow." *AIAA Journal.* **Vol. 41.** 2387 – 2393.

Yang, G., Choi, M. and Lee, J. S. (1999). "An Experimental Study of Slot Jet Impingement Cooling on Concave Surface: Effects of Nozzle Configuration and Curvature." *Int. J. Heat Mass Transfer.* **Vol. 42.** 2199 - 2209.

(1997) "Perry's Chemical Engineers' Handbook 7th Ed."

(2006) "Fluent 6.2 User's Guide.".