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Numerical investigation of an inclined offset jet

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Abstract— **A numerical investigation was conducted in order to study the heat transfer process of an inclined turbulent offset jet. The inclined bottom wall was subjected to a constant heat flux. Ansys Fluent was the used CFD solver for conducting the numerical simulations. Actually, the offset jet was considered two-dimensional with an offset ratio (OR) of 9, while the inclination angle (α) was varying from -20° to +20° and the Reynolds number(Re) was between 20,000 and 40,000. The effects of these two last parameters were examined in details. In this paper, a validation with old experimential data is provided aiming to prove the efficiency of the mesh size and the turbulence model choices. Furthermore, results have shown that the thermal behaviour of such flow is mainly governed by its velocity, which is represented by a corresponding Re number. Regarding the effect of the inclination angle, it was found that the decrease of α intensifies the convective heat transfer. However, α' s effect on the heat transfer turned out to be not significant comparing to the Re' s effect, which was seen to be quite important and dominant.**

Keywords— **Offset jet, Turbulente, Inclination, heat transfer, numerical investigation**

I. INTRODUCTION

Jet flows have been extensively investigated, either through experimental or numerical studies, and still they are the subject of recent and current scientific works. This fact is owing to the multiple and diverse industrial applications of this such particular type of flow. In fact, offset jets may be found in combustion chambers, for the mixing process, in evaporator, in cooling and heating systems and in other different applications. Hence, in this present work, we adopt a two-dimensional Offset Jet flow as the study's subject. First, offset jet is defined when the fluid is discharged from a nozzle, that is situated at certain distance, h, from the horizontal. Besides, it is characterized essentially by the "Coanda" effect, which makes the fluid deflect towards the bottom wall, due to the creation of sub-atmospheric pressure zone that promotes the deviation of the fluid. Further, the fluid attaches the bottom wall at one specific point, called "The reattachment point", Fig 1, which represents the limit point of the recirculation region and the starting point of the impingement one. In fact, offset jet is still considered as one of the complicated flows in term of its dynamic and turbulent features, that is why this work aims to study the thermal behavior of one specific configuration. The investigated flow is a two-dimensional offset jet attaching a heated wall, that makes a varying inclination angle with the horizontal, from -20° to +20°. Moreover, the fluid, the air, is ejected from a nozzle with an OR of 9 and with various inlet velocities, that correspond to Re numbers going from 20,000 to 40,000. Thus, the effects of these changing parameters will be discussed and presented. Among the first scientific works on offset jets are Bourque and Newman [1]'s investigation, in 1960. In fact, they examined experimentally offset jet aiming to understand its mean flow characteristics. Besides, in 1977, Patankar [2] solved numerically a three dimensional turbulent jet flow field using the Reynolds Average Navier Stocks, RANS, method. Additionally, Pelfrey and Liburdy [3,4] conducted two experimental studies in order to examine the flow field characteristics as well as the turbulent features of such a flow. Furthermore, Nasr et al [5,6,7,8], studied extensively offset jet flows. First [5], they compared experimentally, between the dynamic behavior of a two parallel plane jet and a simple offset jet to see which are the common and different features they present. It was found that the size of the recirculation region is considerably larger for a single offset jet compared to the two parallel plane jets flow case. In addition [6], they proved that the Standard k-ε present a good efficiency in predicting this flow and the use of the side plates is mandatory to enhance the two-dimensionality of the flow. Finally [7,8] and most important, they investigated, numerically and experimentally, an inclined offset jet, mainly in the recirculation region. As results, the reattachment point was found to move downstream while the increasing of the inclination angle and the Reynolds Stress turbulence Model it was judged as the most adequate turbulence model owing to its agreement with experimental data. Understanding the dynamic flow field on an offset jet,

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in terms of its velocity field and its turbulence characteristics, was the main purpose of the previously mentioned scientific works. However, as the offset jets exist in several thermal systems, it seemed mandatory to examine the thermal characteristics of different application of offset jet flows. That is why, other several studies of this particular type of flow were done aiming to understand its thermal behavior under certain conditions. In this regard, Holland and Liburdy[9], studied experimentally a heated and turbulent offset jet attaching an adiabatic wall. The obtained temperature field measurements gave evidence on the dependency of the thermal behavior on the offset ratio value, essentially near the wall region. Further, Song [10] examined the simultaneous effects of the wall inclination and the offset ratio variations on the flow's dynamic behavior and the flow's thermal characteristics. In this study, the reattachment point positions was detected to be in the near field of maximum local Nusselt number values, which seemed interesting to find. More recently, Gao[11] examined the Reynolds number and the offset ratio effects on the measurements of the convective heat transfer coefficient for a planar attaching jet. The results showed that the local heat transfer coefficient presented a peak almost at the reattachment point, similar to Song [10].

To conclude, offset jets are still an interesting research subject owing to their complex flow field behavior , their sensitivity towards several parameters and most important their wide range of applications. That is why in this present work an inclined heated and turbulent offset jet is examined. This paper aims mainly at studying the simultaneous effects of two different and independent parameters (Re and α). The main reason of this scientific work is to determine which is the most significant parameters that affect the heat transfer phenomenon and enhances it. Thereby, a two-dimensional and turbulent offset jet will be investigated. The Re is in the range from 20,000 to 40,000, the OR is fixed to 9 and the inclination angle from -20° to +20°, Fig. 2.

II. Mathematical Formulation

During this work we adopted the same geometric configuration as Kim and Yoon[11]. Air is issued from a two-dimensional nozzle, having an aspect ratio of 40, which proves the two-dimensionality of this configuration. Besides, the lower wall is subjected to a constant heat flux. The chosen domain dimensions guaranteed no effect on the flow propagation and development. Moreover, we adopted the following hypothesis to accurately solve the governing equations.

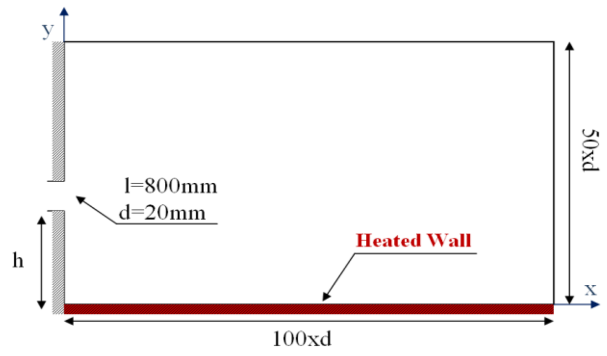

Fig. 1 Adopted Geometry

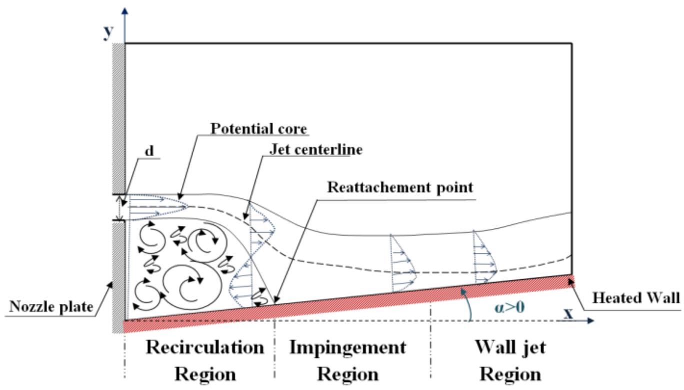

Fig. 2 Working configuration

- The flow is stationary and turbulent fully developed.
- The jet is considered two-dimensional.
- The jet is ejected in the downstream direction.
- The air thermo-physic properties are assumed to be constant.
- The heat flux is assumed to be constant.

The Reynolds-Average Navier-Stocks and energy equations are modeled in a Cartesian tensor as follows:

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0 \quad (1)$$

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right]+\frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \quad (2)$$

$$\frac{\partial}{\partial x_j}\left(\rho T u_j\right)=\frac{\partial}{\partial x_j}\left[\frac{\mu}{Pr}\frac{\partial T}{\partial x_j}-\rho T'\mu'\right] \quad (3)$$

Equation (2), presents an additional term that reflects the effect of turbulence: It is the Reynolds stress constraint, which should be modeled to close (2).

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The Boussinesq approximation gives a relationship between the shear stress and the mean velocity gradient in order to model the Reynolds stress constraint. The relationship is presented as follows:

$$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_t\frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \qquad (4)$$

Furthermore, Figure. 3 represents the different adopted working conditions and the mesh distribution. As for the emission conditions, a uniform velocity profile was applied at the nozzle inlet, U=28.47 m/s, with a constant turbulence intensity of 0.01% and a Reynolds number of 39,000. With regards heat flux, as it was assumed to be constant, 1951 W/m², These conditions were used by Kim and Yoon[11].

III. RESULTS AND DISCUSSION

A. *NUMERICAL VALIDATION*

Validating our numerical code is the first done step in order to show the efficiency of the chosen turbulence model and the selected mesh size and type. In this regard, three sizes of meshes, $Mesh_1$, $Mesh_2$, and $Mesh_3$ each having 11,875, 33,600 and 52,332 non-uniform and quadratic cells, respectively, were compared in terms of their capability of detecting the local Nusselt number on the heated plate. Figure 4 shows a mesh of 33,600 quadratic cells is quite efficient. In addition, four different turbulence models, RNG k-ε, Realizable k-ε, Standard k-ω, and SST k-ω, were tested, Fig. 5, and the SST k-ω proves its great agreement with the experimental result of Kim and Yoon[11].

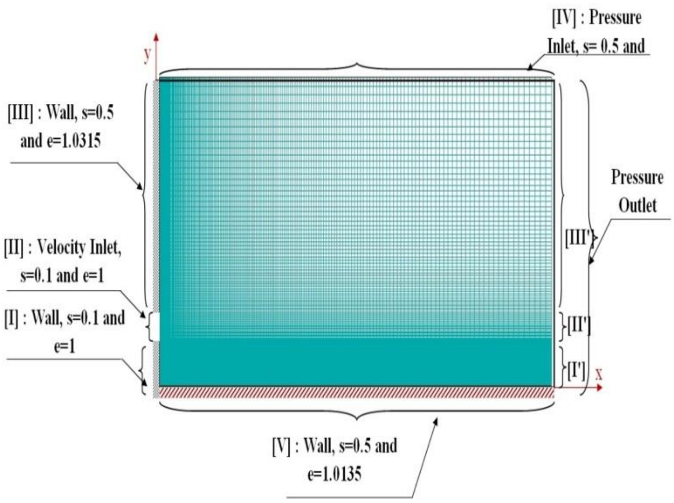

Fig. 3 Adopted working conditions and the mesh distribution, 's' is the spacing value and 'e' is the expansion ratio

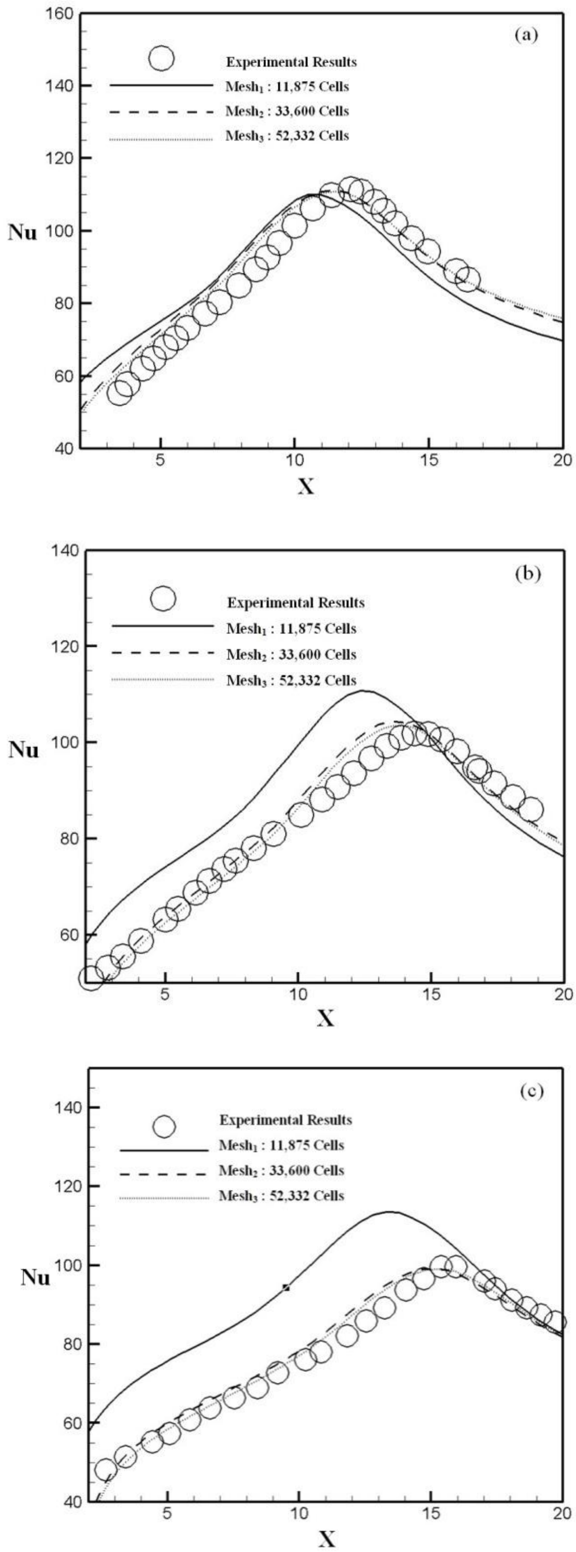

Fig. 4 Mesh size test: (a): OR=5, (b): OR=6.5, (C): OR=7.5

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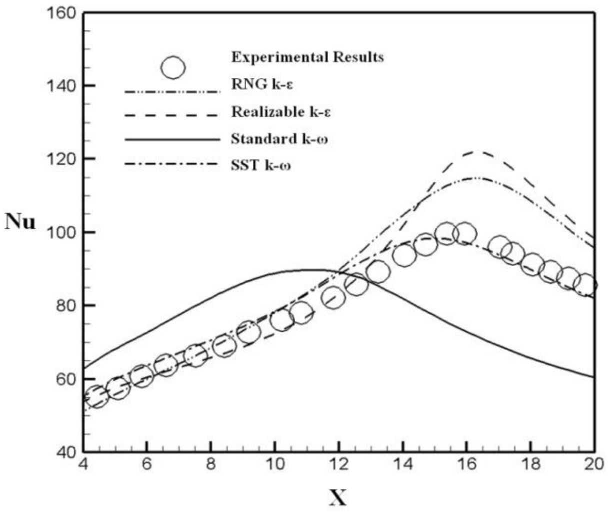

Fig. 5 Turbulence model test

B. THERMAL CHARACTERISTICS

The studied geometric configuration is presented in Fig.2. This figure shows that the fluid is issued from a two-dimensional nozzle, with different velocities that correspond to Reynolds numbers between 20,000 and 40,000, besides the OR is set at 9. Moreover, the heated wall inclination angle is between -20° to +20°, Fig.2. During this work, the mathematical equations, RANS, that govern this flow, are solved numerically in order to investigate the bottom wall inclination and the Re simultaneous effects on the heat transfer phenomenon.

Figure 6 illustrates the local variation of the Nusselt number, detected on the heated plate, in the whole range of inclination angle and two different Reynolds number, 20,000 and 40,000.

This figure demonstrates the effect of the wall inclination, as well as the Re number, on the convective heat transfer between the ejected air and the heated wall. As for α's effect, it is clearly seen that every increase of α' value, from -20° to +20°, leads to the enhancement of the heat transfer process. However, this amelioration is mainly noticeable in the limit of the recirculation region, where Nu_{max} presents a remarkable rise, that reaches 40% from α=-20° to α=+20°, with the increase of the inclination value. In fact, this result makes sense, as the fluid reaches the heated bottom wall with a higher Kinetic Energy that promotes the convective heat transfer phenomenon when α is increasing. Moreover, throughout the impingement and wall jet regions, the variation of the bottom wall inclination seems to have no signifiacant effect.

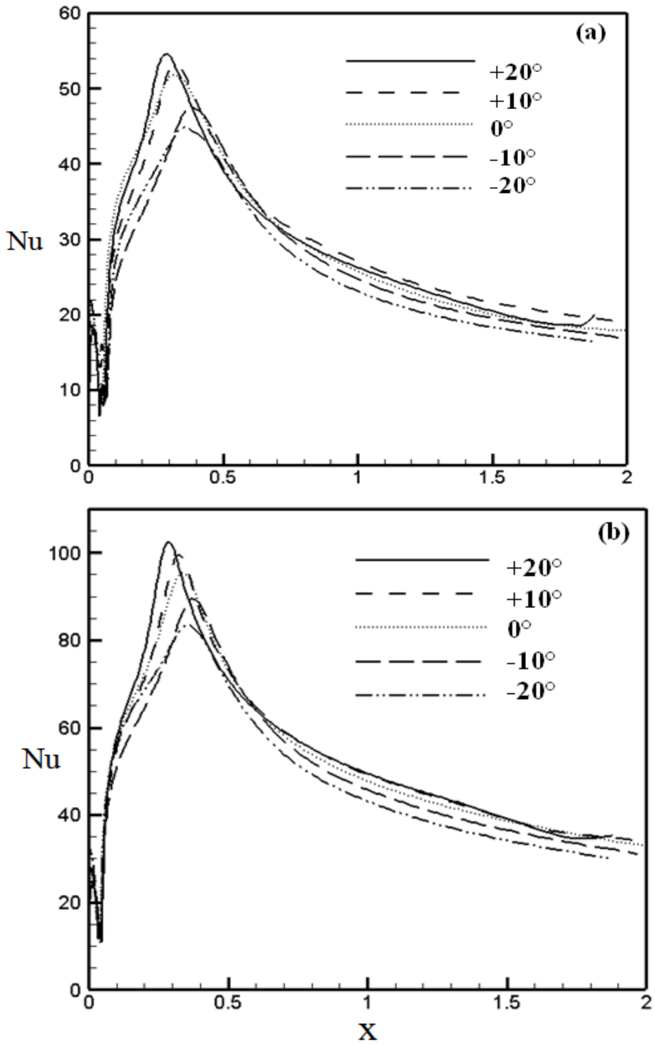

Fig. 6 Local Nu distribution: (a): Re=20,000 (b): Re=40,000

On the other hand, the Re number variation seems to govern more, than the α variation, the convective heat transfer and its effect appear almost throughout the whole plate's length. In fact, the comparison between these two Re number outlines that the heat exchange between the ambient air and the heated plate is intensified with nearly 45%. For instance, for α=+20° and Re=20,000, Nu_{max} is around 55 while for the same inclination angle and Re=40,000 it is detected to be nearly 100.

In fact, the forced convection process depends strongly on the fluid velocity, in other words: the Re number, and as the flow is turbulent fully developed, the kinetic forces are important relative to the viscous forces and this fact ameliorates the convective heat transfer exchange between the fluid and the solid wall.

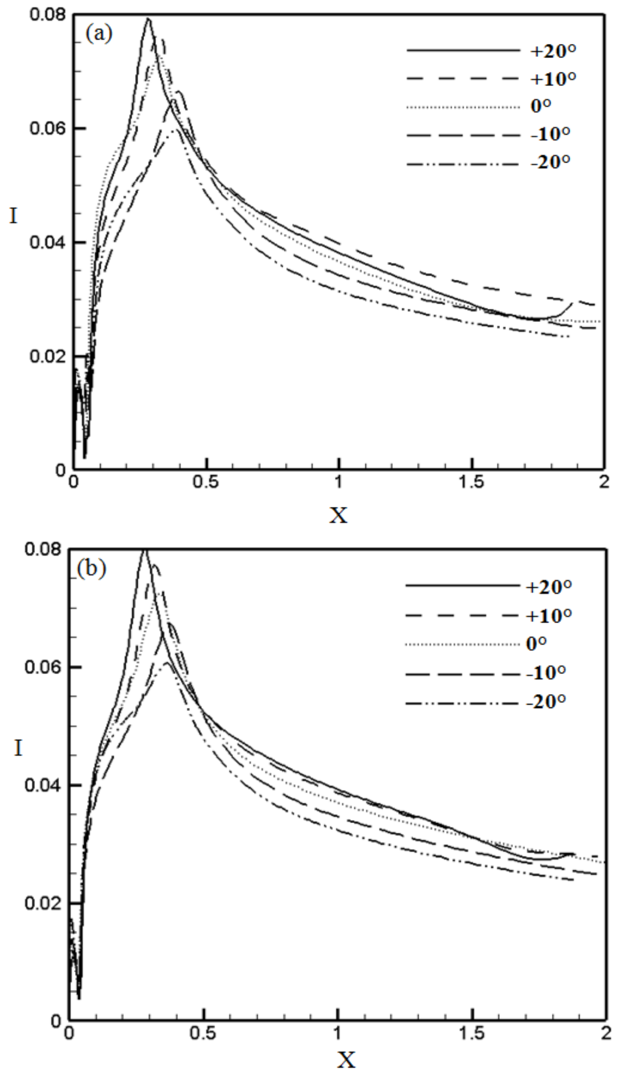

Fig. 7 Local distribution of the turbulence intensity I

Moreover, in order to investigate the turbulent intensity related to the same (Re, OR, α) combinations, Fig. 7 gives information on the local distribution of I.

The first thing to note is that Nu_x and I_x present almost the same local paces, which highlights the dependecy relationship betwwen the heat transfer and the turbulent features. Moreover, I and Nu_x peak almost at the same downstream positions, which means that the maximum heat transfer is along with a maximum turbulence intensity.

In addition, unlike the Nu_x evolutions, the Re has partically no effect on I. In fact, only a slight increase of I is noted with the rise of Re number. Meanwhile, the inclination's effect turns out to be more significant as it is more noteworthy.

Further, in the recirculation region, the turbulence intensity increases with α, for both Re number. While in the impingement and wall jet regions and for low Re, I is maximum for α=10°.

IV. Conclusion

This paper represents a numerical investigation of a two-dimensional and turbulent offset jet. The offset ratio (OR) was fixed in 9 while the Re number was varied from 20,000 to 40,000 and the bottom wall inclination was between -20° and +20°. Besides the bottom wall was subjected to a constant heat flux. The simultaneous effects of Re and α were studied in order to see which parameter governs the most heat transfer process. The local Nusselt distributions on the bottom wall have shown that the enhancement of the heat transfer, between the heated wall and the ejected fluid, is more guaranteed with the increase of the fluid velocity, which corresponds to the Re number. Furthermore, the turbulence intensity highlighted the presence of a relationship between the turbulent features of this particular flow and the amelioration of the heat exchange phenomenon.

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