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# IMPINGEMENT COOLING OF A SEMI-CIRCULAR CONCAVE CHANNEL BY 2D AIR-JET

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## ABSTRACT

This study provides a numerical solution to the flow in a cylindrical cavity of which the upper wall contains a two-dimensional slot. The air injected through the slot impinges and diffuses laterally on the lower wall. The jet enfluxed through the slot is assumed to have uniform velocity and temperature, and the temperature at the lower wall is kept constant. The resulting Navier-Stokes equations are solved by transforming simpler algorithm into a form useably in cylindrical co-ordinate system. The effect of cavity curvature, and the height ratio on velocity and pressure distribution is analyzed. The jet Reynolds number ranged from 100 to 1500 in the analysis.

**Key Words :** Impingement, Jet flow, Curvature, Simpler algorithm

## YARISİLİNDİRİK BİR KANALDA 2 BOYUTLU HAVA JETİ İLE ÇARPMA SOĞUTMASI

## ÖZET

Literatürde yüzeylerin hava jeti yardımı ile ısıtılması veya soğutulması üzerine çeşitli araştırmalar bulunmaktadır. Ancak bu araştırmaların hemen tamamı, düz yüzey veya kanallar içindir. Bu çalışmada, silindirik bir kanalın iç yüzeyindeki bir yarıktan kanala dik bir jet akışı olması durumu için, eğriliğin akışa ve ısı geçişine etkisi araştırılmıştır. Laminer jet akışı durumu için, Simpler algoritması olarak bilinen sayısal algoritma silindirik koordinatlara uyarlanarak bir bilgisayar programı hazırlanmış ve çeşitli eğrilikler için çalıştırılarak hız, sıcaklık ve basınç dağılımlarının eğriliğe bağlı değişimleri incelenmiştir. Çarpan jetin Re sayısı 100-1500 arasında değiştirilmiş, jet üfleme genişliğinin kanal yüksekliğine oranı 0.25 olarak sabit tutulmuştur. Sonuçlar grafikler halinde verilmiş, ayrıca elde edilen sayısal sonuçlar kullanılarak ısı geçiş katsayısı için ampirik bir bağıntı çıkarılmıştır.

**Anahtar Kelimeler :** Yarısilindirik, Jet akışı, Silindirik kanal, Simpler algoritması

## 1. INTRODUCTION

Due to use of Brayton cycle in energy producing facilities, high gas temperature is required for improving the thermodynamic efficiency of the cycle. However, display of turbine blades to such a high temperature gas stream will decrease the life span of the blades. A method in reducing the blade surface temperature is to inject air through a pressurized cavity. One has to analysed the resulting flow field to understand the effectiveness of such a method. The pressurised air in a cavity of a turbine blade is injected to the turbine channel through slots and flows out at trailing edge zone as in Figure (1).

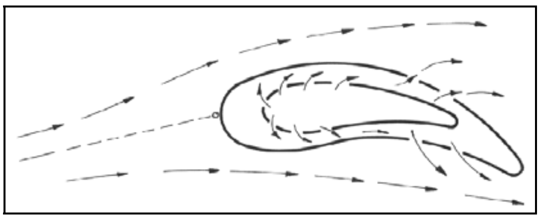

Figure 1. The cooling of a turbine blade by impingement air jet

In contrast to channel flow, the important reason for using jet flow is to maintain a reduced temperature at the blade surface by locally high heat transfer coefficients. So, heat transfer is very high on critical zones. For a slot jet, heat transfer coefficient at impingement surface is shown schematically in Figure 2.

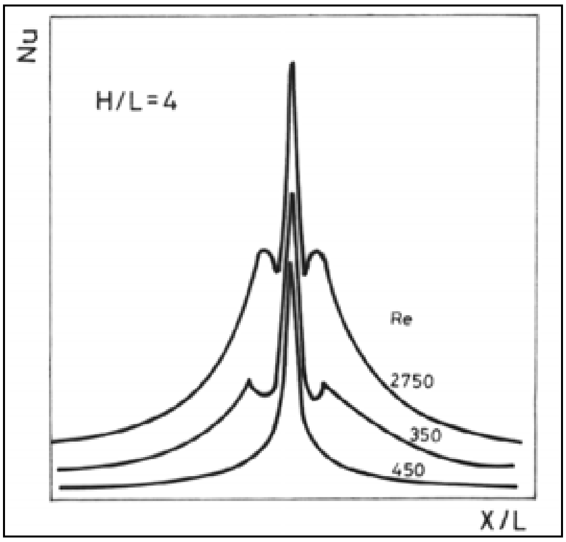


Figure 2. Variation of local heat transfer coefficients between a plate and impinging two dimensional air jet (Gardon ve Akfırat, 1966)

In contrast to the number of publications for jets impinging on flat surfaces, there is a lack of work related to the flow formed in a cylindrical concave channel by injection air through a slot located at the symmetry line of the upper wall. This paper numerically investigates velocity and pressure distribution of such a flow field. Then, solving the energy equation, the effect of curvature, and the jet Reynolds number on heat transfer coefficients are analyzed.

One of the firstly experimental works on impingement jets was done by Gardon and Akfırat (1966) that has been often referred by others. They did measure heat transfer coefficients at different points on impingement surface and Reynolds number was between 450 and 22000. So that local and average heat transfer coefficients were established experimentally. Later, Metzger et al. (1969), and Hrycak (1981) studied experimentally on jet flow impinged on concave surfaces. One circular jet or array of circular jets were used in these experimental studies and relations between the heat transfer coefficient at curved surface, the distance from the jet nozzle to the surface and the radius of the jet were examined.

Later 1970's, computer technologies and also numerical methods were improved and so, much studies were done to obtain numerical solutions of jet flow using these methods.

Gosman et al. (1969), studied on a finite different method for solution of rotationally flow problems. Using their method, heat transfer coefficients on an impingement surface were estimated for laminar slot jets by Heiningen et al., (1976), and for laminar circular jets by Ravuri and Tabakoff (1975) and Saad et al. (1977).

Later was studied also on the numerical solutions of turbulent jet flow (Agarwal and Bower 1982; Chuang 1989; Hwang and Liu 1989). These three papers aimed to solve pressure and velocity distributions in a channel that a jet flow directed in it.

However almost all of these studies are about flat surfaces or channels. There are few studies in which impingement surfaces are concave. However there is no any paper published in literature that studies the curvature effects of a jet flow in a cylindrical channel.

Numerical method used in this study is Simpler algorithm that was improved by Patankar (1980) as a finite difference algorithm. The advantage of this algorithm is that the pressure and velocity distributions are calculated without using vorticity equations. The common numerical methods using to solve the fluid flow and heat transfer problem has been introduced with details in reference (Minkowycz et al., 1988).

## 2. THE MODEL

In this study, it is considered a cylindrical channel that a jet flows towards in it from a slot. The slot is on one of the surfaces that its radius is smaller than the other (Figure 3). The channel consists of a half cylindrical central zone and a flat tail zone. Channel length to be measured on inner surface from the central of the slot to the channel outer edge, is 30 times of the channel height and arc width of the slot is one quarter of the channel height.

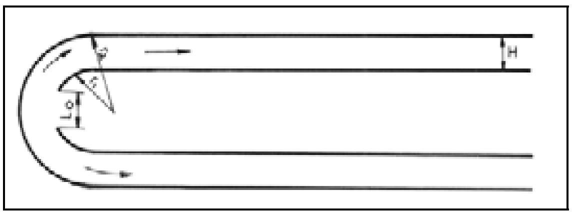


Figure 3. The geometric model

For a cylindrical channel, the parameter describing the curvature is the ratio of the channel height to the channel radius. Additionally, the jet Reynolds number; $\rho u_0 S_0/m$, is determined to be sufficient for fully describing the flow.

Jet inlet temperature is constant through slot. The channel inner wall temperature is the same as the jet inlet temperature and the outer wall temperature are kept constant. Direction of the jet velocity at the slot exit has been considered for two different cases. One of them is that direction of the streamlines at the slot exit are in radial direction, which is named as radial jet. For the other state, the streamlines are parallel to each other and perpendicular to the slot exit surface, which is named as flat jet. The velocity of the jet is constant through inlet nozzle. At the exit side of the channel, direction of the flow is perpendicular to the exit area and contains no component parallel of the exit surface.

To provide a system of equations that is proper for numerical analysis, momentum and energy equations were derived on limited control volume for Cartesian and cylindirical co-ordinate systems. Later, these equations were reorganized to properly Simpler algorithm. Details of these derivations are given in reference (Patankar, 1980; Küçüka, 1993). In this study, it is examined steady state flow and is neglected viscous work effects. The jet fluid (air) is taken as incompressible.

## 3. NUMERIC RESULTS AND DISCUSSION

To obtain numerical results, a computer program was prepared and has been run for different states. The work field (channel) was divided 36 x 55 grids. The grids were very dense near the impingement surface and become wide apart toward the channel outer zone. The program was run as a loop so that the flow at the channel exit area was closer than 99 per cent from the flow inside with the jet. But this condition has been maintained by 5 per cent error only as the Reynolds number was 1500 and also the curvature was 2. For these running conditions, it was necessary 1500 - 15000 loops and 12-24 hours running time for obtaining a result. The computer used for this purpose was processor was 486 DX-2 66. The program was written in GW-BASIC and it was compiled and run as an executable file.

The numerical results were been obtained that the curvature was between 001 (flat) and 2. In the analysis, the Reynolds number ranged from 100 to 1500. The channel length as described in previous paragraphs was assumed 30 times of the channel height to prevent reverse flow at the channel exit area at high Reynolds number as 1500. The Prandtl number of fluid is assumed to be 0.71 for all cases. The numerical results were obtained by this program as the curvature is 0.001, are closer to the results given at the reference (Heiningen et al., 1976) for a flat channel (Figure 4).

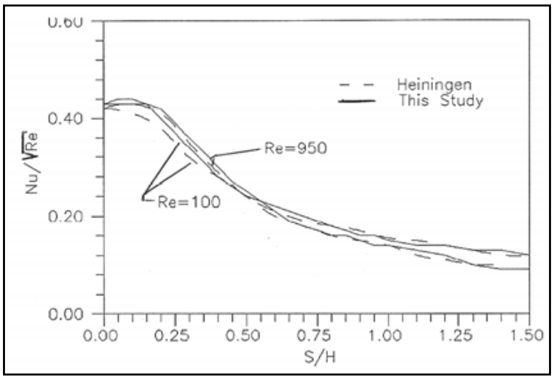


Figure 4. The comparison of the results with given by Heiningen (1976).

The results of the radial jets are shown in Figures (5, 6, 7, 8).

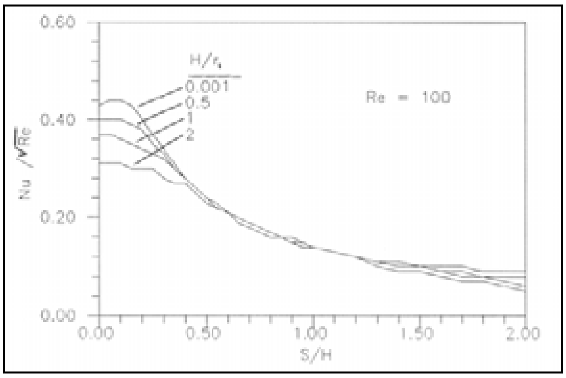


Figure 5. Non-dimensional heat transfer coeff. (Re = 100)

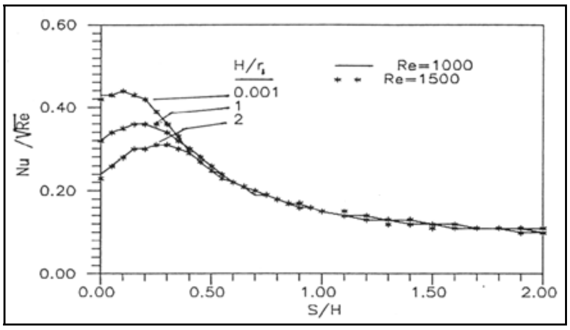


Figure 6. Non-dimensional heat transfer coff. (Re = 1000, 1500)

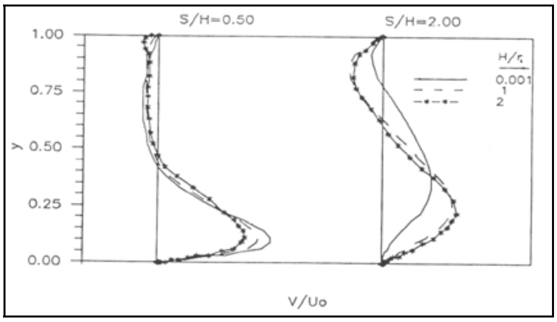


Figure 7. The velocity profile in angular direction (Re = 100, Radial Jet)

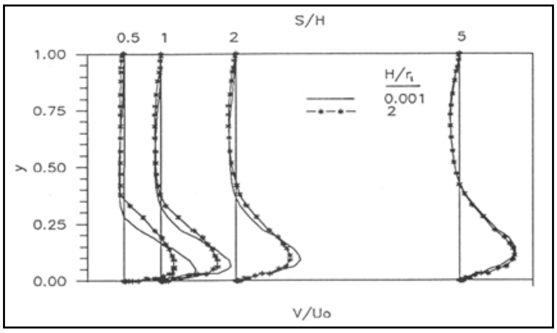


Figure 8. The velocity profile in angular direction (Re = 100, Radial Jet)

The curvature affects strongly heat transfer coefficients for radial jet flow. At the stagnation zone, the following relationship derived between non-dimensional heat transfer coefficient and curvature (Figure 9).

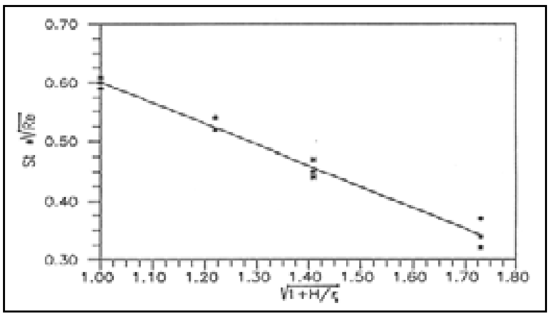


Figure 9. Variation of heat transfer coefficients at stagnation point depending on curvature

$$St_0\sqrt{Re}=0.995-0.354\sqrt{1+\xi} \qquad (1)$$

This equation is valid with 8 per cent error for Reynolds number greater than 500. The results were obtained as Reynolds number was 100 have not been used to determine the constants of this equation because of they were a some different from the other results and these low Reynolds numbers are not important practically.

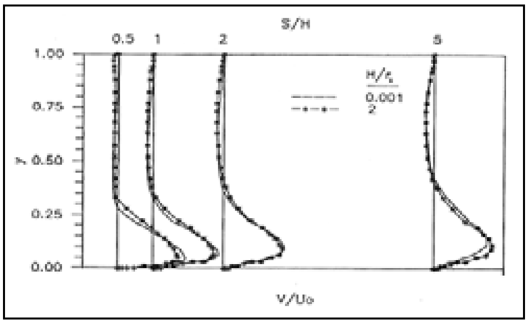


Figure 10. The velocity profile in angular direction (Re = 1000, Flat Jet)

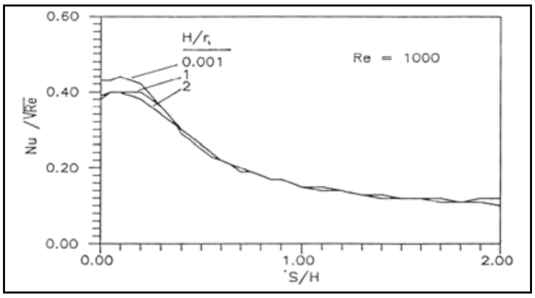


Figure 11. Non- Dimensional heat transfer coefficients (Re = 1000, Flat Jet)

The results obtained for the flat jet are shown in Figures 10, 11.

At the stagnation zone, heat transfer coefficients for the flat jets are greater than heat transfer coefficients for the radial jets (Figure 12-13).

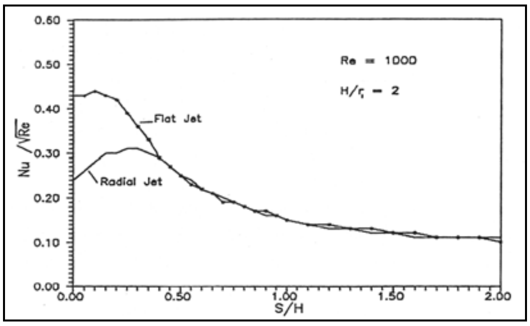


Figure 12. Variation of non - dimensional heat transfer coefficients for flat and radial jets (Re = 1000)

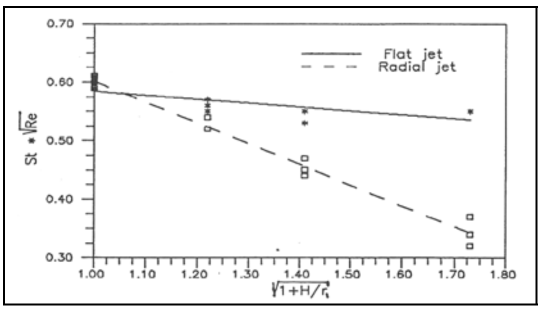


Figure 13. Variation of heat transfer coefficients at stag. Point for flat and radial jets

For the flat jet flow, the jet Reynolds number is calculated for the flat width of the slot, this is smaller than the radial width of the same slot (Figure 3). So the velocity of the flat jet is greater than the velocity of the radial jet for same Reynolds number, but the flow capacities of the jets are equal.

## 4. CONCLUSIONS

This study points at the effect of curvature on impingement heat transfer coefficients. The results show that the heat transfer coefficients on stagnation zone are affected strongly by the curvature of a radial jet in a cylindrical channel, but this effect is negligible for a flat jet flow. These results give some hints for the design of cooling and heating jets. But to obtain more precision results, this study should be repeated for different curvatures, nozzle widths and for the other geometrical parameters. The effect of turbulence on such a flow should also be investigated.

## 5. NOTATIONS

h : Convective heat transfer coefficient
H : Channel height
k : Convective heat transfer coefficient
$L_0$ : Slot width
Nu : Nusselt number, h $S_0$/k
Pr : Prandtl number
Re : Jet Reynolds number : for flat jet : $\rho u_0 L_0/\mu$ :
for radial jet : $\rho u_0 S_0/\mu$ :
$r_1$ : The radius of inner surface
$r_2$ : The radius of the lower wall
S : The arc length measured from the stagnation point to a point on the lower wall
$S_0$ : Slot arc length
St : Stanton Number, Nu/(Re*Pr)
u : Flow velocity on radial direction
$u_0$ : Jet injection velocity
v : Fşow velocity on angular direction
$\mu$ : Dynamic viscosity
$\xi$ : Curvature, H/$r_1$
$\rho$ : Density

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