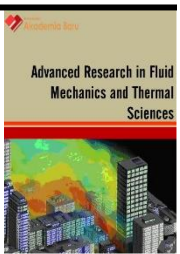
Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 57, Issue 2 (2019) 208-215

Penerbit
Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Numerical and Experimental Study of Convective Heat Exchanges on a Rotating Disk with an Eccentric Impinging Jet

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Chadia Haidar[1,*], Rachid Boutarfa[1], Souad Harmand[2]

[1] Laboratory of engineering, Industrial Management and Innovation (IM2I),Hassan 1st University, Faculty of Science and Technology of SETTAT, Morocco
[2] Laboratory of TEMPO - D2FT, Universities of Valenciennes and Lille Nord of France, 59313 Valenciennes, France

ARTICLE INFO

Article history:
Received 20 September 2018
Received in revised form 22 November 2018
Accepted 15 December 2018
Available online 17 May 2019

Keywords:
Heat transfer, rotating disk, impacting jet, numerical simulation, infrared thermography

ABSTRACT

This article presents an experimental and numerical study of the heat transfers in rotating disk with an impinging jet. The disk is cooled using the impingement of an eccentric air jet. Local Nusselt numbers are experimentally determined on the entire surface the rotating disk using infrared thermography. A numerical study is carried out with ANSYS-Fluent computation code and based on a k-ε RNG numerical turbulence model. the obtained result was compared in term convective heat transfer with numerical and experimental data for rotational Reynolds number between Re_{ω}=2.38× 10^5 and 5.44 × × 10^5. A good agreement between the two approaches has been reached. This agreement validates a numerical model for calculating the convective heat transfer in a rotating disk.

1. Introduction

At present, the concept of sustainable development imposes an increase in the production of so-called " green" energy. Therefore, wind turbines have developed in recent years, as they allow to convert mechanical energy from wind into electrical energy, without producing greenhouse gases such as CO_2. Study of the alternators optimization they carry has highlighted the so-called "discoidal" technology. Indeed, this technology, which rotates a disk facing a fixed disk, is able to obtain high power at low rotational speeds. The major disadvantage is the air flow induced by this alternator's rotation is insufficient for optimal cooling of the installation [1,2]. High local temperature increases are responsible for premature degradation of materials, which limits the life of the equipment. Therefore, the energy optimization of rotating systems consists in researching innovative and efficient cooling technological solutions to lower these temperature levels. For this reason, we are interested to modify the flow and heat exchange on the surface in a single rotor with an eccentric air jet.

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[*] *Corresponding author.*
E-mail address: c.haidar@uhp.ac.ma (Chadia Haidar)

The rotation of a disk generates a three-dimensional flow in its vicinity. Von Karman [3] thus highlighted the presence of a tangential flow due to the disk entrainment. The centrifugal efforts that are exerted create a radial flow on the disk surface. The fluid ejection is then compensated by an axial suction. In rotating machines, the convective transfer is strongly related to the system geometry and temperature distribution on the disk surface.

The Convective heat transfer on a rotating disk was studied by Goldstein [4], Cobb and Saunders [5], and Dorfman [6] which showed the dependence between convective transfer on the disk and temperature distribution law of its surface. For a temperature distribution on its surface expressed as a power law $T(r)= T_\infty + c.r^n$, Dorfman [6] proposes two correlations giving the local Nusselt number Nu in the single disk: for a laminar regime Rer <$1.82\times\times 10^5$.

$$\mathrm{Nu} = 0.308\ \digamma\ (\mathrm{Pr})\sqrt{(\mathrm{n}+2)\mathrm{Re_r}} \tag{1}$$

For a turbulent flow regime (Rer$>2.82\times 10^5$)

$$\mathrm{Nu} = 0.0197 \times (n+2.6)^{0.2} \times \mathrm{Pr}^{0.6} \times \mathrm{Rer}^{0.8} \tag{2}$$

He therefore deducts an average Nusselt number which can be expressed as follows

$$\overline{\mathrm{Nu}} = 0.0197[(n+2) / (n+2.6)^{0.8}] \times \mathrm{Pr}^{0.6} \times \mathrm{Re}^{0.8} \tag{3}$$

Pellé [7] studied experimentally the heat transfers in the case a single rotating disk without an air jet. He investigated how laminar flow loses its stability near a single rotating disk and two critical local Reynolds numbers have been defined $\mathrm{Re}_{r,lam} = 2.3\times 10^5$ and $\mathrm{Re}_{r,tur} = 3.58\times 10^5$. Fluid flow and heat transfer in the case a rotating disk with an impinging jet is poorly documented, although it is significant in cooling processes for numerous industrial applications, such as cooling bearings, gearboxes, hard disks, gas turbines and wind turbine generators [8,9]. Angioletti [10] showed that heat transfers are significant near the impinging point on the disc. Indeed, the jet renews air more quickly and perturbs a boundary layer created by the disc's rotation at this location, because vortices appear at the jet's outlet. The effects of jet diameter (D), the jet's Reynolds number Re_j, and the distance between the jet outlet and the impacted surface H/D are highlighted by Chen [8], Owen [11] and Astarita [12].

For round jet impacting a heated rotating disk vertically in an unconfined computation field, Minagawa and Obi's [13] measurements for the hydrodynamic fields and Popiel and Boguslawski [14] for convective heat transfer have provided a highly relevant experimental database. Among other matters, Popiel [14] distinguished three areas on the disk surface subjected to an axisymmetric jet: an area near the impingement point where the jet's influence is preponderant on heat transfers, an area outside the disk where rotation is preponderant and a mixed area, between these two areas. Axcel [15] studied the impact of a jet on heat transfer in a rotating disk with a certain roughness. it highlights a modified Reynolds number to take into account both the rotation and jet effects at the same time.

The reader can refer to the experimental research by PIV and LDA of O'Donovan [16] which is dedicated to the influence of nozzle-wall distance on flow and heat transfer. The rotational Reynolds number ranges from 10^4 to $3.\ 10^4$ while the nozzle-wall distance H/D is between 0.5 and 8. These authors have shown that the stagnation point is confused with the symmetry axis and is fixed for a distance H/D< 2.5. For higher values, its instantaneous position fluctuates over time but remains constant.

Manceau [17] studied the influence of rotation on flow structure and heat transfer for a turbulent jet impinging (Re_{j}= 14500) on a disk located at H/D = 5. This author compared his numerical results from turbulence models (ζ - f, ϕ - f, *EB-RSM* et k-ωSST) with those obtained experimentally. In general, these turbulence models overestimate the jet's development, leading to a poor representation of physical phenomena at impact. This strongly encourages to use direct numerical simulation or large-scale simulation.

The authors also demonstrate that in the case on a rotating disk with a jet, heat exchanges strongly depend on the jet's position on the disk's surface. For this reason, this configuration with an eccentric jet is studied in this study. In this work, our experimental data are used to validate a numerical study performed with ANSYS Fluent code and to study the jet's effect on rotor cooling for Reynolds numbers: $2.38\times 10^5 \leq Re_{\omega} \leq 5.16\times 10^5$ and $16.5\times 10^3 \leq Re_{\mathrm{j}} \leq 49.6\times 10^3$. The aim of this work, in a longer term, is to study the flow structure and heat transfers in the air gap between a rotor and a stator with an eccentric impinging jet.

2. Experimental Set-up

Figure 1 shows the experimental bench used. The rotor consists of 43 mm aluminum with high thermal conductivity (λ = 200 W/mK), on which 2.5 mm zircon [18], thermal conductivity insulation λ_{zir}=0.7 W/mK, was deposited via plasma projection. It is then heated from its back side using infrared lamps. The rotor is rotated up to a speed of 850 rpm, or Re_{ω} = 5.44×10^5. Aluminum is used to homogenize the temperature at the zircon/aluminum interface. The insulation allows to transcribing the variations of the convective exchange on its surface by temperature variations that can be measured using an infrared camera. A jet is imposed, with a nozzle diameter D=26 mm, to obtain the jet's Reynolds numbers such as $16.5 \times 10^3 \leq Re_{\mathrm{j}} = U_0.\mathrm{D}/\nu \leq 49.6\times 10^3$.

Ambient temperatures at the zircon / aluminum interface are measured with thermocouples. The numerical resolution the heat equation (Eq. (4)) in the insulation allows us to obtain a temperature cartography inside the insulation. Considering the radiated φ_{ray} flux by writing a flux balance on the rotor surface in steady state then allows us to know the local convective flux on the rotor, as well as the convective exchange coefficient h (Eq. (5)), calculated with the ambient temperature T_{∞} measured outside the gap. This temperature serves as a reference for calculating all thermo-physical quantities of air. The device used provide us to perform calculations assuming zero tangential heat flows in the insulation, considering radial flows in the insulation depth. Placing ϕ_{cd} the conductive heat flux in the insulation at z=0 gives the expression of the local Nusselt number in Eq. (6).

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \times \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = 0 \tag{4}$$

$$h = \frac{\varphi_{cd} - \varphi_{ray}}{T_{(r,z=0)} - T_{\infty}} = \frac{\lambda_{zir}\left(\frac{\partial T_{(r,z)}}{\partial z}\right)_{z=0} - \sigma\varepsilon_r\left({T_{(r,z=0)}}^4 - {T_{\infty}}^4\right)}{T_{(r,z=0)} - T_{\infty}} \tag{5}$$

$$Nu = \frac{\lambda_{zir}\left(\frac{\partial T_{(r,z)}}{\partial z}\right)_{z=0} - \sigma\varepsilon_r\left({T_{(r,z=0)}}^4 - {T_{\infty}}^4\right)}{T_{(r,z=0)} - T_{\infty}} \times \frac{r}{\lambda_{air}} \tag{6}$$

The following expression could be used to obtain the average Nusselt number.

$$\overline{Nu} = \frac{2}{R} \times \frac{\int_0^r Nu_r\,(T(r,z=0)-\mathrm{T}_\infty)\,dr}{T(r,z=0)-T_\infty} \tag{7}$$

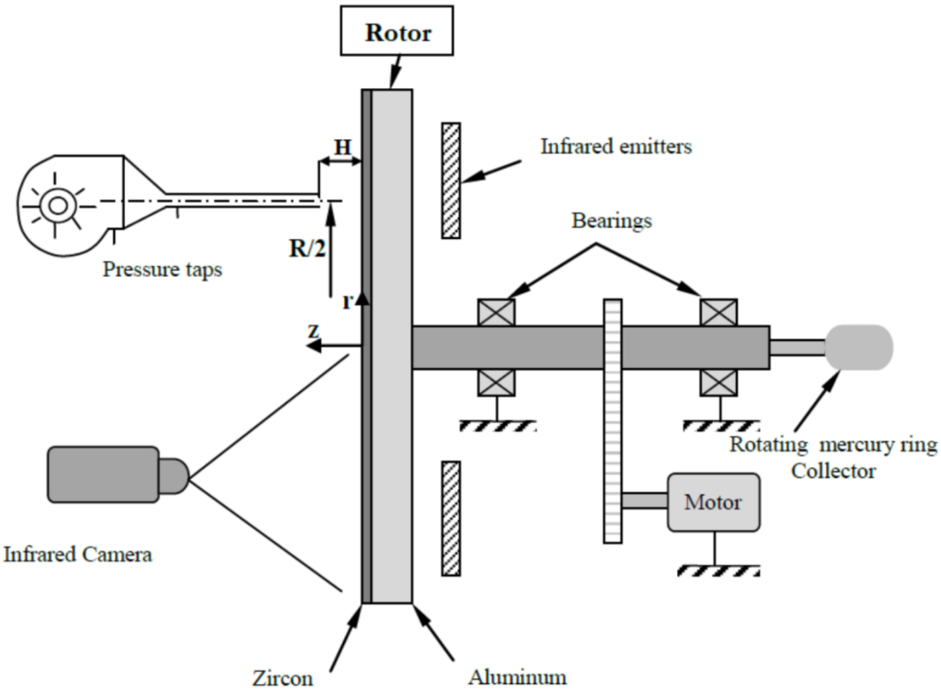

Fig.1. Experimental set-up

3. Numerical Simulation

In this work, convective transfers onto a rotor are modeled using the ANSYS Fluent [19] commercial numerical code, which is based on the finite volume method. The calculation is done for the steady state. The flowing fluid is air with assumed constant physical properties independent of temperature within the temperature range tested. Turbulence is accounted in a flow using a k-ε [20] turbulence model, which is commonly used for the calculation of fully turbulent flow. This model improvement is available in ANSYS Fluent, it is k-ε RNG (ReNormalization Group) [21] which is more suitable for computing rotational flows. Also, it is more reliable in terms to compute near the walls. Moreover, Yuan [22] obtains very good results for heat transfers on a stator facing a rotor using this turbulence model. So, we can achieve satisfactory results in a rotor. For using this model, the advanced option for wall treatment is activated to best calculate flows and heat transfers. This option enables resolution within the boundary layers rather than using correlation. It requires precise mesh sizes such as $Y^+ = 1$. In order to compare with literature and experimental data, we model a disk with an external diameter of D=0.62m for rotational Reynolds numbers Re_ω= 2.38× 10^5 to 5.44× 10^5 and the jet's Reynolds number Re_j= 16.5× 10^3 to 49.6× 10^3.

3.1 Mesh and Boundary Conditions

The computation field is illustrated in Figure 2 with the axis system, boundary conditions, and mesh topology. The problem is asymmetrical because adding an eccentric air jet imposes a three-dimensional model. We are modelling a disk having the same radius (R=0.31m), as well as the geometric characteristics of the rotor as described in section 2. a jet is imposed with a nozzle diameter D=26 mm. In order to converge the computation, it is recommended in a software documentation [19] to change the reference for defining speeds. Thus, it is not the disk that rotates but the air. At the inlet of the field, a uniform velocity and temperature (U_0 and T_∞) are imposed. On the rotating disc walls, an adhesion condition and a uniform temperature T_p=80°C are imposed. In order to properly describe the local thermal characteristics, a regular mesh of hexahedral is generated in the study domain. An adequate refinement is imposed near the walls so that a first parietal mesh satisfies condition $Y^+ = 1$. The independent study of the solution vis-à-vis mesh size leads to the use of a mesh size with a cell number ranging from 6×10^6 to 7×10^6 hexahedral cells. The rotation speed is taken zero in the fixed marker. The rotor is defined as stationary in the rotating marker related to air.

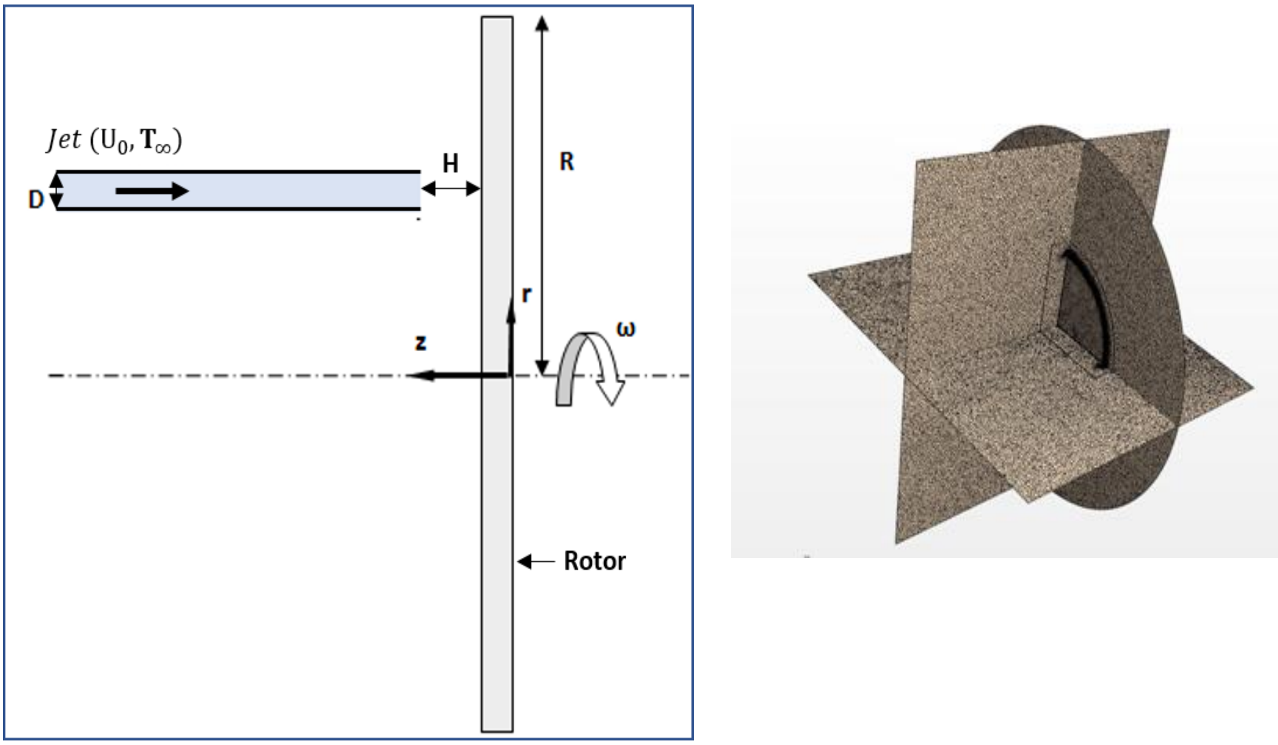

Fig. 2. Field of study and boundary conditions

3.2 Numerical Scheme

In this work, ANSYS Fluent is used for the computation of fluid dynamics, as well as for drawing, meshing and setting boundary conditions. The Navier Stokes equations, turbulent field transport, and energy equation are solved using finite volume method. The SIMPLE algorithm is used to solve the coupled velocity-pressure equation. A second order upwind discretization [23] is chosen for solving convective terms except the pressure correction equation where the PRESTO scheme is used. The convergence criterion is fixed at 10^{-6} in order to achieve more precise convergence.

4. Results and Analysis

In this study, we present an analysis of local and average convective exchanges on a rotating disk, characterized respectively in terms local and average Nusselt number for different rotational Reynolds number Re_ω and jet's Reynolds numbers Re_j. The jet's Reynolds number jet Re_j is between

16.5×10^3 and 49.6×10^3. The effect of rotation on convective transfers is evaluated for $2.38\times 10^5 \leq Re_\omega \leq 5.44\times 10^5$.

Figure 3 illustrates local Nusselt numbers evolution obtained experimentally and numerically on the rotating disk surface according to a dimensioned radius (r/D) for $Re_j = 33\times 10^3$ and $Re_\omega = 2.38\times 10^5$ to 5.44×10^5. In the same figure, Pellé's experimental results [7] for a rotating disk without jet are also reported.

For a jet's Reynolds number Re_j fixed, the local Nusselt number is an increasing function of rotational velocity and radius. Near the impingement point r/D=6.5, there is a peak in local convective exchange, corresponding to higher Nusselt numbers in this region. This significant increase in heat exchange can be explained by an increase in radial velocities in the rotor boundary layer. This induces higher shear stresses near the rotating disk and consequently, an increase in the local Nusselt. This result was also observed by Poncet [24] and Angioletti [10] in the case of a rotating disk with an axial jet.

On the other hand, for small radii, the local Nusselt graphs for different rotational velocities tend to join as we move further away from the impact point towards the disk's center. For higher radii (r/D > 10), the rotation effect results in a faster increase in convective exchange. So, this shows decrease in jet influence in the disk's peripheral region where rotation velocity becomes more and more influential. Comparison of our numerical and experimental results with those obtained by Pellé [7], shows that the addition of an air flow induces greater heat exchanges compared to the case without jet.

Analysis of these results indicates that three areas can be identified: a jet-dominated area near the impingement point, a mixed area with low radii where heat transfers are dependent on both injection flow and rotational velocity. Finally, an area near the disk periphery where the jet's influence is reduced in favor of the rotational velocity. This distinction was carried out by Owen [11] and Popiel [14] in a rotating disk with a central jet. However, the delimitation of these influence areas in a single rotating disk in presence to an eccentric jet remains to be completed using supplementary investigation.

In Figure 4, we have presented the average Nusselt number evolution as a function of Re_j for the K-ε RNG turbulence model and for a fixed rotational Reynolds number $Re_\omega = 3.87\times10^5$. We also represented our experimental results on this graph.

Globally, it is noted that the increase in the injected air flow rate results in an increase of global heat exchange. In other words, increasing the injection fresh air flow increases global cooling of the rotating disk. In the range of rotational and jet's Reynolds numbers studied, our numerical results are in good agreement with experimental results. The mean relative deviation between the numerical and experimental values of Nusselt number remains in the error margin of experimental measurements with a mean relative deviation of less than 5%. Considering the accuracy of the experimental results, we can conclude that K-ε RNG turbulence model appears to give reliable results for heat transfers on a single rotating disk with an eccentric impinging jet.

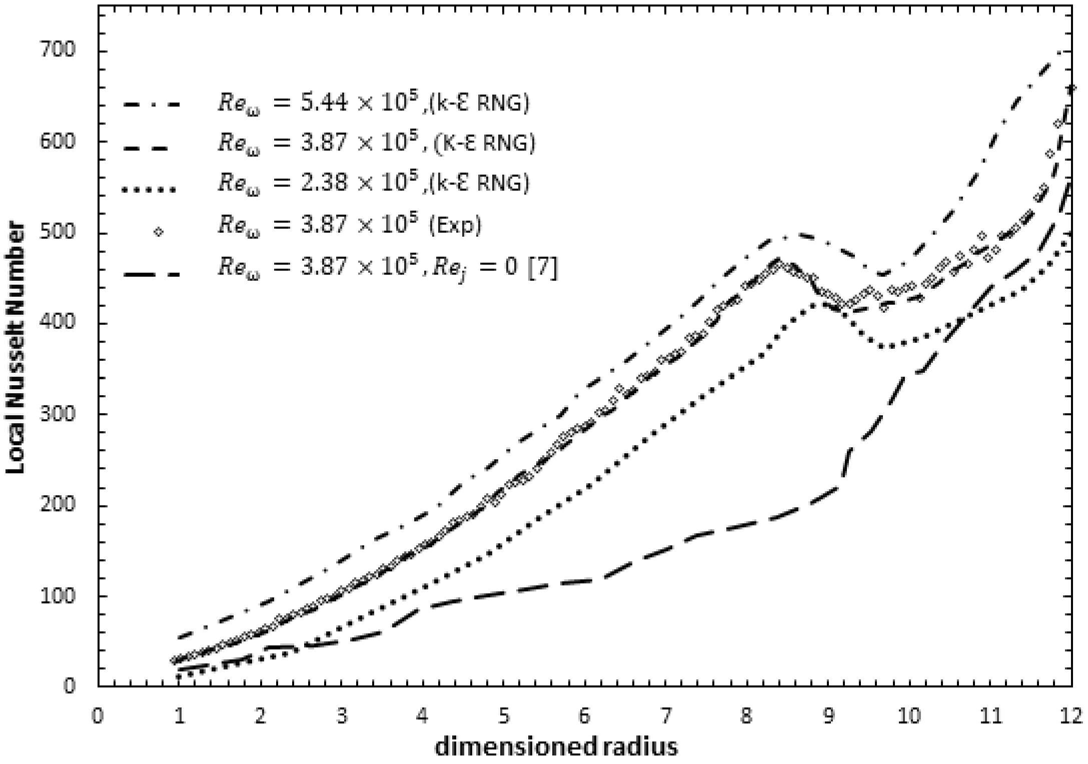

Fig. 3. Numerical and experimental local Nusselt numbers $Re_j = 33\times 10^3$

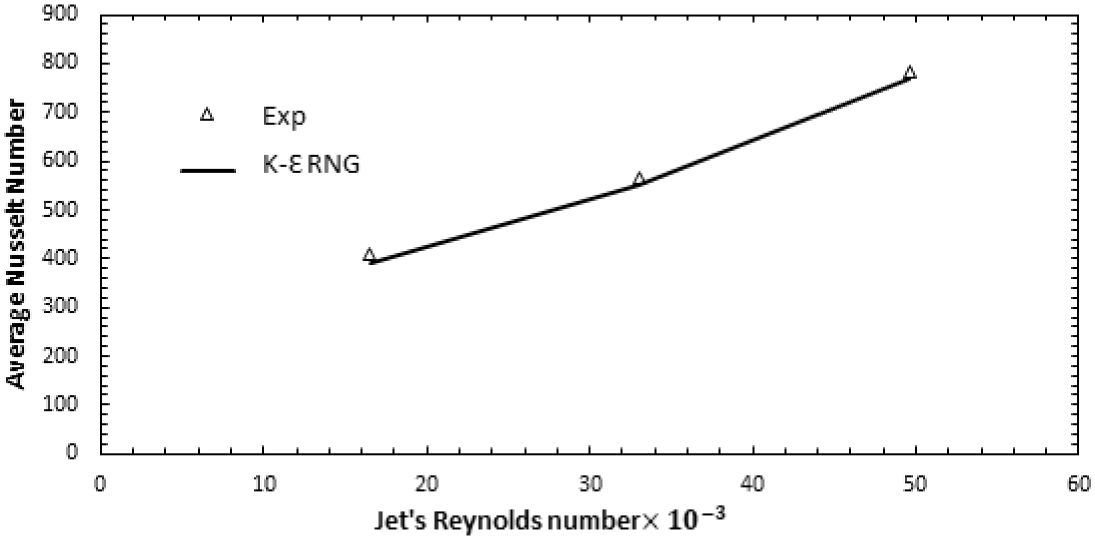

Fig. 4. Numerical and experimental average Nusselt numbers $Re_\omega = 3.87\times 10^5$

5. Conclusions

In this study, we present the influence of an eccentric impinging jet on convective heat transfers in a single rotating disk surface. The air jet influence on the Nusselt number radial profile has been studied for different values of Re_ω and Re_j. The fluid flow rate addition induces higher heat exchanges compared to the case without jet. This study also highlighted areas where the influence of rotation and jet are predominant for disk cooling. A numerical model for calculating convective transfer could be validated by comparing our numerical and experimental results. Numerical results also provide a satisfactory approximation of increasing the Nusselt number based on Re_ω and Re_j. This comparison revealed a satisfactory agreement using k-ε RNG turbulence model.

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