Optimization Of Heat Transfer Enhancement in Cooling Passage with Turbulence Promoters

Samir Laouedj[1] ; Abdelylah Benazza[1] ; Mokhtar Derras[2]
1 : Laboratoire de matériaux et systèmes Réactifs, Université Djillali Liabes de Sidi Bel Abbes
samirladz@yahoo.fr

Abstract: In this study the three-dimensional nonlinear finite volume method is used to determine the heat transfer amelioration along ducts with attached and detached turbulence promoters. It is known that several parameters influence the heat transfer amelioration quality such as the promoter depth, the distance between promoters and the distance of the promoter to the wall. The lower wall is subjected to a uniform heat flux condition while the upper wall is insulated. The Navier–Stokes equation along with the energy equation has been solved using SIMPLE technique and the RNG k–ε formulation was chosen for turbulence closure. The experimental design methodology is used to investigate the effects of these three parameters in order to achieve an optimization of the heat transfer. This optimization allows us to determine the most influencing parameter on the heat transfer performances.

Keywords :

Heat transfer enhancement, turbulence promoters, optimization, experimental design.

1. Introduction

Thermal performance of heat transfer devices can be improved by heat transfer enhancement techniques. Many techniques based on both active and passive methods have been proposed to enhance heat transfer in these applications. Among these methods one can find systems involving vortex generators such as fins, turbulence promoters and other cylinders. The turbulent generator with different geometrical configurations have been used as one of the passive heat transfer enhancement techniques and are the most widely used in several heat transfer applications, such as cooling of electronic systems, internal cooling inside turbine blades, compact heat exchangers, biomedical devices, etc. The geometrical characteristics of vortex generators play a significant role in the rate of heat transfer. Disturbance promoters increase fluid mixing and interrupt the development of the thermal boundary layer, leading to enhancement of heat transfer.

However, the complex flow characterized by the onset of successive separations, recirculation, reattachment and deflection of the flow make comprehension of the flow behavior and heat transfer evolution in such systems more difficult. Several investigators have studied heat transfer enhancement from surface mounted heated blocks. A. Alamgholilou and E. Esmaeilzadeh [1] observed the enhancement of heat transfer from turbulence promoters to the main flow, passive, active and compound methods in Experimental investigation on hydrodynamics and heat transfer of fluid flow into channel for cooling of rectangular turbulence promoters. Shiang-Wuu Perng et al [2] performed to study the heat transfer enhancement on a porous vortex-generator applied to a block-heated channel. Himadri Chattopadhyay [3] studied the Augmentation of heat transfer in a channel using a triangular prism. Korichi, A., Oufer, L. [4] numerically studied on the heat transfer characteristics in a rectangular channel with mounted obstacles on the upper and lower walls and in [5] for pressure drop in channels with upper and lower walls mounted obstacles. Leung et al. carried out an experimental study on the effect on heat transfer enhancement of perforated holes. He found that the mean heat transfer coefficient was enhanced up to 33.15%. Wu and Perng [2] investigated the effect of installing an oblique plate on heat transfer over an array of five obstacles mounted in a horizontal channel and observed an enhancement of heat transfer of up to 39.5% in the value of Nusselt number.

The technology of enhancing heat transfer in the forced convection regime by means of vortex generators was discussed in several papers. Sparrow et al. [6] experimentally investigated the effect of implemented barriers in arrays of rectangular modules and reported significant improvement in the heat transfer coefficient of the module in the second row downstream of the barrier. Chou and Lee [7] conducted an experimental work on the possibility of reducing flow non-uniformities in LSI packages by vortex generating from a rectangular plate on the top of a downstream chip. Myrum et al. [8] have conducted a series of experiments on dealing vortex generators (circular rods) induced enhancement of heat transfer from ribbed ducts in which different generator configurations were investigated by changing rod diameter, rod–rib spacing and rod–rod spacing. The purpose of this study is to quantify the influence of the turbulence promoter height to channel height ratio, the wall-turbulence promoters distance to channel height ratio and the inter-turbulence promoters distance to channel height ratio on heat transfer enhancement.

2. Numerical Approach

The two-dimensional flow geometries are shown in Fig. 1.

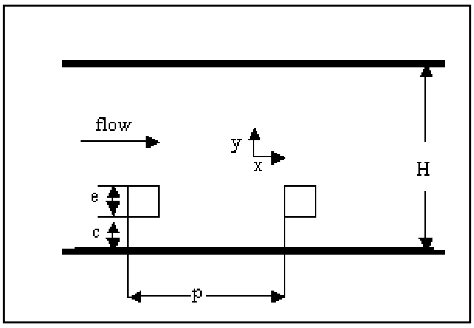

Figure 1: 2D channel with detached turbulence promoters.

2.1. Turbulence model

The solution of the Reynolds Averaged Navier-Stokes Equations is obtained by using finite volume method with a body-fitted structured grid. A cell-centered layout is employed in which the pressure, turbulence and velocity unknowns share the same location. The momentum and continuity equations are coupled through a pressure correction scheme and several implicit first and second order accurate schemes are implemented for the space and time discretizations. In the present computation, convection terms written in convective form are discretized with a second order upwind-biased scheme.

Smith Eiamsa-ard and Pongjet Promvonge [20] suggested that RNG k−ε turbulence model or the k−ε turbulence model is more suitable in predicting heat transfer and fluid channel flow over periodic grooves on one wall. The turbulence closure here is done with the help of the RNG K-ε with enhanced wall treatment. The details of the Reynolds Averaged Navier Stokes equations as well as the RNG K-ε turbulence model are not given here since they are well documented in the literature.

2. 2. Experimental design methodology

Experimental design (commonly referred to as DOE) is a useful complement to multivariate data analysis because it generates “structured” data tables, i.e. data tables that contain an important amount of structured variation. This underlying structure will then be used as a basis for multivariate modeling, which will guarantee stable and robust models, the efficiency is to Get more information from fewer experiments. Experimental design [15, 21, 23], was used for the determination of the optimum dimensions.

The promoter dimensions process is described by a quadratic model:

$$y = a_0 + \sum_{i=1}^{4} a_i x_i + \sum_{1 \le i < j \le 4} a_{ij} x_j + \sum_{i=1}^{4} a_{ii} x_i^2 + e$$

Where y is the response of the process (i.e., the Nusselt Number) and x_i is the normalised centered value for each factor u_i:

$x_i = (u_i - u_{ic})/\Delta u_i = u_i^*$
$u_{ic} = (u_{imax} + u_{imin})/2$; $\Delta u_i = (u_{imax} - u_{imin})/2$.

For the considered factors in the present study, i.e. the depth (e/h), the promoter separation from the wall (c/h), and the separation between promoters (p/h), the quadratic model of the response (Nusselt Number) will take the following form:

$Nu = a_0 + a_1 (e/h)^* + a2\,(c/h)^* + a_3 (P/h)^* + a_{12} (e/h)^*(c/h)^* + a_{13} (e/h)^*(P/h)^* + a_{23}(c/h)^*(P/h)^* + a_{11} (e/h)^{*2} + a_{22}(c/h)^{*2} + a_{33} (P/h)^{*2}$

The main objective of this study is to maximise the Nusselt Number, the experimental design method is appropriate to achieve this goal. In this particular case the maximisation of the Nusselt number will be performed by optimising the three geometrical parameters of the Promoer: the height, the distance of separation from the wall and the distance between promoters. One will optimise for a full experiment design which takes all possible combinations of the values of these factors. Three values (called levels) are affected to each promoter dimension: the height e/h (0.05 to 0.3), the distance of separation from the wall c/h (0 to 0.4) and the distance between promoters P/h (5 to 25). These values are selected randomly in an ascending order. Therefore, one has 3^3 runs of the optimization program.

3. Results and discussions

The software MODDE 5.0 (Modeling and Design) [22] is used for the model elaboration and the statistical analysis of the experimental design, a known response based on: the height, the distance of separation from the wall and the distance between promoters can be predicted.

The experimental design used in this study is a comprehensive quadratic plan, which deals with a mathematical model of second order. Table 3, presents the coefficients of the different parameters and their interactions. According to the figure 4 which represent the different parameters effect, two not significant terms e/h*c/h and P/h*c/h are neglected. The mathematical model suggested by MODDE 5.0 is:

$$Nu = 68,4887 + 13,38\,(e/h)^{*} + 0,44\,(c/h)^{*} - 11,94\,(P/h)^{*} + 11,8875\,(e/h)^{*}(P/h)^{*} - 16,9803\,(e/h)^{*2} - 4,78028\,(c/h)^{*2} + 7,71972\,(P/h)^{*2}$$

Where (e/h)*, (c/h)*, (P/h)*, are coded values of the height, the distance of separation from the wall and the distance between promoters respectively. These coded values of the promoter parameters vary between +1 and -1. The formulas used for coding are as follows:

$$\left(\frac{e}{h}\right)^{*} = \frac{\left(\frac{e}{h}\right) - \frac{\left(\left(\frac{e}{h}\right)_{max} + \left(\frac{e}{h}\right)_{min}\right)}{2}}{\frac{\left(\left(\frac{e}{h}\right)_{max} - \left(\frac{e}{h}\right)_{min}\right)}{2}} = \frac{\left(\frac{e}{h}\right) - 0.175}{0.125}$$

$$\left(\frac{c}{h}\right)^{*} = \frac{\left(\frac{c}{h}\right) - \frac{\left(\left(\frac{c}{h}\right)_{max} + \left(\frac{c}{h}\right)_{min}\right)}{2}}{\frac{\left(\left(\frac{c}{h}\right)_{max} - \left(\frac{c}{h}\right)_{min}\right)}{2}} = \frac{\left(\frac{c}{h}\right) - 0.2}{0.2}$$

$$\left(\frac{P}{h}\right)^{*} = \frac{\left(\frac{P}{h}\right) - \frac{\left(\left(\frac{P}{h}\right)_{max} + \left(\frac{P}{h}\right)_{min}\right)}{2}}{\frac{\left(\left(\frac{P}{h}\right)_{max} - \left(\frac{P}{h}\right)_{min}\right)}{2}} = \frac{\left(\frac{P}{h}\right) - 15}{10}$$

After calculations the following equation are obtained:

$$Nu = 68.636902 + 344.7487\,(e/h) + 50.0028\,(c/h) - 2.315916(P/h) + 9.51\,(e/h)\,(P/h) - 1086.7392\,(e/h)^2 - 119.507\,(c/h)^2 + 0.0771972\,(P/h)^2. \quad (4)$$

According to the results of Fig.3, it can be noted that the dominant factors on the heat transfer performance are respectively the height of the promoter and it's distance to the wall. Fig.3a presents the variation of the Nusselt number as a function of the promoter height, one can notice that the increases the promoter height leads to an augmentation of the Nusselt number, which improve the heat transfer efficiency. In addition, it is found that the coefficient increases with the height of the promoter, especially in areas inter-promoters, this tendency is also demonstrated by the experimental work by ALIAGA [3]. This is due to the increase in the intensity of turbulence to the height of the obstacle. The use of a promoter height greater than 0.2 is not recommended because it will provokes a recirculation zone between the two promoters causing a stagnation zone of the fluid which causes the decrease of Reynolds number. The promoter height must be optimised.

Fig.3b presents the variations of the Nusselt number according to promoter distance from the wall. The highest values of the Nusselt number are obtained for the case of a detached promoters to the wall with c/h = 0.2. The Nusselt number decreases asymptotically if the promoter distance from the wall is more this value. Nusselt number is less in the case of attached promoter, heat transfer depends essentially on the spacing wall-promoter, because the main idea of adding a promoter that is increase fluid mixing and interrupt the development of the thermal boundary layer, leading to enhancement of heat transfer, which one can conclude that the use of a promoter detached at the wall gives better results compared to the attached promoter.

The variation of the Nusselt number according to the distance between promoters is represented in Fig.3c. The Nusselt number is slightly influenced by the variation of the distance inter-promoter. The increase of inter-promoter distance leads to asymptotic decrease of the Nusselt number. When the spacing between promoters is weak, it happens that the detachment and reattachment of the fluid on the wall do not occur and the space between promoters is the seat of a swirling flow leading to a good heat transfer. The nature of the wake vortex between promoters causes a significant mixing of the flow, thus promoting transport phenomena from the wall to the boundary layer. turbulence characterization near the wall, and the wake behind the obstacle shows that these vortices are responsible for a significant heat transfer.It is clear that the inter-promoter distance (P/h) do not be larger than 5 to favorise the recirculation zone which influence directly on the heat transfer. The maximum values of the Nusselt number corresponding to the reattachment of the flow in the inter-promoters. This zone decreases with increasing spacing of promoters. When the spacing is small, it happens that the detachment and reattachment of the fluid on the wall do not occur and the space between promoters is the seat of a turbulent flow which leads to a poor heat transfer because the recirculation leads to hot areas, which causes the heating of the fluid. MIYASHITA et al [13], LIOU et al [14], Webb [14], are in disagreement with our results, however, experimental studies performed by ALIAGA [3], and CHYU WU [2], are consistent with ours ie the coefficient of heat transfer medium is maximal if the gluing can happen, that is to say, when the space between two successive barriers is reduced.

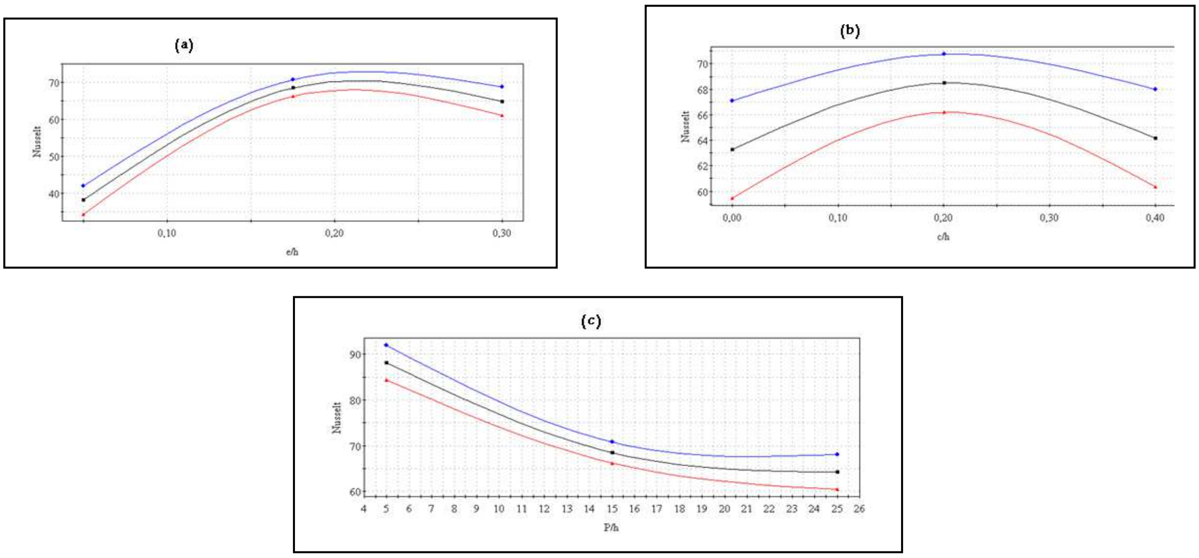

Fig.3. Prediction plots according to: (a) Nusselt Number versus promoter height; (b) Nusselt Number versus wall-promoter distance (c) Nusselt Number versus inter promoters distance.

For an average value of the promoter height (e/h = 0.1821) (Fig. 4a), the mathematical model will have the following form:

$Nu = 87.9153866 - 261.19475\,(c/h) + 0.17149(P/h) + 86.584908(c/h) + 0.016389(P/h) - 0.38125\,(c/h)(P/h) + 309.73\,(c/h)^2 - 0.002233\,(P/h)^2$.

If the promoter-wall (c/h) is maintained constant for average value of 0 (Fig. 4b), one can obtain the following form of the model:

$Nu = 38.899043 + 549.77208\,(e/h) + 0.17149(P/h) + 0.09\,(e/h)\,(P/h) - 1540.9088\,(e/h)^2 - 0.002233\,(P/h)^2$.

For the inter-promoter distance (P/h) = 23 (Fig. 4c), the model will take the following form:

$Nu = 41.662056 + 549.77208\,(e/h) - 261.19475\,(c/h) + 475.48\,(e/h)(c/h) + 2.07\,(e/h) - 8.76875\,(c/h) - 1540.9088\,(e/h)^2 + 309.73\,(c/h)^2$.

The optimum value of the Nusselt number can be directly read from the graph. By substitution, the Nusselt number will have a value which is considered as the optimal point.

In order to discuss about the effects of different parameters and their interactions effects on the Nusselt number. One can classify the most dominant promoter dimension parameters upon the heat transfer flow-wall as follow: height, promoter inter-promoter distance and wall-promoter distance. This classification can be explained by the fact that the turbulence production by the promoter occurs mainly through the promoter height.

4. Conclusion

The study presented in this paper is part of the improvement of convective transfer in a duct by the addition of turbulence promoters. The final objective of this study is a conclusion about the use of turbulence promoters in terms of reliable alternative for the improvement of convective transfer in a duct. The results of this study may be of interest to engineers attempting to develop thermal control of electronic devices and to researchers interested in the turbulent flow-modification aspects of heat transfer enhancement of mixed convection in a horizontal channel. The distribution of heat transfer coefficient was determined numerically. Many conclusions are deduced as:

- Promoter height is the most dominant promoter dimension parameters upon the heat transfer flow-wall.
- The latter increases with the size of the promoters and decreases when the spacing is inter promoters above 5 on the occasion of a vortex flow between the two promoters when the pitch is 5.
- Detached promoters allowed us to increase the heat transfer enhancing turbulence and avoiding the problem of hot pockets that are the major disadvantage of the attached promoters.
- The wall-promoter distance does not have significant effect on the heat transfer enhancement by turbulence promoters.
- The inter promoter distance must be maintained in it minimum value.
- The nature of the wake vortex between promoters causes a significant mixing of the flow, thus promoting transport phenomena from the wall to the heart of the boundary layer. Characterization of turbulence near the wall, and the wake behind the obstacle shows that these vortices are responsible for a significant heat transfer.

References

[1] A. Alamgholilou , E. Esmaeilzadeh. Experimental investigation on hydrodynamics and heat transfer of fluid flow into channel for cooling of rectangular turbulence promoters by passive and EHD active enhancement methods. Experimental Thermal and Fluid Science 38 (2012) 61–73.

[2] H.W. Wu, S.W. Perng, Effect of an oblique plate on the heat transfer enhancement of mixed convection over heated blocks in a horizontal channel, Int. J. Heat Mass Transfer 42 (1999) 1217–1235.

[3] Himadri Chattopadhyay, Augmentation of heat transfer in a channel using a triangular prism.

[4] Korichi, A., Oufer, L., 2005a. Numerical heat transfer in a rectangular channel with mounted obstacles on the upper and lower walls. International Journal of Thermal Sciences 44, 644–655.

[5] Korichi, A., Oufer, L., 2005b. Unsteady heat transfer and pressure drop in channels with upper and lower walls mounted obstacles. Numerical Heat Transfer Part A 48 (7), 711–729.

[6] E.M. Sparrow, S.B. Vemuri, D.S. Kadle, Enhanced and local heat transfer, pressure drop, and flow visualization, Int. J. Heat Mass Transfer 26 (1983) 689–699.

[7] J.H. Chou, J. Lee, Reducing flow non-uniformities in LSI packages by vortex generator, in: W. Aung (Ed.), Cooling Technology for Electronic Equipment, Hemisphere Publishing Corporation, New York, 1988, pp. 113–124.

[8] T.Myrum, S. Acharya, S. Sinha, X. Qiu, Flow and heat transfer in a ribbed duct with vortex generators, ASME J. Heat Transfer 118 (1996) 294–300.

[9] Shiang-Wuu Perng a,b, Horng-Wen Wuc,and, Tswen-Chyuan Jue.d. Numerical investigation of heat transfer enhancement on a porous vortex-generator applied to a block-heated channel.

[10]MIYASHITA, Kondo, Hata et Nishimura. Characteristics of heat-transfer enhancement due to various turbulence promoters. Heat transfer – Japanese research, 22(2): 184-197, 1993.

[11] Webb, R, L., Eckert, E.R.G., and Goldstein, R.J. “Heat Transfer and Friction in Tubes With Repeated Rib Roughness” Int.J.Heat and Mass Transfer Vol, 14, 1971, pp, 601-617.