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Simulation of Turbulent Flow and Heat Transfer Through a Duct with Baffle Plates

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Abstract

In this paper, a numerical study of the turbulent air flow and heat transfer through a duct with baffle plates is performed. The effect of baffles arrangement baffles number, baffle height and baffle thickness on the flow and heat transfer characteristics is investigated. The fully elliptic differential equations that describe the flow and heat transfer are integrated using the finite volume approach. The standard k-є model with wall functions has been submitted to model the turbulence.

The obtained computed results show that the boundary layer separation and recirculation regions are significantly affected with the height, thickness and arrangements of the baffle plates. Also the results demonstrate that in the presence of the baffle, the heat is significantly enhanced. The bulk temperature values along the duct are decreased with the increase of Reynolds number for all the studied cases.

الخلاصـــــة

في هذا البحث أجريت دراسة عددية للجريان الاضطرابي وانتقال الحرارة داخل مجرى هوائي يحتوي على صفائح إعاقة. تم دراسة تأثير ترتيب الصفائح، عدد الصفائح، المسافة بين الصفائح وطول الصفيحة وسمكها على خصائص الجريان الاضطرابي وانتقال الحرارة. تم دراسة المعادلات التفاضلية التي تصف الجريان وانتقال الحرارة بأستحدام إسلوب الحجم المحدد.عولج تأثير الاضطراب بأستحدام نموذج (k-є) مع دالة الجدار.

بينت النتائج المستحصلة من هذه الدراسة أن انفصال الطبقة المتاخمة ومناطق إعادة التدوير قد تأثرت بصورة ملحوظة بارتفاع الصفيحة، سمك الصفيحة وترتيب الصفائح. كما بينت النتائج إن انتقال الحرارة قد ازداد مع وجود هذه الصفائح. أيضا لوحظ أن قيم متوسط درجة الحرارة على طول المجرى قد قلت مع زيادة رقم رينولدز.

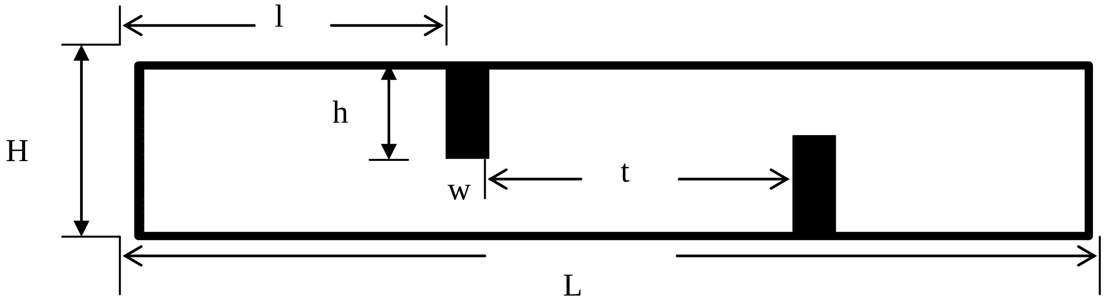
1. Introduction

Flow in channels with baffle plates occurs in many industrial applications such as heat exchangers, chemical reactors, filtration and desalination. In shell and tube heat exchangers, the baffle plates are commonly used in the shell-side fluid to flow across the shell. These baffles increase the turbulence and the heat exchange time between the cross flow and heated surfaces. The turbulent flow and heat transfer through a channel with baffle plates has been the topic of extensive the experimental and numerical research. Bemer et. al. [1] studied the forced convection in a channel with baffle plates. They conducted that the laminar behavior is expected at a Reynolds number below 600. They mentioned that the situation of the flow was free from vortex shedding. Kelkar and Patankar [2] demonstrated that the presence of baffle plates caused the increase of the Nusselt number and friction coefficient. They reported that theses parameters increased with the increase of Re. They showed that the flow is characterized by strong deformation and large recirculation regions. Web and Ramathyani [3] studied the flow characteristics and heat transfer in a parallel plate channel with staggered baffles. Their models depend on the periodically fully developed flow conditions proposed by Patankar et. al. [4]. The turbulent flow and heat transfer through a duct with baffle plates were analyzed by Habib et. al. [5]. The heat flux was uniform on the upper and lower walls. The results show that the local and average Nusselt numbers increased with the increase of Re. Also the pressure drop increased as baffle height did. Demartini et. al. [6] used the experimental techniques to investigate the pressure drop and stream wise velocity distribution of the turbulent flow through a channel with baffles. Flow visualization and pressure drop measurements have been involved to study the effect of baffle configuration on the flow behavior [7,8,9,10]. Prithiviraj and Andrews [11] investigated three dimensional flows in shell and tube heat exchanger. They adopted collocated fully implicit control based calculation procedure. They focused on the spacing between the baffles and pressure drop. An experimental study of the local heat transfer characteristics and the associated frictional head loss in a rectangular channel with inclined solid and perforated baffles has been donning by Prashanta [12]. The flow Reynolds numbers was varied between (12,000 to 41,000). The results show that the local Nusselt number increased with the increase of Re.

In this work, the turbulent flow and heat transfer through a duct with baffle plates is studied. Multiple arrangements of baffles with variation of the number and the spacing between these baffles have been investigated. The turbulence was modeled using k-ϵ turbulence model. The aim of the present study is to investigate the turbulent flow in a duct with varying the arrangements and dimensions of the baffle plates. Also to asses the ability of the standard k-ϵ with wall function to predict the complex inherent turbulent flow and heat transfer in this type of the problems.

2. Problem Description

The problem treated is a 2D turbulent flow and heat transfer in a duct with baffle plates of varying arrangements. The solid walls are hot while the inlet flow is cold. Different dimensions of the baffles with various arrangements are examined. The general features of the physical problem are depicted in **Fig.(1)**.



$$L=1.78\text{m},\quad H=0.146\text{m},\ \frac{h}{H}=0.58$$

Figure (1) Schematic of the physical problem

3. Mathematical Formulation

The turbulent flow and heat transfer through a duct with baffle plates are depicted by the steady Navier-Stockes and energy equations. Assuming constant properties and using a Boussinesq approximation to account for the coupling between the energy equation, momentum and k-ϵ equations. The average Reynolds governing equations that describe the motion of the turbulent flow and energy are defined as follows:

$$\frac{\partial}{\partial x_i}(\rho U_i)=0 \qquad (1)$$

$$\frac{\partial U_i U_j}{\partial x_j}=\frac{-\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial U_i}{\partial x_j}-\overline{\rho u_i u_j}\right) \qquad (2)$$

$$\frac{\partial U_i T_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\mu}{Pr}\frac{\partial T_i}{\partial x_j}-\overline{\rho u_i t_j}\right) \qquad (3)$$

where, $\overline{\rho u_i u_j}$ *and* $\overline{\rho u_i t_j}$ *constitute the second-moments statistical correlation or so-called Reynolds stresses and thermal stresses.*

4. Turbulence Model

One of the most widely spread models is the standard k-ϵ model proposed by Launder and Spalding [13]. This model implies two transport equations i.e. turbulent kinetic energy and the dissipation of turbulent kinetic, as follows:

$$\frac{\partial \rho U_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \rho\left(P_k - \varepsilon\right) \quad \text{(4)}$$

$$\frac{\partial \rho \varepsilon U_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho\frac{\varepsilon}{k}\left(C_{1\varepsilon} P_k - C_{2\varepsilon}\varepsilon\right) \quad \text{(5)}$$

where, the shear production term, (P_k) are define as:

$$P_k = \upsilon_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \quad \text{(6)}$$

and the eddy viscosity is define as:

$$\mu_t = \rho c_\mu \frac{k^2}{\varepsilon} \quad \text{(7)}$$

The model coefficients are (σ_k; σ_ϵ; $C_{1\epsilon}$; $C_{2\epsilon}$; $C\mu$) = (1.0, 1.3, 1.44, 1.92, 1.0, 0.09) respectively. The flow parameters at inlet are described as follows:

$$k_o = 0.01 U_o^2$$

$$\varepsilon_o = k_o^{1.5} / \lambda H \;,\; \lambda = 0.005$$

$$U_{inlet} = U_o$$

To remedy the large steep gradients near the walls of the duct and the baffle plates, wall function approximation used by Versteege [14] is adopted.

5. Numerical Procedure

Finite volume method (FVM) is used to solve the considered mathematical model. This gives a system of discretisation system which means that the system of elliptic partial differential equations is transformed in to a system of algebraic equations. The essence of discretisation is to select appropriate option of the balance between convective and diffusion terms through the boundary of each control volume. The general governing equations take the following form [14]:

$$\mathrm{div}\left(\rho U \Phi\right) = \mathrm{div}\left(\Gamma \,\mathrm{grad}\Phi\right) + S_\Phi \quad \text{(8)}$$

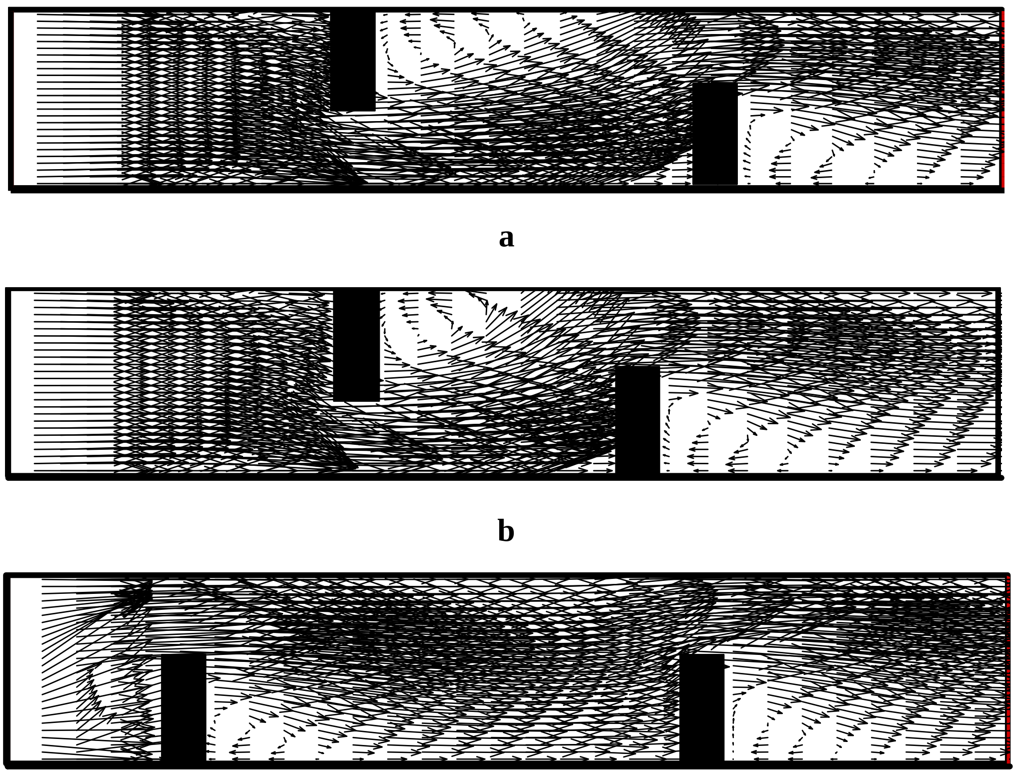
By using finite volume method the discretisation of east side flux by hybrid scheme gives the form [14]:

$$\left(\rho U\Phi - \Gamma\frac{\partial\Phi}{\partial x}\right)_e = (\rho U)_e\frac{\Phi_p + \Phi_e}{2} - \Gamma_e\frac{\Phi_p + \Phi_e}{\Delta x_e} \quad \text{.................................} \quad (9)$$

The solution of these equations is performed by implicit line by line Gauss elimination scheme. A teach computer program is developed to attain the results of the numerical procedure using the pressure velocity coupling (SIMPLE algorithm). There is non linearity inherent in this coupling of equations. A relaxation factors are needed to obtain the convergence. The values of these relaxation factors depends on the conditions of the flow and on the type of the case studied. In this work, the constructed grids are non-uniform rectangular grids. These grids are staggered for the vector variables and not staggered for the scalar ones.

6. Results and Discussion

The computational results of the velocity vectors for staggered and inline baffle plates are found in **Fig.(2)**.



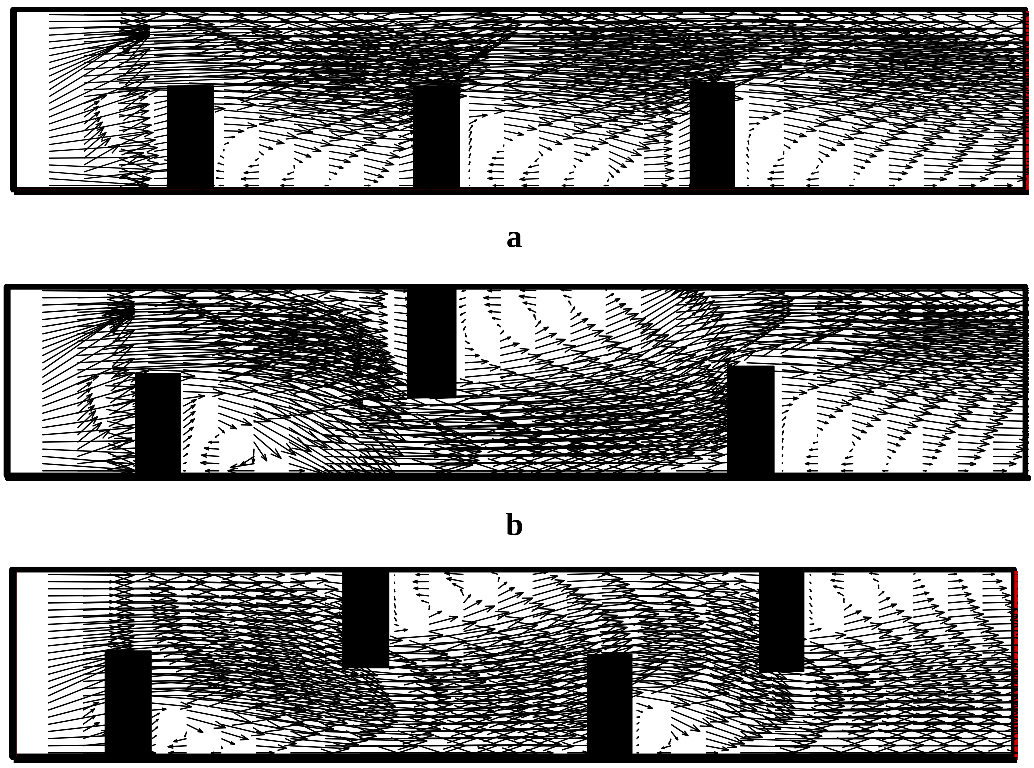
a

b

c

Figure (2) Effect of baffle plates arrangement on the velocity field distribution For Re =6100

It is evident there is a separation of boundary layer, just close the upstream of the baffle and a recirculation zone behind the baffle plate. The figure shows that the spacing between the baffle plates affected the recirculation region length as depicted in case (a) and (b). The spacing between the baffles in case (a) is larger and the recirculation is increased. The arrangement of case (a) and case (b) is called a staggered. Also the figure shows that the flow between the baffle is accelerated and the values of the velocity are high at the upper part of the duct. In case (c), the baffle plates are in line arrangements. The recirculation region is less compared with case (a). **Figure (3)**, demonstrates the effect of increase the number of the baffles on the velocity field distribution. It is clear that in inline arrangement, case (a), the increase of the number of the baffles increases the recirculation region especially down stream the second and third baffle.



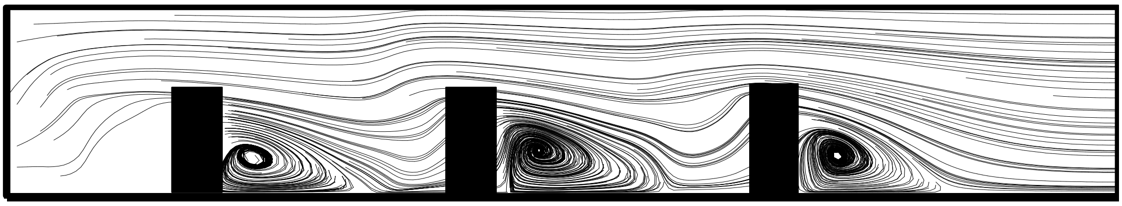
a

b

c

Figure (3) Effect of number of baffle plates on the velocity field distribution

When the number of baffles in the staggered state is increased ,the recirculation regions and separation of boundary layer is increased for the three baffle plates and decreased for the four ones as shown in case (b) and case (c). The stream lines are deflected just close to the baffles and a recirculation occurs down stream of the baffle as shown in **Fig.(4)**.



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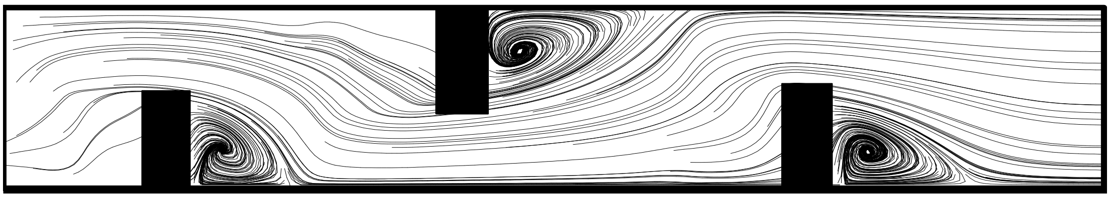

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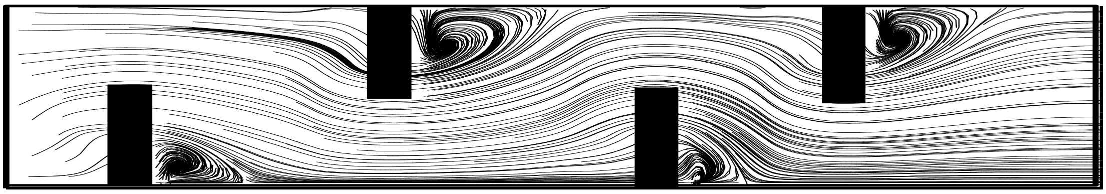
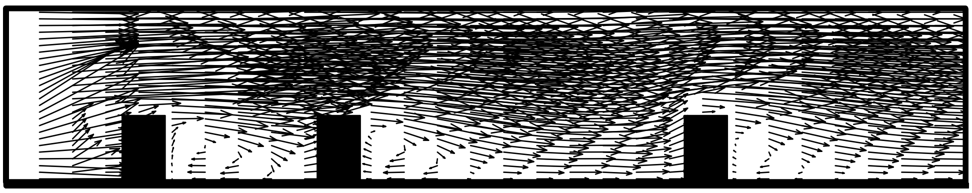


c

Figure (4) Streamlines with different numbers and locations of baffle plates

The separation of the boundary layer and recirculation regions are strongly effected with the baffle thickness and baffle height as depicted in **Fig.(5)** and **Fig.(6)**. **Figure (5)**, shows the influence of baffle height on the boundary layer separation regions both in inline and staggered arrangements. It is evident that the recirculation regions are decreased with decrease of the baffle height. The acceleration of the flow is decreased, hence the values of the velocity is less because the contraction area is larger.



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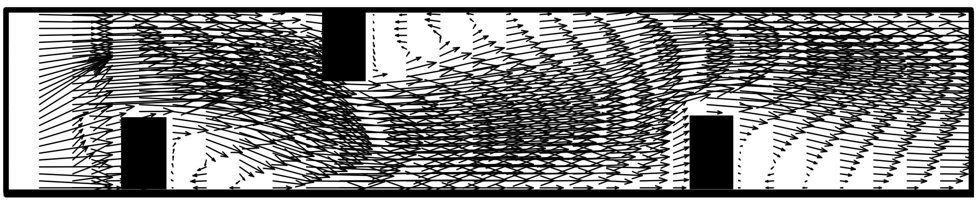
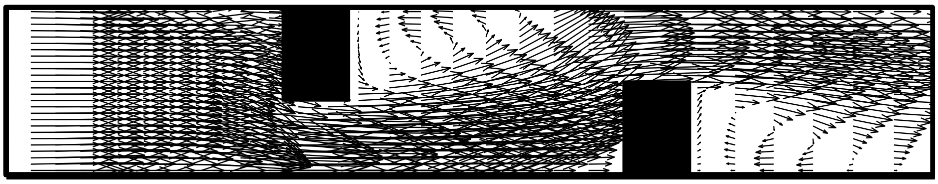


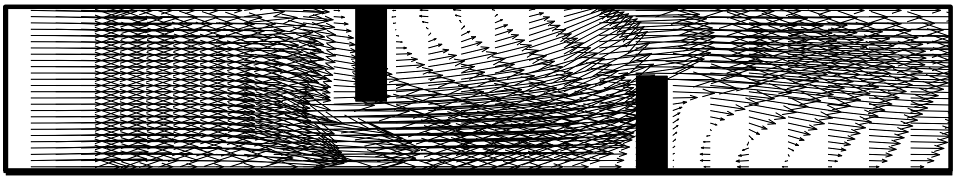
b

Figure (5) Effect of baffle plate height on the flow field

Figure (6), exhibits the effect of the baffle thickness on the flow field distribution for both mentioned arrangements. As the case (a) shows, the recirculation becomes stronger when the baffle thickness increased. However, the values of the velocity on the upper wall is less than that in **Fig.(1)**.



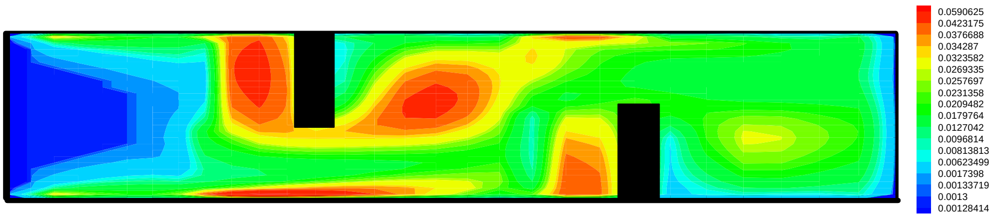
a



b

Figure (6) Effect of baffle plate width on the flow field

In case (b), when the thickness is decreased, the separation of boundary layer and recirculation region is decreased. **Figure (7)**, demonstrates the contour plots of the turbulent kinetic energy. The figure shows that the higher values of the turbulent kinetic energy occur at the regions upstream and just above the baffle. This due to acceleration of the flow in these regions, however the case (a) offers the higher values of the turbulent kinetic energy.



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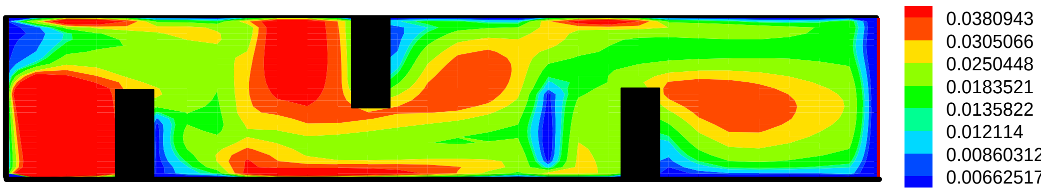

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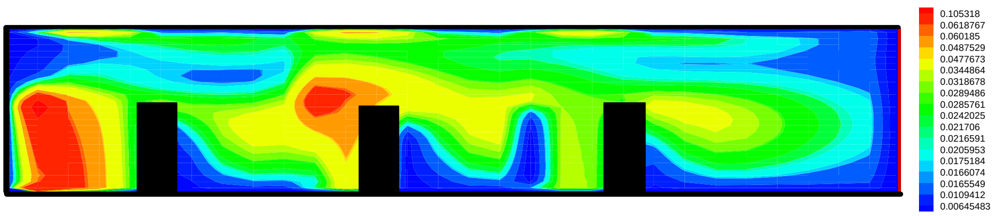

c

Figure (7) Contours of turbulent kinetic energy with Re=6100

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Figure (8), exhibits the variation of the local Nu on the duct length for different baffle plates arrangements with a specified Reynolds number. As the figure shows, the largest values of Nu occur at the three staggered baffles, hence the heat transfer enhancement is more than the two staggered and three baffles inline. This fact is clarified when these results are compared with the results of the flow in a duct without baffle plates, as shown in **Fig.(9)** .

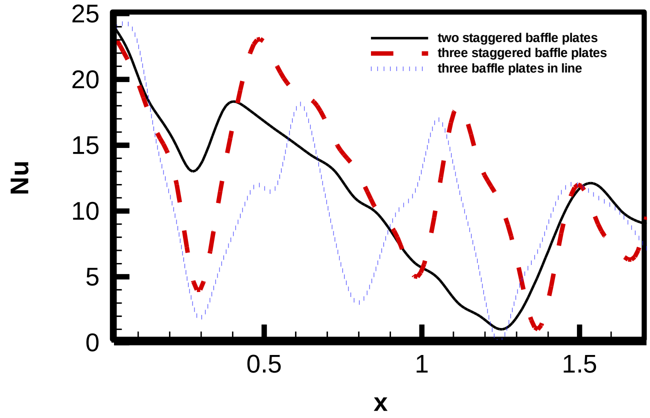
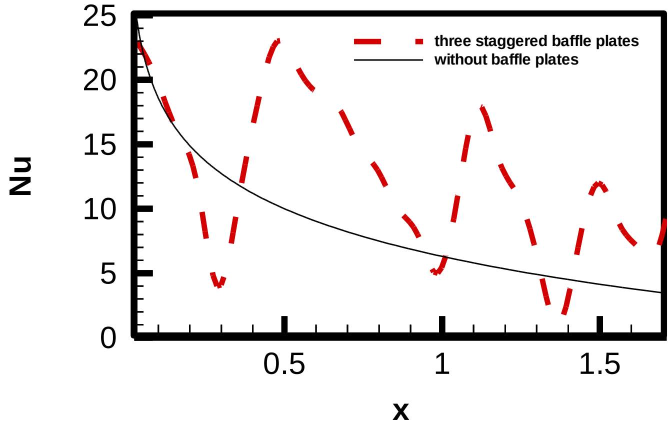


Figure (8) Variation of Nusselt number along the channel length with Re=6100



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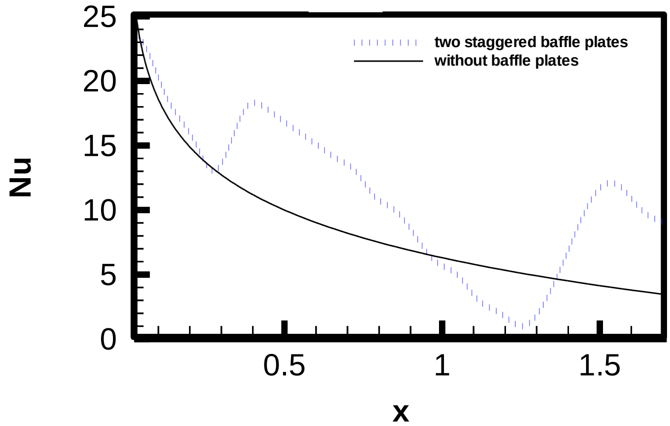

b

Figure (9) Comparison of distribution of Nu with and without baffle plates

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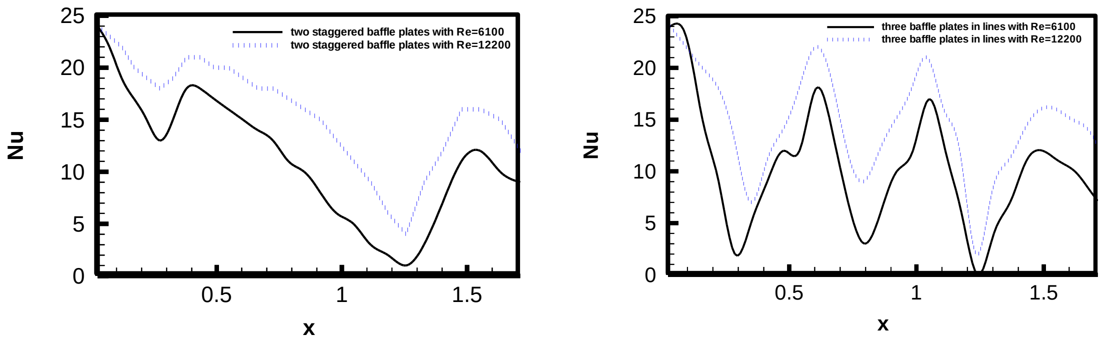
The Nu values of the flow with baffle plates are higher than that with no baffles. This enhances heat transfer. The enhancement of heat transfer is more pronounced than the momentum. The effect of Re on the local Nu values is seen in **Fig.(10)**. The results show that the local Nu is increased with the increase of Re, because when the Re increase, the turbulence increases and the recirculation region becomes stronger and consequently the heat dissipation increases.



a **b**

Figure (10) Effect of Re on Nu numbers distribution

Figure (11), shows the effect of Re on stream wise velocity. The velocity increase with the increase of Reynolds number, this is dominant in all the studied cases. The variation of averaged Nu versus Re is depicted in **Fig.(12)**. The results show that the average Nu increases with increase of Re for a specified range after the average Nu seems to be have constant values.

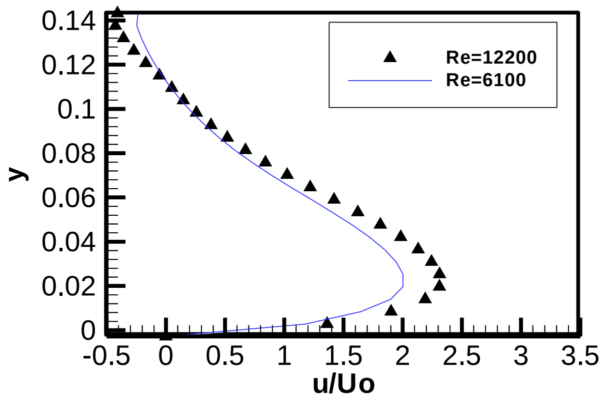


Figure (11) Effect of Re on dimensionless velocity profile for two staggered baffle plates (x=0.82)

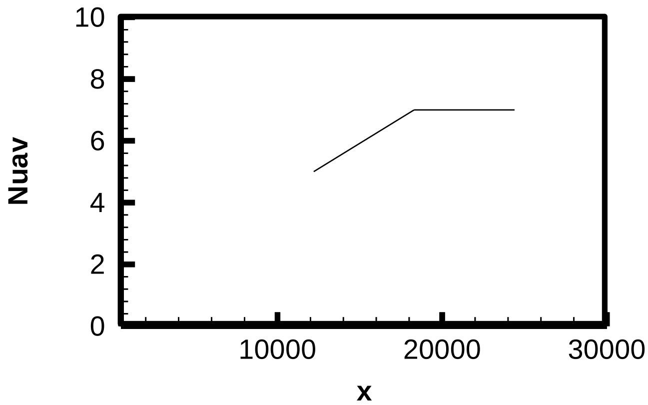
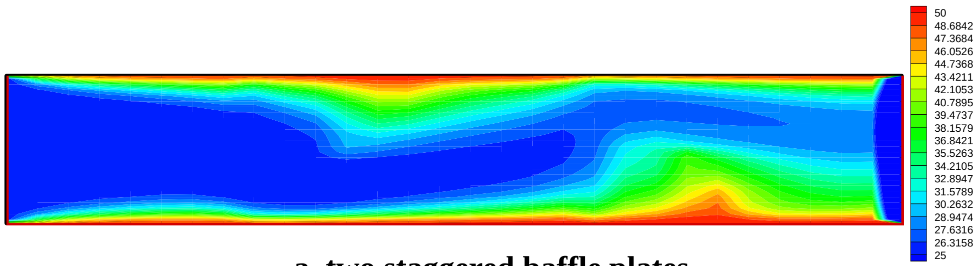
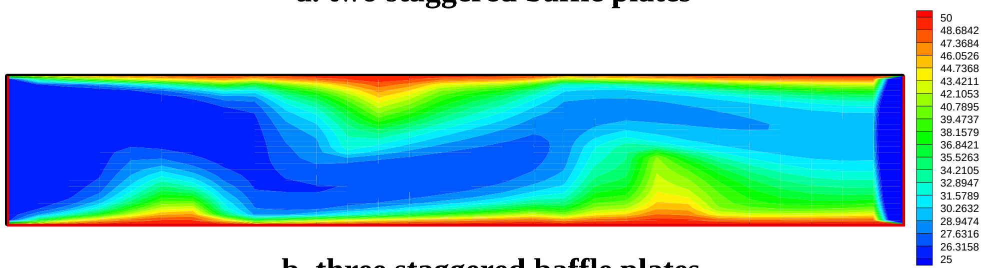


Figure (12) Variation of average Nu for two staggered baffle plates

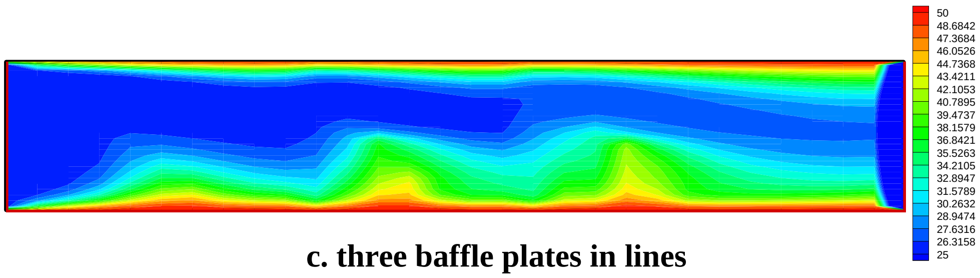
The contour plots of temperature distribution for the considered cases are shown in **Fig.(13)**. The figure shows that the baffle plates plays an effective factor to dissipate the heat from the solid walls and the temperature of the flow increases in the regions occupied by the baffles and between the baffle plates. This enhances the heat transfer. To verify our numerical simulation, a comparison between the present results with these reported by Demartini [6] is carried out in **Fig.(14)**.



a. two staggered baffle plates



b. three staggered baffle plates



c. three baffle plates in lines

Figure (13) Isotherm contours for Re=6100

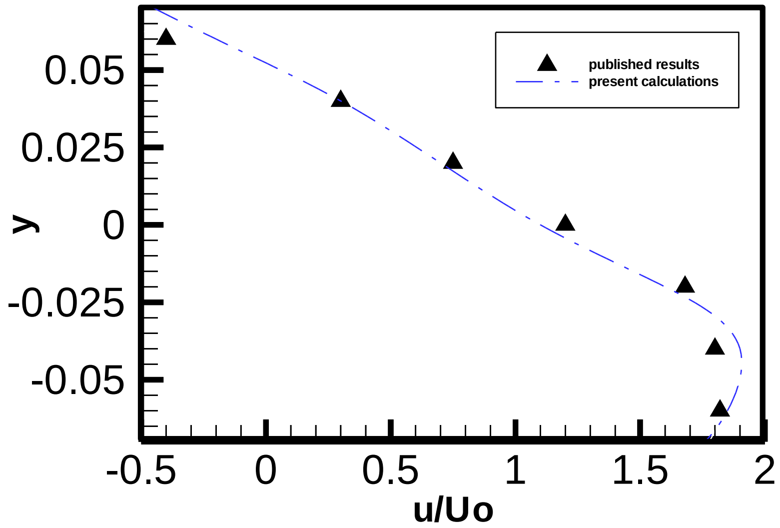


Figure (14) Validation of the present code with the published results [7]

The figure shows a good agreement between these results and the published ones. The baffle arrangements affect the variation of the bulk temperature as shown in **Fig.(15)**. The bulk temperature significantly increases with the presence of the baffle plates compared to that of the situation with no baffle plates. The three staggered baffle plates exhibited the maximum bulk temperature values over the other considered cases.

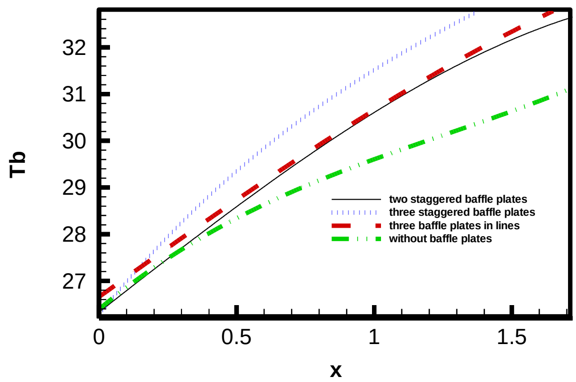


Figure (15) Variation of bulk temperature for different baffle plates arrangements

The effect of Reynolds number on the bulk temperature variation is shown in **Fig.(16)**. It is clear that the bulk temperature decreased with the increase of Reynolds number for all the studied cases. When the incoming flow velocity is high, the heat exchange time is less and hence decreasing of the bulk temperature.

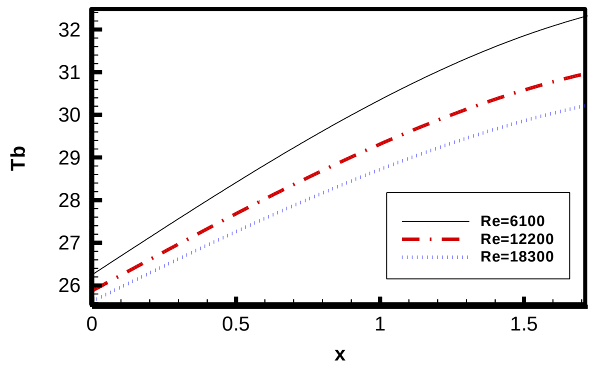


Figure (16) Effect of Re on bulk temperature for two staggered baffle plates

7. Conclusions

In this study the k-є turbulence model has been adopted to predict the details of the turbulent flow and heat transfer through a duct with baffle plates. From the presented results, the following conclusions can be obtained.

1. The spacing between the baffles significantly affected the separation of boundary layer and recirculation zone behind the baffle.
2. The increase Reynolds number increases the recirculation zone length and local Nusselt number, consequently enhance the heat transfer.
3. The boundary layer separation, recirculation zone and the values of Nu are influenced by the baffle height and thickness.
4. The higher values of Nu are found in three staggered baffle arrangements.
5. The standard k-є model can successfully predict the characteristics of the flow and heat transfer for this type of the problems.

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Nomencluture

h: *Height of the baffle plate*
H: *Height of the duct*
i, j: *Tensor notation*
L: *Length of the duct*
p: *Pressure*
Pr: *Prandtl number*
t: *Spacing between the baffle plates.*

U_o: Velocity at inlet
w: Thickness of the baffle plate

Greek Symbols

μ: Molecular viscosity
ν_t: Eddy viscosity
ρ: Air density
σ_k: Turbulent Prandtl number for turbulence
σ_ϵ: Turbulent Prandle numbers for dissipation of turbulence
κ: Von Karman constant
Γ: Exchange coefficient
E: Empirical constant
S_ϕ: Source term