The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2022

Volume 21, Pages 452-463

IConTES 2022: International Conference on Technology, Engineering and Science

Numerical Investigation of a Tubular Heat Exchanger Fitted with Triangular Ribs

Nabil BENAMARA
Djillali Liabes University of Sidi-Bel-Abbes

Djelloul LAHMER
Djillali Liabes University of Sidi-Bel-Abbes

Mohamed MERZOUG
Djillali Liabes University of Sidi-Bel-Abbes

Abdelkader LAHCENE
Djillali Liabes University of Sidi-Bel-Abbes

Abdelkader BOULENOUAR
Djillali Liabes University of Sidi-Bel-Abbes

Miloud AMINALLAH
Djillali Liabes University of Sidi-Bel-Abbes

Abstract: In the present work we numerically study the effect of the presence of triangular shaped promoters on the efficiency of a tubular heat exchanger. When we talk about efficiency, we are generally faced with problems of dynamic and thermal behavior within the latter. The main objective is to optimize the geometric parameters of the triangular-shaped promoters in order to collect the maximum energy at a minimum cost. Indeed, in the case of a two-dimensional simplified geometry, we considered the flow of an incompressible fluid (air) in a cylindrical heat exchanger tube equipped with baffles placed perpendicular to the direction of flow. Several baffle arrangements are considered according to the angle of inclination β, the space between the two successive baffles (space ratio PR: P/Dh) and the length of the baffle (blocking ratio BR: e/Dh) . The calculations are carried out by means of the fluent computer code using the k-ε turbulence model, RNG, with a Reynolds number Re varying from 3000 up to 13000. The results found indicated that the best thermal performance obtained corresponds to β=30°;BR=0.2; PR=1 and Re=4000.

Keywords: Turbulence ribs, Nusselt number Nu, Friction number Fr, Turbulence model K-ε RNG, Thermal-hydraulic factor

Introduction

The heat exchanger is one of the most important pieces of equipment in industry because it allows the recovery of energy, by convective transfer, between two or more fluids. In order to improve the heat transfer rate with minimal pressure drop, researchers have tried to develop several techniques. Two major classes of heat transfer enhancement techniques are used in heat exchangers: so-called active and passive techniques (Alam et al., 2018). In our study, we focus on passive methods (Sheikholeslami et al., 2015), as they do not require an external power supply and generally use modified surfaces by inserting vortex generators into the main flow. According to the published works in this field, the method which succeeded, successfully, in improving the heat exchange with a reduced cost and bulk with a low pressure drop of the fluid is the promoters of longitudinal turbulence (Kumar B et al., 2018). Indeed, several studies are carried out on this technique in order to give a better design of the turbulence generator inserted on the heat exchanger which can improve the heat transfer by the destruction of the thermal boundary layer (Nakhchi et al., 2019; Targui et al., 2008). In some experimental studies, Han et al. (1991) used ribs on two walls of a square channel with different angles of attack for pitch ratio (P/e = 10) and blocking ratio (e/D = 0.0625). They found that the angled "V" shaped ribs have a significant effect on the performance of the heat exchanger. According to Promvonge et al (2010) baffles with a 45° angle of attack increase the heat transfer coefficient from 150% to 850%. Torii et al (2002) concluded that installing "winglet" delta type baffles on a finned tube heat exchanger significantly improves heat transfer and reduces the friction factor. The effect of baffle angle of attack on heat transfer and fluid flow is investigated numerically by Kwankaomeng et al. (2010) for which they used baffles inclined at 30° with different values of the blocking ratio (BR). They found that baffles angled at 30° significantly increased the heat transfer coefficient in the channel because they generated vortices in the fluid flow. But this increase in heat transfer associated with a large pressure drop ranging from 1 to 17 times over the channel without baffles. Zhang et al, (2013) studied the effect of the arc belt inserted in the tube heat exchanger. They found that the arc belt can swirl the fluid pipe and plays the role of enhanced heat transfer, but also significantly increases fluid resistance, where the PEC is anything above 1.5. A numerical analysis of vortex generators (VG), placed on the tubes of an exchanger, was carried out by J. Jang et al. The results obtained showed that the optimal values of the angle of inclination (θ) and the transverse location (Ly), are respectively between: 30° < θ < 60° and 2 mm < Ly < 20 mm. Omidi et al (2019) numerically investigated the effect of alumina nanofluid inside a three-lobe twisted ribbon tube on heat exchanger performance for various volume fractions of nanofluid from 0 .01, 0.02 and 0.03 with a Reynolds number between 5000 and 20,000; they noticed that increasing the nanoparticle concentration improves the heat transfer rates for these cases, while it does not increase the relative Nusselt number inside the twist tube with a Y-insert at a Reynolds number and high nanoparticle concentration. Shobahana et al (2018) concluded that the overall performance of the double fin and tube heat exchanger can be improved by 27-91% using 20 degree RWVGs for the studied Reynolds number range.

As part of the understanding and improvement of the convective transfer phenomenon in tubular heat exchangers with the presence of inclined baffles, the objective of this work is to numerically study the optimal geometry, the angle of attack, the ratio pitch (PR) and blocking ratio (BR), which provides the best efficiency of a heat exchanger.

Geometry Studied

The configuration of the rough circular duct proposed for the ram air stream is a simple two-dimensional (2D) rectangular channel with dimensions: $H \times L2 = 0.05 \times 1.3\ m^2$ and a hydraulic diameter D_h=50 mm, The dimensions of the heat exchanger tubular are given in the following table:

Table 1. Geometry dimensions.

Parameters	Range
Reynolds number (Re)	3000-13000 (7 valeurs)
Hydraulic diameter (Dh)	50 mm
Angle of inclination Ribs (β)	20°, 30°, 40°, 60°
Roughness height(e)	5 et 10 mm
Block report (BR: e/Dh)	0.1et 0.2
spacing roughness(P)	50, 100,150 et 200 mm
Space ratio(PR:P/Dh)	1, 2,3 et 4

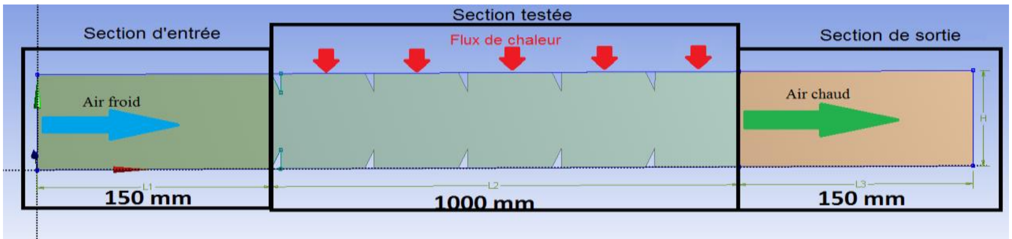


Figure 1. Geometry of an exchanger equipped with artificial roughness

In our studied tubular heat exchanger two other rectangles are placed, one before the test area of dimensions H×L1= 0.05×0.150 m^2 and the other after the test area of dimensions H×L3= 0.02×0.150 m^2. The objective of adding these two rectangles are to obtain a steady state before the air enters the test area, and on the other hand, to ensure a good mixture of air leaving the latter. The ribs of triangular geometric shape are arranged at a fixed spacing ratio, on the internal wall of the exchanger.

Boundary Conditions

In our numerical study, we take a uniform airflow velocity at the U_{inlet} inlet section with a fixed temperature of 300K corresponding to the Prandtl number (Pr) equal to 0.7. The tube wall temperature of the test section is set at 350K while the baffle walls and the inlet and outlet extension tube wall are considered adiabatic. The pressure of the fluid flow at the outlet is atmospheric (fig.1). The physical properties of air are given in the table below (Table 2).

Table 2. Thermo-physical properties

Properties	Tube (al)	Fluid (air)
Cp (J/kg k)	871	1006.43
ρ (kg/ m3)	2719	1.225
λ (w/m k)	202.4	0.0242
μ (N.s/ m2)	-	1.7894e-05

Governing Equations

In order to study the problem of heat transfer of an incompressible fluid in a two-dimensional turbulent regime of our heat exchanger design, one has to solve the equations of continuity, momentum and energy.

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial V}{\partial y}=0 \qquad (1)$$

Momentum conservation equation:

$$\frac{\partial}{\partial x_i}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\rho x_i}\left[\mu\left(\frac{\partial u_i}{\partial u_j}-\overline{\rho u_i' \rho u_j'}\right)\right] \qquad (2)$$

Energy conservation equation

$$\frac{\partial}{\partial x_i}\left(\rho u_i T\right)=\frac{\partial}{\rho x_i}\left[\left(\Gamma+\Gamma_t\right)\frac{\partial T}{\partial x_j}\right] \qquad (3)$$

Knowing that (Γ) is the thermal diffusion given by:

$$\Gamma=\frac{\mu}{Pr} \qquad (4)$$

In this study, the standard k-ε turbulence model is adopted over other turbulence models available in the ANSYS Fluent computer code, because it is robust and gives accurate results in the case of convective transfer of a flow fully turbulent in the test section of a heat exchanger equipped with turbulence promoters.

$\overline{-\rho u_i' u_j'}$: is called Reynolds constraints defined by the turbulence model ε.

μ_t : is the turbulence viscosity defined by:

$$\mu_t=\rho c_\mu \frac{k^2}{\varepsilon} \qquad (5)$$

For ANSYS-Fluent software the coefficient $c_\mu = 0.9$ and for the other empirical constants are defined as indicated below:

$$c_{1\varepsilon}=1.44\ ;\ c_{2\varepsilon}=1.92\ ;\ \sigma_k=1.0\ ;\ \sigma_\varepsilon=1.3\ .$$

To evaluate the heat transfer in each geometric configuration of our exchanger, we calculate the average Nusselt number given by:

$$\mathrm{Nu} = \frac{hD_h}{\lambda} \quad (6)$$

h: is the heat transfer coefficient of the heated wall obtained from ANSYS fluent.

Where D_h: is the hydraulic diameter defined as follows:

$$D_h = \frac{4\times\text{section}}{\text{perimeter}} = D_{tube} \quad (7)$$

Reynolds number

$$\mathrm{Re} = \frac{u_{in}D}{\mu} \quad (8)$$

The friction factor is calculated by the following equation:

$$f_r = \frac{2\,\Delta P}{\rho u_{in}^2 (\frac{L}{D_h})} \quad (9)$$

Where ΔP: is the pressure drop along the tube.

The best baffle arrangement in the heat exchanger is the one with the highest thermal enhancement factor value given by (Webb and Eckert., 1972) :

$$\eta = \frac{Nu/Nu_0}{(\frac{Fr}{Fr_0})^{\frac{1}{3}}} \quad (10)$$

Geometry Mesh

In this numerical work a block-structured, quadratic type mesh is used in order to control the size and the spacing of the first line of the mesh close to the heated wall and to minimize the iterative calculation error.

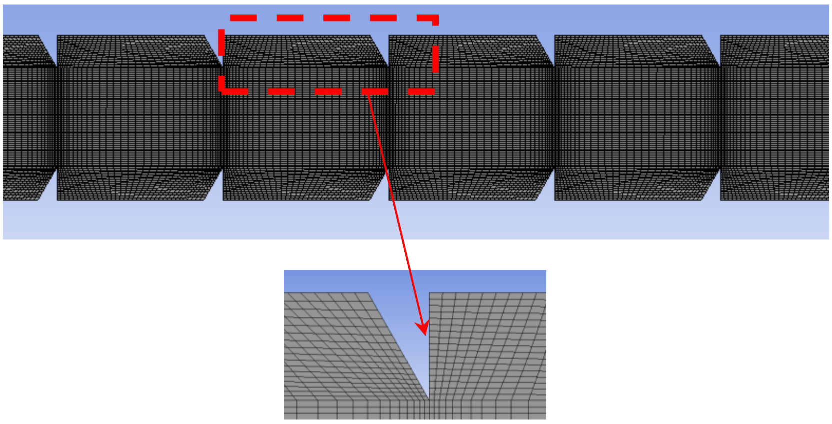


Figure 2. Mesh of the computational domain

Table 1. Mesh size sensitivity

N° of elements	Element size	Nu	Fr	% diff Nu	%diff Fr
46350	1	30,84557	0,278849	--	--
53766	0,9	30,35513	0,276743	0,49044	0,002106
59328	0,8	29,96112	0,274552	0,39401	0,002191
67671	0,7	29,73213	0,272688	0,22899	0,001864
77868	0,6	29,719913	0,271979	0,012217	0,000709

The strategy of using a more refined block-structured mesh close to the walls aims to minimize errors and calculation stability, particularly in regions where temperature and speed gradients are the greatest, as in the case of thermal boundary layers and hydraulics. The sensitivity of the mesh size on the variations of the Nusselt number and the coefficient of friction is represented in Table 3. It was found that at larger grid numbers the relative error of Nusselt and of the coefficient of friction is almost zero.

Results and Discussions

Validation of Results

In order to validate the results of our numerical study obtained, we compared the values of the number of Nusselt and coefficient of friction in the case of a smooth tube with the correlations of Dittus-Boelter (1930) and Gnielinski (1976) (see figures 3 and 4).

Dittus-Boelter Correlation:

$$Nu = 0.023\, Re^{0.8} Pr^{0.4}$$

Gnielinski Correlation:

$$Nu = \frac{(fr/8)RePr}{1+12.7(fr/8)^{\frac{1}{2}}(Pr^{2/3}-1)} \qquad \text{For} \quad 2300 \leq Re \leq 5.106$$

with:

$$Fr = (0.76 lnRe - 1.64)^{-2} \qquad \text{For } 2300 \leq Re \leq 5.106$$

Moody Correlation (1944):

$$Fr = 0.316Re^{0.25} \qquad \text{For } Re \leq 2.104$$

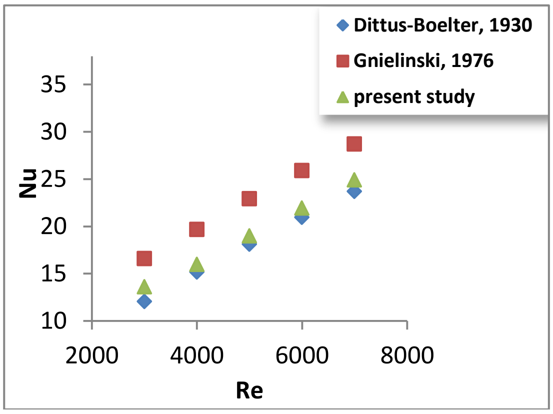


Figure 3. Comparison between the Nusselt Nu number of the present study and Gnielinski, Dittus-Boelter.

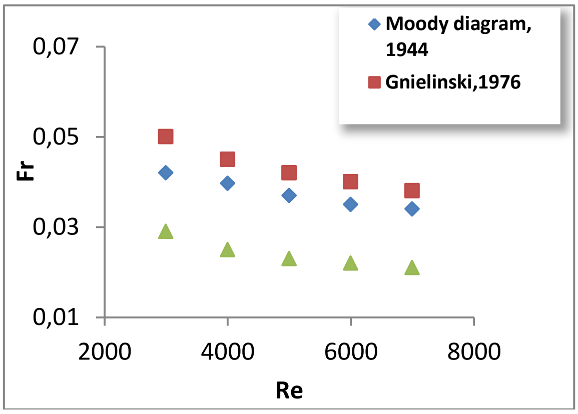


Figure 4. Comparaison between the friction facor Fr of the present study and Gnielinski, Moody diagram.

Effect of Reynolds Number on Nusselt Number

Figures 5 and 6 show the evolution of Nusselt numbers as a function of Reynolds numbers, for different parameters of deflector arrangements and inclinations: β (20°, 30°, 40° and 60°), PR (1, 2, 3 and 4) and for two fixed values of BR (0. 1 and 0. 2). The results obtained indicate that the Nusselt number increases with the increase in the Reynolds number for the different angles of inclination β. The best heat transfer recorded corresponds to the following geometric parameters (β, PR and BR) = (30°, 1 and 0.2) at a number of Re equal to 13000. This improvement in convective transfer is about 97% compared to the smooth tube due to the presence of the ribs which disturbs the main flow by creating zones of separation and reattachment of the turbulent boundary layer, thus promoting heat transfer through the appearance of secondary flows. We also notice that the increases in the thickness of the ribs (BR=0.1 and 0.2), for fixed values of β, PR and Re, have a great influence on the improvement of the exchange coefficient of about 32% at fixed values of (β, PR and Re) = (30°, 1 and 13000) respectively.

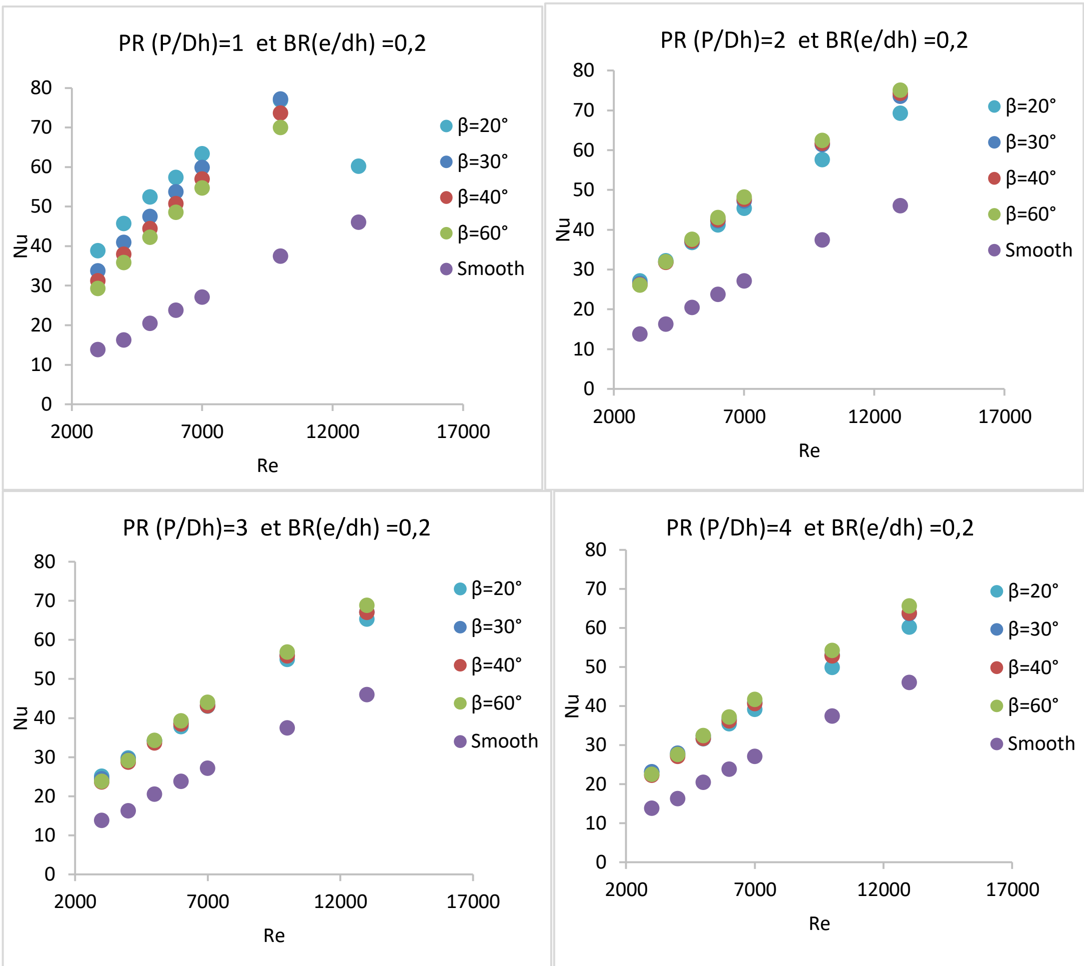
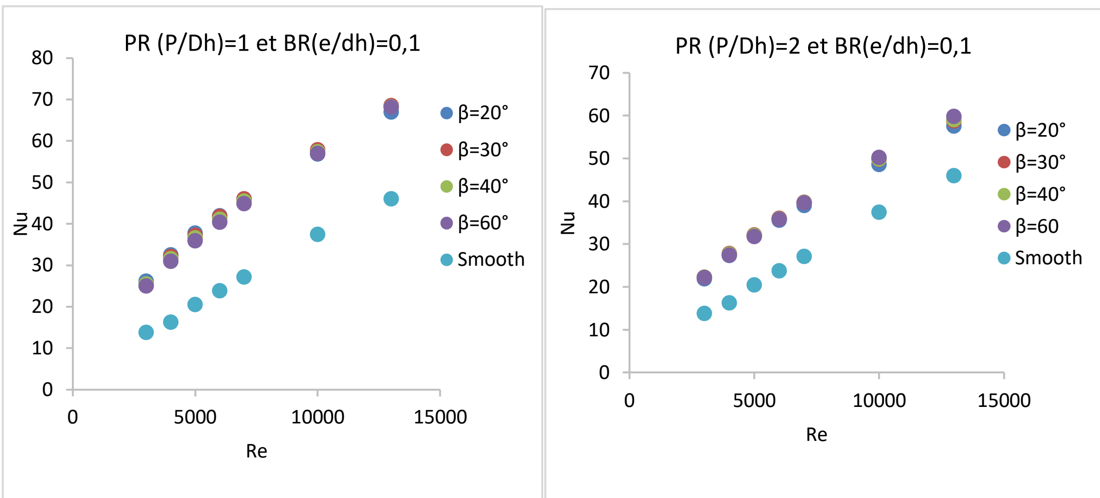


Figure 5. Effect of the Re number on the average Nu number for different inclination angles β (PR = 1, 2, 3.4 and BR = 0.2).



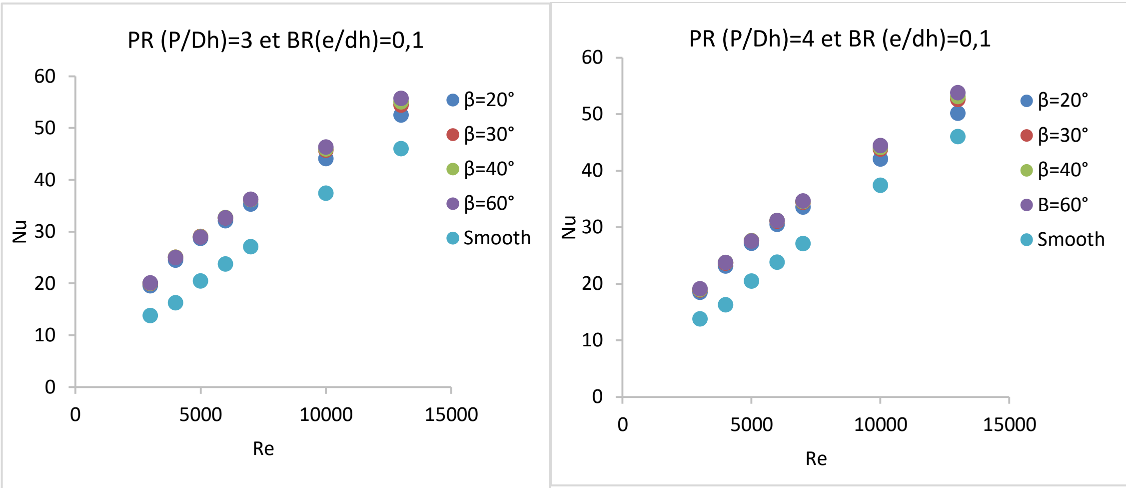


Figure 6. Effect of the number Re on the average number Nu for different angles of inclination β (PR =1, 2, 3.4 and BR=0.1).

Effect of the Reynolds Number on the Coefficient of Friction Fr

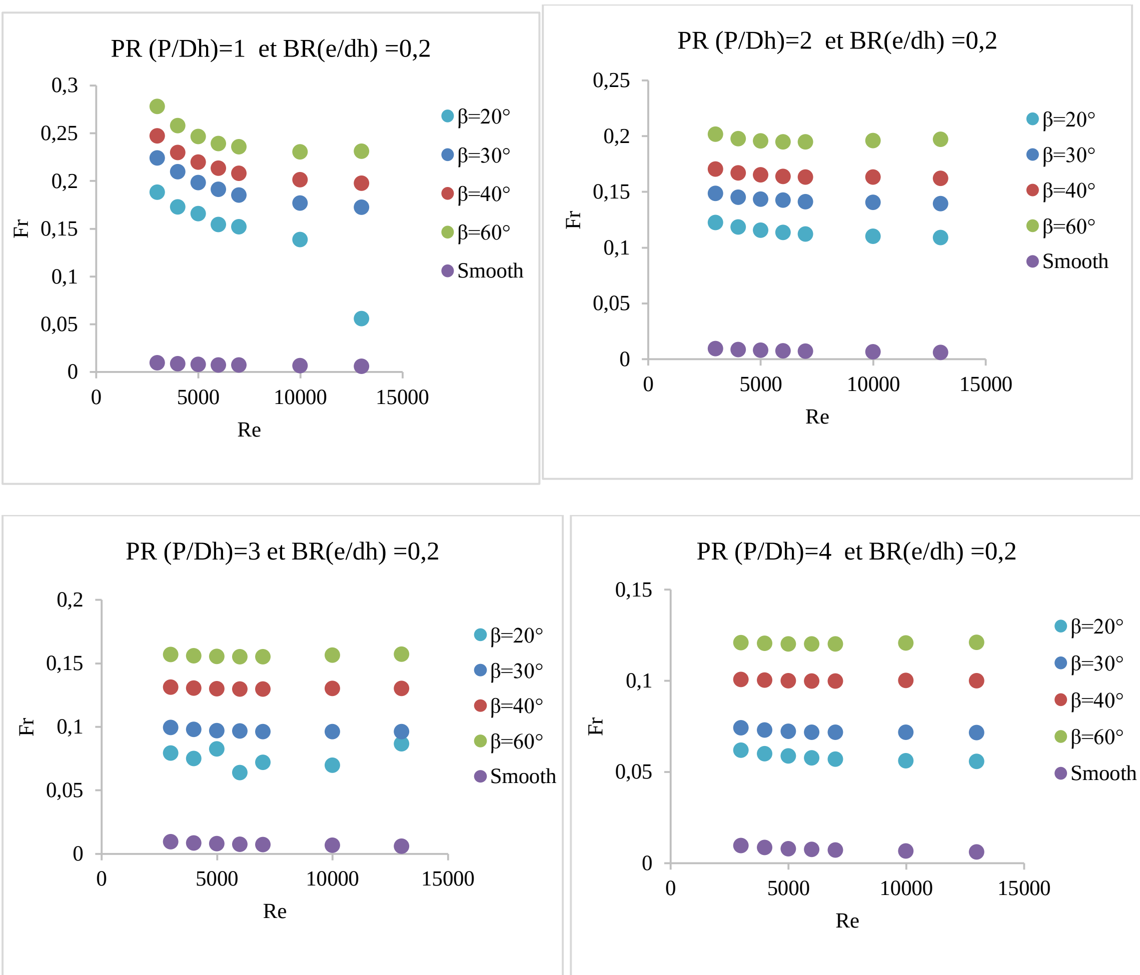


Figure 7. Effect of the number Re on the friction number Fr for different angles of inclination β (PR =1, 2, 3.4 and BR=0.2)

The turbulent flow generated by the baffles increases both the heat exchange coefficient and the friction factor, due to the development and increase in thickness of the turbulent dynamic boundary layer. Figures 7 and 8 shows that all the arrangements of the baffles examined at different values of (β, PR and BR) increase the friction factor in comparison with the case of a smooth tube. A high friction factor value of around 0.27 is obtained at Re = 3000 and geometric values equal to (β = 60°; PR = 1; BR= 0.2). There is a great influence of the angle of inclination (β) on the increase in the friction factor which can reach 12% at β = 60° compared to an inclination of 40°. A significant increase in the coefficient of friction is recorded with the increase in the blocking ratio BR in comparison with the other parameters examined, which is quite logical since the duct becomes more and more obstructed.

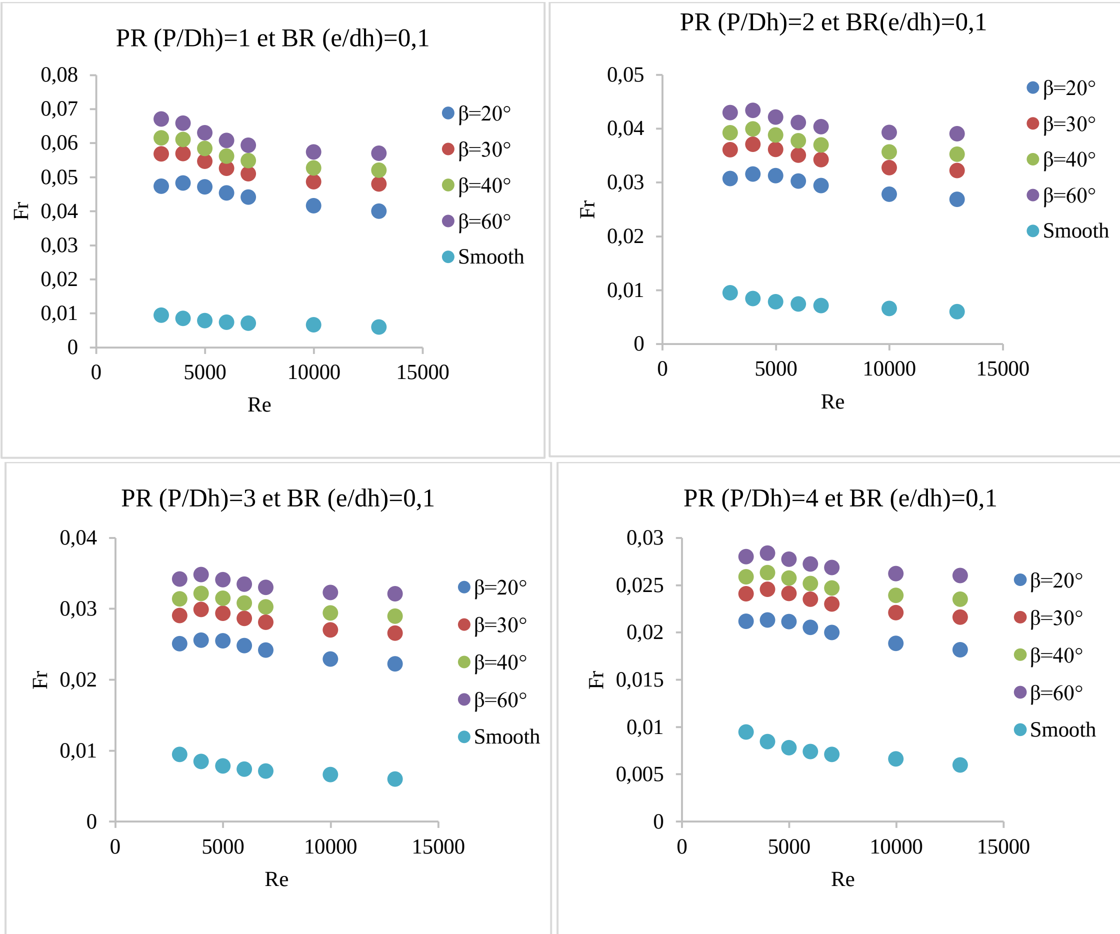
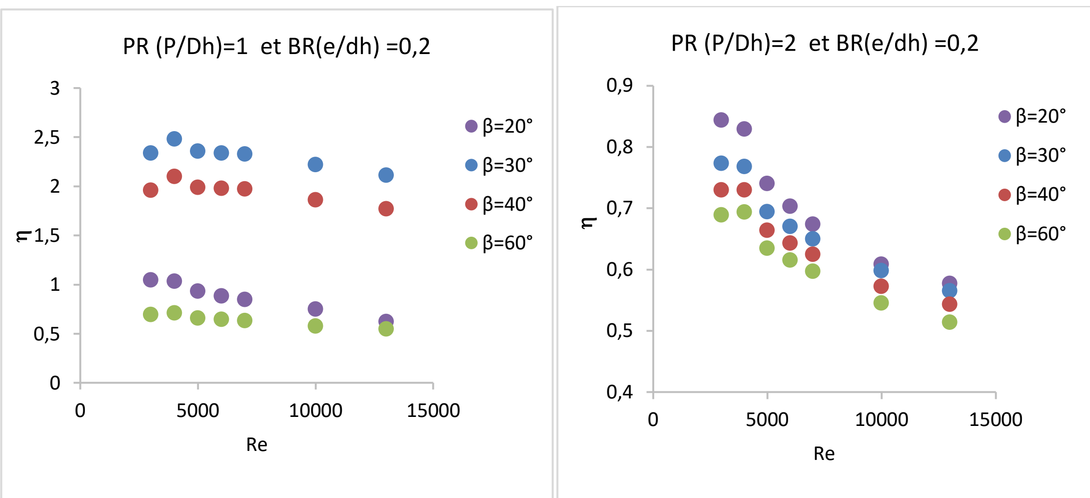


Figure 8. Effect of the number Re on the friction number Fr for different angles of inclination β (PR =1, 2, 3.4 and BR=0.1)

Effect of Reynolds Number on the Thermal-Hydraulic Performance (η)



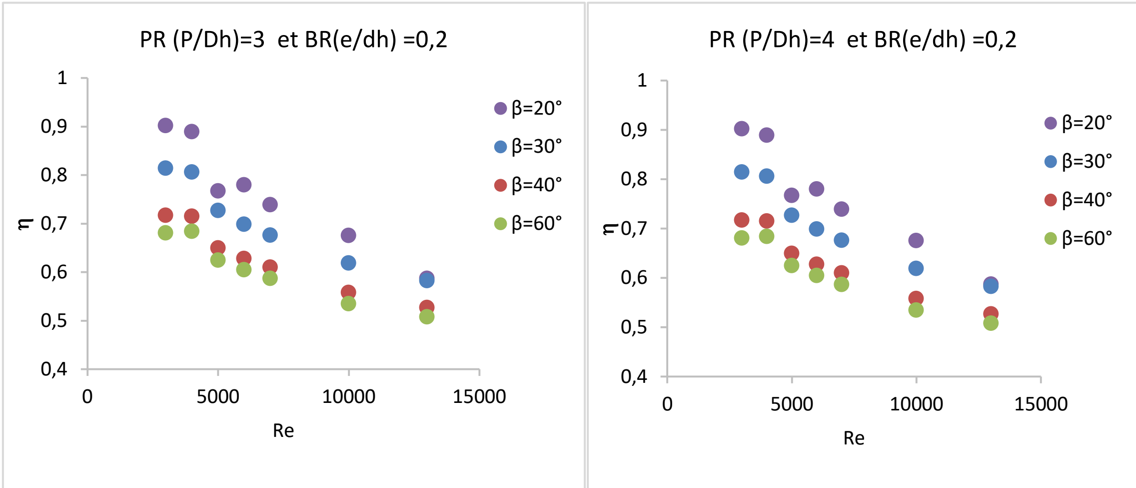


Figure 9. Effect of the number Re on the efficiency η for different angles of inclination β (PR =1, 2, 3.4 and BR=0.2).

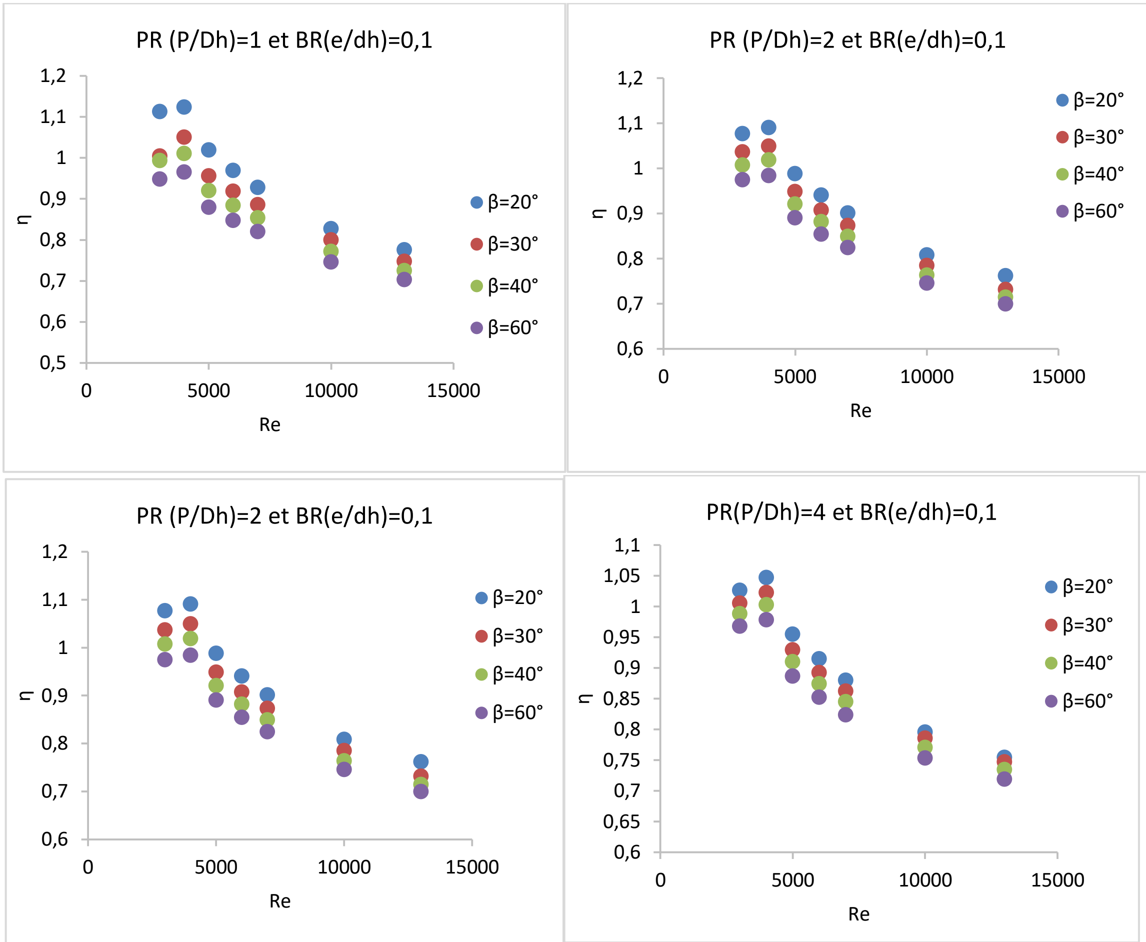


Figure 2. Effect of the number Re on the efficiency η for different angles of inclination β (PR =1, 2, 3.4 and BR=0.1).

In this part, we will analyze another important parameter called thermal-hydraulic performance factor (η) often used as an optimization parameter. This coefficient of performance therefore allows us to find a compromise between the increase in transfer and the pressure drop. From the results obtained, it is possible to define the optimal parameters for thermal improvements at a minimum cost.

Figures 9 and 10 represent the variation of the performance factor for different values of the pitch ratio (PR), of the blocking ratio (BR) and of the angle of inclination (β) as a function of the Reynolds number. It is clear that the performance factor decreases with the increase of β and BR. It can be seen that the best efficiency of 2.48 is obtained for β = 30°; PR=1; BR = 0.2 and a Reynolds number equals 4000. Also, the obstruction effect disappears at large Reynolds numbers.

The Case Where the Main Flow is Reversed

In this part, in order to improve the thermal-hydraulic performance factor as much as possible, we have tried to see the impact of reversing the conditions of entering and leaving our exchanger. Reversing the flow direction completely changes the geometric shape of the baffles. To do this and according to our subsequent results, we took the case which provided us with the best performance factor corresponding to the following geometric parameters: β=30, BR= 0.2 and PR=1 to 4000 Re (see Figure 9 : η depending on Re case P=50). On the whole, the reversal of the inlet and outlet conditions (case AA) gave an acceptable improvement in the performance of the exchanger, but it remains insignificant in comparison with the first case examined (case A) (see histogram figure 11).

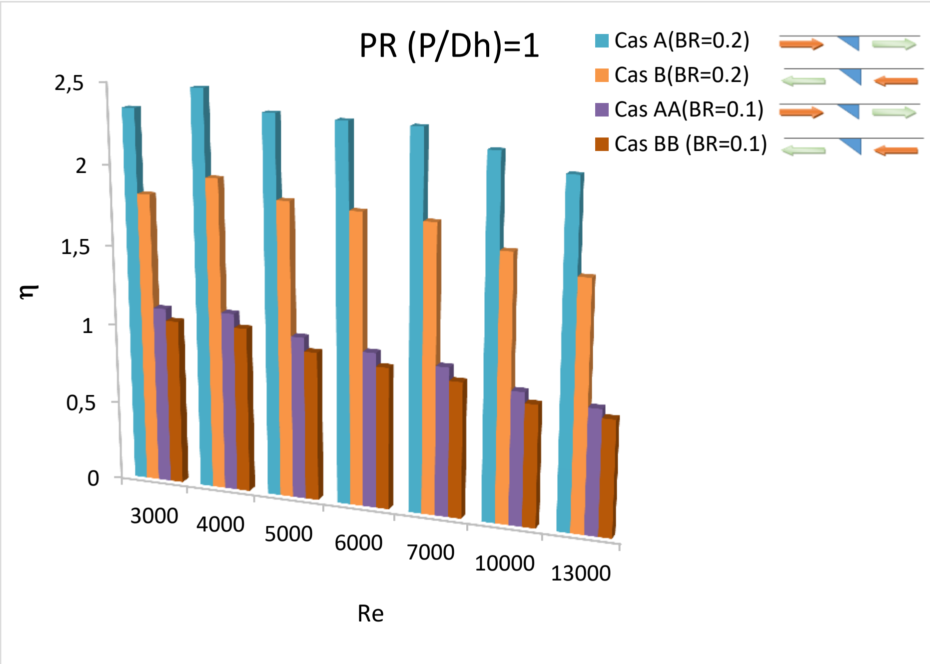


Figure 3. Comparison of efficiency between the case of a flow from left to right and the case of a reversed flow of the optimal values obtained under the conditions: (β=30, BR= 0.2 and PR=1) and (β=20, BR= 0.1 and PR=1).

Conclusion

In this work we have numerically studied the effect of the variation of the geometric parameters of the ribs (β; PR; BR) on the dynamic field of the flow of the fluid and the improvement of the convective transfer in a tubular exchanger. The results obtained showed that all the ribs arrangements examined increase both heat transfer due to vortex generation in the flow and the friction factor. This study also allowed us to show the effect of the layout of the ribsand their shapes on the thermo-hydraulic performance compared to a smooth wall:

• In comparison with the smooth case, the presence of roughness disturbs the flow and increases both the convective transfer and the pressure losses.

• The Nusselt number increases with increasing Reynolds number and decreasing inclination angle β due to the modification of the laminar sublayer of the fully developed turbulent flow in the near-wall region.

• Of all the parameters examined, the blocking ratio is the most influential on the thermal-hydraulic performance factor.

• The observations, from the results obtained, have shown that there are two optimal efficiency values that can be reached at a number of Re = 4000. The first corresponds to β=30°; PR=1; BR = 0.2 and the second at β = 20°; PR = 1 and BR = 0.1. Between these two baffle layout values, the first case is more interesting.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements

* This article was presented as an oral presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Turkey on November 16-19, 2022.

References

Alam T., & Kim M.-H. (2018). A comprehensive review on single phase heat transfer enhancement techniques in heat exchanger applications. *Renew. Sustain. Energy Rev. 81*, 813–839.

Dittus, F. W., & Boelter, L. M. K. (1985). Heat transfer in automobile radiators of the tubular type. *International Communications in Heat and Mass Transfer*, *12*(1), 3-22.

Fluent (2003). Fluent user's guide. *Fluent Inc.*, *2*(3).

Gilinsky, V., (1976). New equations for heat and mass transfer in turbulent pipe flow and channel flow. *Int. Chem. Eng, 16***,** 359–368.

Han, J.C., Zhang, Y.M., & Lee, C.P. (1991). Augmented heat transfer in square channels with parallel, crossed and V-shaped angled ribs. *ASME Journal of Heat Transfer, 113*, 590-596.

Jang, J. Y., Hsu, L. F., & Leu, J. S. (2013). Optimization of the span angle and location of vortex generators in a plate-fin and tube heat exchanger. *International Journal of Heat and Mass Transfer*, *67*, 432-444.

Karima A., (2018). CFD investigations of thermal and dynamic behaviors in a tubular heat exchanger with butterfly baffles. *Frontiers in Heat and Mass Transfer (FHMT), 10*, 27. http://dx.doi.org/10.5098/hmt.10.27

Kumar B., Srivastava G.P., Kumar M., & Patil A.K. (2018). A review of heat transfer and fluid flow mechanism in heat exchanger tube with inserts. *Chem. Eng. Process. – Process intensif. 123*, 126–137.

Kwankaomeng, S., Jedsadaratanachai, W., & Promvonge, P. (2010, June). Laminar periodic flow and heat transfer in square channel with 30° inclined baffles. In *Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies (ESD 2010)* (pp. 1-7). IEEE.

Moody, L. F. (1944). Friction factors for pipe flow. *Transactions of the American Society of Mechanical Engineers*, *66*(8), 671-678.

Nakhchi, M. E., & Esfahani, J. A. (2019). Numerical investigation of rectangular-cut twisted tape insert on performance improvement of heat exchangers. *International Journal of Thermal Sciences*, *138*, 75-83.

Omidi, M., Rabienataj Darzi, A. A., & Farhadi, M. (2019). Turbulent heat transfer and fluid flow of alumina nanofluid inside three-lobed twisted tube. *Journal of Thermal Analysis and Calorimetry*, *137*(4), 1451-1462.

Targui N., & Kahalerras H. (2008). *Analyse du transfert de chaleur et de la chute de pression dans un échangeur de chaleur muni de chicanes poreuses*. Retrieved from https://www.sft.asso.fr/Local/sft/dir/user-3775/documents/actes/congres_2008/354.pdf

Promvonge, P., Sripattanapipat, S., & Kwankaomeng, S. (2010). Laminar periodic flow and heat transfer in square channel with 45° inline baffles on two opposite walls. *Int. J. Therm. Sci, 49*, 963–975.

Sheikholeslami M., Gorji-Bandpy M., & Ganji D. D. (2015). Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices. *Renew. Sustain. Energy Rev. 49*, 444–469.

Singh, S., Sørensen, K., & Condra, T. (2018). Investigation of vortex generator enhanced double-fin and tube heat exchanger. *Journal of Heat Transfer*, *141*(2), 021802. https://doi.org/10.1115/1.4042050.

Sun Z., Zhang K., & Li W. (2020). Investigations of the turbulent thermal-hydraulic performance in circular heat exchanger tubes with multiple rectangular winglet vortex generators. *Applied Thermal Engineering 168*, 114-838.

Torii, K., Kwak, K.M., & Nishino, K. (2002). Heat transfer enhancement accompanying pressure-loss reduction with winglet type vortex generators for fin tube heat exchangers. *Int. J. Heat Mas Transfer, 45*, 3795–3801.

Webb, R. L., & Eckert, E. R. G. (1972). Application of rough surfaces to heat exchanger design. *International Journal of Heat and Mass Transfer*, *15*(9), 1647-1658.

Zhang, D. H., & Gao, J. (2013). Numerical study of circular tube inserted arc belt on fluid flow and heat transfer under laminar flow. In *Key Engineering Materials* (Vol. 561, pp. 460-465). Trans Tech Publications Ltd.

Zina, B., Filali, A., Laouedj, S., & Benamara, N. (2019). Numerical investigation of a solar air heater (SAH) with triangular artificial roughness having a curved top corner. *Journal of Applied Fluid Mechanics*, *12*(6), 1919-1928.

Nabil BENAMARA
Materials and Reactive Systems Laboratory,
Mechanical Engineering Department,
Djillali Liabes University of Sidi-Bel-Abbes (22000),
BP. 89, City Larbi Ben Mhidi, Algeria
benamarana@gmail.com

Abdelkader LAHCENE
Materials and Reactive Systems Laboratory,
Mechanical Engineering Department,
Djillali Liabes University of Sidi-Bel-Abbes (22000),
BP. 89, City Larbi Ben Mhidi, Algeria

Djelloul LAHMER
Materials and Reactive Systems Laboratory,
Mechanical Engineering Department,
Djillali Liabes University of Sidi-Bel-Abbes (22000),
BP. 89, City Larbi Ben Mhidi, Algeria

Abdelkader BOULENOUAR
Materials and Reactive Systems Laboratory,
Mechanical Engineering Department,
Djillali Liabes University of Sidi-Bel-Abbes (22000),
BP. 89, City Larbi Ben Mhidi, Algeria

Mohamed MERZOUG
Materials and Reactive Systems Laboratory,
Mechanical Engineering Department,
Djillali Liabes University of Sidi-Bel-Abbes (22000),
BP. 89, City Larbi Ben Mhidi, Algeria

Miloud AMINALLAH
Materials and Reactive Systems Laboratory,
Mechanical Engineering Department,
Djillali Liabes University of Sidi-Bel-Abbes (22000),
BP. 89, City Larbi Ben Mhidi, Algeria

To cite this article:

Benamara, N., Lahmer, D., Merzoug, M., Lahcene, A., Boulenouar. A., & Aminallah, M. (2022). Numerical investigation of a tubular heat exchanger fitted with triangular ribs. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 21,* 452-463.