HEAT TRANSFER QUALITY INVESTIGATION PAST 2-D BACKWARD-FACING STEP IN PARTITIONED CHANNEL USING DMRT-LBM METHOD

El Bachir Lahmer[1*], Jaouad Benhamou[1], Youssef Admi[1], Mohammed Amine Moussaoui[1], Mohammed Jami[1], Ahmed Mezrhab[1]

[1]*Mechanics & Energetics Laboratory, Faculty of Sciences, Mohammed First University, 60000 Oujda, Morocco.*

[*]For correspondence; E-mail: lahmerelbachir@gmail.com, lahmer_elbachir1718@ump.ac.ma

ABSTRACT: *Nowadays, the advancement of electronic components technology is considered one of the challenges that generally focus on improving the quality of operation and efficiency of electronic systems. Although the evolution of these electronic systems, the successive increase in temperature induces a decrease in the operating performance and occasionally the failure of these electronic components (processors, high-performance servers, etc.). This paper presents a work on enhancing heat transfer quality over a Backward-facing step in a partitioned channel using a simulation code based on the double multiple relaxation times of the lattice Boltzmann method. The numerical results obtained show that the participation of different shapes of partitions had a significant impact on the thermal exchange between the cold fluid flow and the heated wall downstream of the step. Several standard parameters were examined to check the best improvement of the heat transfer quality.*

Keywords: Backward-facing step, heat transfer quality, fluid flow, local Nusselt number, inclined partitions.

1. INTRODUCTION

Fluid flow and convective heat transfer along a backward step (BFS) in the partitioned channel have been identified as one of the most researched areas demanding heat transfer enhancement with the progression of technology systems for various industrial and engineering purposes[1-3]. Several kinds of literature worked on this species of problem to understand the effects involved during the fluid flow process and the improvements of heat transfer for different complex geometries. Tuqa *et al.* [4], conducted a numerical study of the double backward-facing step using the k-ε standard model and Finite volume numerical method with various studied parametric such as Reynolds number, BFS step size for three different studied fluids. The results show that the augmentation in the values of Reynolds number increases the evolution of the local Nusselt number and skin friction coefficient, where the critical enlargement was situated at the entrance of the first and second step-sides lower wall. Furthermore, the evaluation of different fluids was carried out in this research, and the average Nusselt number increases very satisfactorily for ethylene glycol (EG) compared with the water and ammonia. As a result, the thermal exchange is more improves for EG liquid. Abu Talib *et al.* [5], led experimental and numerical research over corrugated backward-facing steps employing the RNG k-ε turbulent model. They conclude that the participation of the corrugated BFS shape increases the skin friction evolution. Consequently, the heat transfer quality is enhanced.

The primary purpose of our research is to pursue the evaluation of the heat transfer quality and fluid flow mechanism over backward-facing step with the involvement of different partitions using a simulation code based on the double multiple relaxation time of the lattice Boltzmann method DMRT-LBM.

2. NUMERICAL METHOD

The progression of the Boltzmann lattice method over the last decade has allowed us to simulate the behavior of fluid flow and heat transfer in a more convenient way. This method combines the Navier-stokes equations and particle dynamics at the macroscopic and microscopic scales, respectively. It has the particularity of modeling the fluid at an accurate level compared to conventional methods [6].

The simulation of fluid flow and convective heat transfer focalized on the resolution of the lattice Boltzmann equation (LBE), which describes the fluid advection and the collision process of the fluid particle using the MRT [7] scheme as shown in the following expression:

$$f_i(x + e_i \times \Delta t, t + \Delta t) - f_i(x,t) = M^{-1} \times S_i \times \left(m_i(x,t) - m_i^{eq}(x,t)\right) , \quad i = 0 \qquad 1$$

The LBE equation is characterized by the quantity f_i that defines the distribution function or the probability to found fluid particle at position x at a given time t. The quantities M and S_i denote the 9×9 transformation matrix and the diagonal relaxation time matrix, respectively. m_i and m_i^{eq} consider the moment vector and equilibrium momentum, respectively, in the moment space [8–10].

The numerical results obtained by the resolution of the LBE equation enables to define of the fluid flow behavior from the macroscopic quantity of the density and momentum as illustrated in the following expressions [6]:

$$\rho = \sum_{i=0}^{8} f_i \quad , \quad \rho\, u = \sum_{i=0}^{8} f_i\, e_i \qquad 2$$

For the thermal problem, the thermal lattice Boltzmann equation (TLBE) associated with multiple relaxation time scheme (MRT) was employed in this study to model the temperature distribution g_i as expressed below:

$$g_i(x + e_i \times \Delta t, t + \Delta t) - g_i(x,t) = N^{-1} \times Q_i \times \left(n_i(x,t) - n_i^{eq}(x,t)\right) , \quad i = 0, \dots, 4 \qquad 3$$

The quantities N and Q_i define the 5×5 transformation matrix and the diagonal relaxation time matrix, respectively. The quantities n_i and n_i^{eq} denote the thermal momentum and equilibrium thermal momentum in the moment space, respectively [11].

The numerical calculation of the TLBE equation allows to describe the temperature field in the macroscopic scale by the given expression below:

$$\mathrm{T} = \sum_{i=0}^{4} g_i \qquad 4$$

The D2Q9 and D2Q5 schemes were applied in this study to model the fluid flow behavior and the heat transfer process, respectively, as shown in Figure 1 [7].

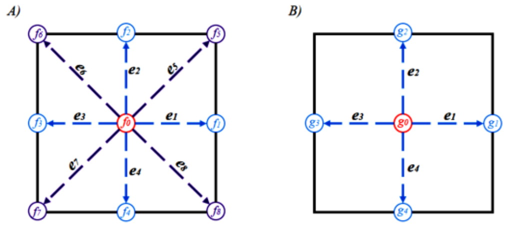

Figure 1: D2Q9 model for velocity pattern B) D2Q5 model for a thermal problem.

One can note that all setting parameters for the fluid flow and thermal field were discussed in the literature.

3. PHYSICAL PROBLEM AND BOUNDARY CONDITIONS

The system under investigation is a 2-D horizontal channel, consists of two heights, which are the height upstream channel he and the height downstream channel H, and the length L. The channel expansion ratio $ER = H/he$ of the backward-facing step equals 1.5. The channel flow consists of four inclined partitions with the length $lp = \frac{H}{4}$ is attached in the upper channel wall, where each partition was separated by the distance $D = 10$. At the inlet, the velocity $uo = 0.1$ and the cold temperature $\Theta_{in} = 0$ of the fluid flow characterized by a parabolic profile, where the maximum speed of the core fluid is positioned at the center of the upstream channel flow as given by the expression below:

$$\mathrm{u}(Y) = \frac{3}{2} \times \mathrm{uo} \times (1 - Y) \times \left(Y - \frac{h}{H}\right) \qquad 5$$

Where h denotes the step height of the backward-facing step. The Reynolds number used for the main problem is illustrated in the following equation:

$$\mathrm{Re} = \frac{2u_o \times h}{3\nu} \qquad 6$$

where ν and uo denote the kinematic viscosity and the maximum speed at the channel entrance, respectively.

The velocity and temperature gradients are assumed to be zero at the channel outflow (see Figure 2).

For thermal problems, the temperature of all channel walls is supposed to be insulated, except the step-side lower wall downstream kept a constant temperature or heated flux, as shown in Figure 2.

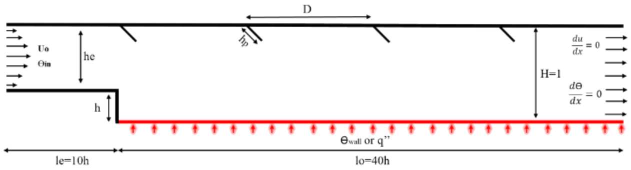

Figure 2: Schematic of the configuration system.

Regarding the boundary condition for the fluid flow, the Zou and He boundary condition [12] was applied at the inlet and the outlet of the channel flow, and the bounce-back boundary conditions [6; 9] were utilized for the solid wall and the inclined partitions (see Figure 3). Concerning the thermal flow, Equation 4 allows defining the unknown distribution function from the known distribution functions at the inlet. While the second-order extrapolation is performed to determine the unknown distribution function at the outlet [7].

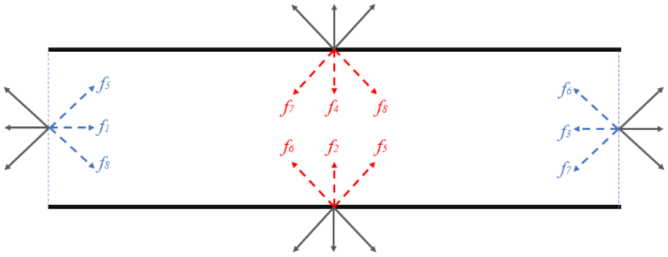

Figure 3: Unknown distribution function at the solid boundary.

4. VALIDATION CODE

To verify the credibility and accuracy of our simulation code. The obtained results have been compare**d** with the numerical results of other literature.

Table 1: Comparison of the flow reattachment length at Re=100, ER=1.5.

Reynolds number	*Re=10*	*Re=20*	*Re=50*	*Re=100*
Kondoh et al.	1.47	2.0	3.9	6.3
Armaly et al.	-	-	-	6.0
Our results	1.2	1.9	3.5	6.0

As shown in Table 1, the reattachment point was compared with the numerical results obtained by Kondoh et al. [13] and the experimental results performed by Armaly et al. [14]. The results obtained by our numerical simulation had a good agreement with the experimental and numerical results of the literature. Regarding the thermal field, the numerical investigation of the temperature field has the same results as Kondoh et al. [13], as displayed in Figure 4.

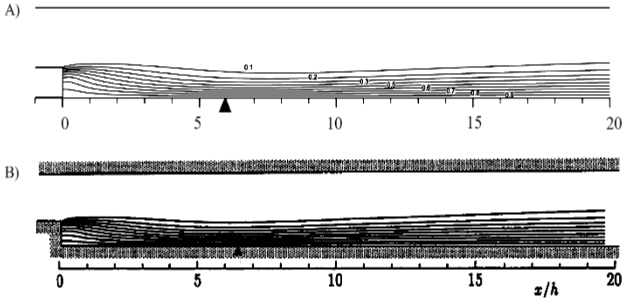

Figure 4: **comparison of isotherms field at Re=100, ER=1.5.**

The local Nusselt number is also analyzed in this work to interpret the evolution of heat transfer along with the channel domain, where the following equation allows to define the local Nusselt number as shown in the given formula:

$$Nu = \left.\frac{\partial \theta}{\partial Y}\right|_{Y=0} \qquad 7$$

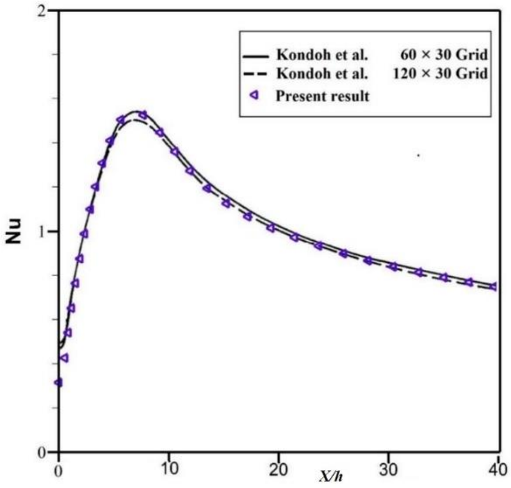

Figure 5: **Local Nusselt number evolution at Re=100, ER=1.5.**

Figure 5 illustrates the evolution of the local Nusselt number for $Re = 100$ and $ER = 1.5$. There is a good agreement between the numerical result obtained and the reference [13]. As a result, the code based on the DMRT-LBM method is suitable to simulate fluid flow and convective heat transfer.

5. NUMERICAL RESULTS AND DISCUSSION

In this research, the values of the step height, velocity, temperature, position, and shape of the four partitions will be assumed fixed during the numerical simulation. The effect of the Reynolds number and Prandtl number is taken into account to evaluate the evolution of heat transfer and fluid flow behavior.

The structural study was assured to found the best grid to simulate the fluid flow and heat transfer for this proposed work. The results indicate that the mesh 2000×120 was enabled to investigate all numerical simulations of the studied problem to avoid mesh independence.

Figure 6 shows the streamlines of the fluid flow at a fixed Prandtl number for two different values of Reynolds number. The results exhibit that the appearance of recirculation zones of different shapes after each partition and at the bottom wall downstream of the step. The formation of these vortices is due to the difference in velocity between the mainstream fluid and the low speed of the fluid behind each partition. As the Reynolds number increases, the structure of the recirculation zones increases. It can be observed that the fluid flow becomes oscillatory due to the participation of the inclined partitions.

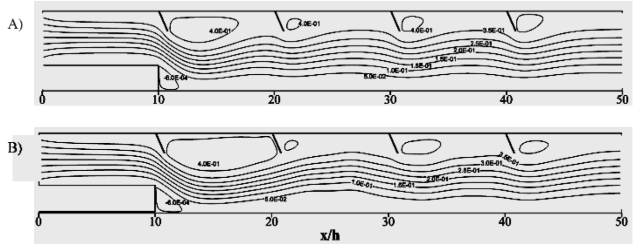

Figure 6: **Velocity streamlines of the fluid flow at Pr=0.71: A) Re=50, B) Re=120.**

Figure 7 displays the temperature field for Two different values of Reynolds numbers. The numerical results illustrate that with the augmentation of Reynolds number the thickness of temperature layers decreases, where a thin thermal boundary layer is installed near the lower wall downstream of the step.

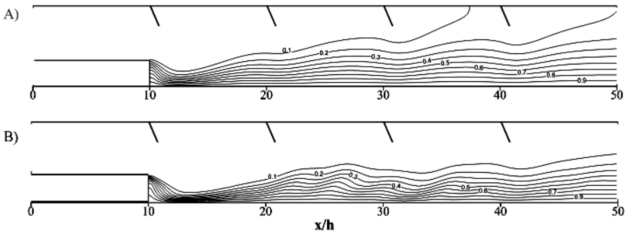

Figure 7: Temperature contours at Pr=0.71: A) Re=50, B) Re=120.

In order to observe the heat transfer evaluation in the partitioned channel, the local Nusselt number has been analyzed for two different values of Reynolds numbers as shown in Figure 8. an excellent evolution of local Nusselt number near the step-side wall downstream for both cases of Reynolds number. When $Re = 50$, a critical peak is located in the vicinity of the channel step, and three low peaks are positioned near each partition. The apparition of these peaks is due to the involvement of the four partitions, where the direction of the main fluid flow was oriented by the participation of these partitions, then the heat transfer rate increases. When $Re = 120$, the principal peak near the step reaches the value 3.6. A critical peak appears near the position $x/h = 30$ due to a disturbance in the flow of the fluid because of the high value of Reynolds numbers. One can interpret that the increase of Reynolds number enhances the heat transfer quality at a fixed Prandtl number.

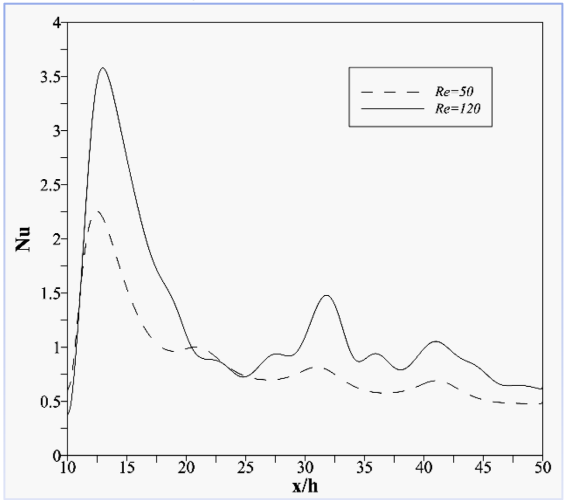

Figure 8: Local Nusselt number evolution at Pr=0.71.

The variation of Prandtl number (Pr) is also performed in this work. This dimensionless number Pr evaluates the rate of the promptness of thermal and hydrodynamic phenomena in a fluid. As shown in Figure 9, the augmentation in the Pr number provokes a decrease in the thin thermal layers at the vicinity of the lower wall downstream of the step. Thus, the hydrodynamic phenomena dominate in front of the thermal proprieties of the fluid, where the isotherm lines are compressed towards the lower wall (see Figure 9-C).

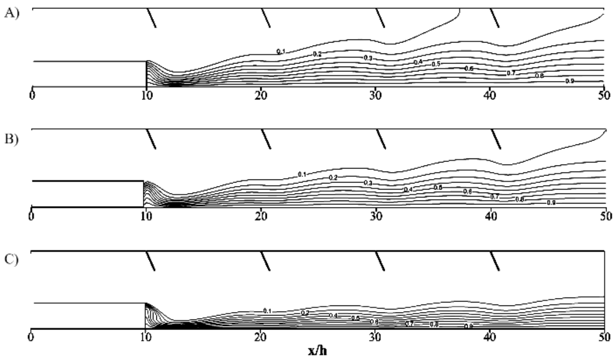

Figure 9: **Isotherms lines at Re=50: A) Pr=0.71, B) Pr=1, C= Pr=3.8.**

Figure 10 displays the evolution of the local Nusselt number for various values of Prandtl numbers. When Pr increases, the thermal properties of the fluid change, where the local Nusselt number increases when Pr increases at a fixed Reynolds number. As a result, the heat transfer quality increases when the Prandtl number reaches the hydrodynamics effects that prevails over the thermal impacts.

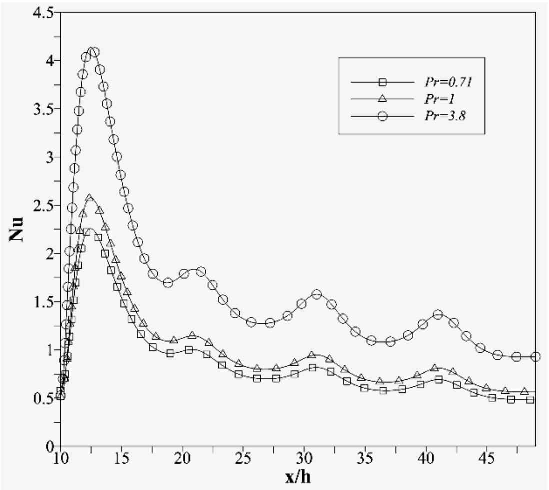

Figure 10: Local Nusselt Number evolution for Re=50.

6. CONCLUSION

This research leads numerical study 2-D partitioned channel over a backward-facing step. The code based on double multiple relaxation times of the lattice Boltzmann method had a good agreement with previous numerical and experimental literature to ensure the accuracy during the simulation of realistic phenomena of the fluid flow and heat transfer. The numerical results of this study are presented in the form of streamlines, isotherms, and local Nusselt number evolution. To summarize the results obtained during this work, Table 2 illustrates the development of the average Nusselt number for the variation of Reynolds number and the Prandtl number. When the Reynolds number raised from $Re = 50$ to $Re = 120$, the heat transfer quality increases by around 41.65% for $Pr = 0.71$. While the increase of the Pr number from $Pr = 0.71$ to $Pr = 3.8$, the thermal exchange increase by 84.14% at a fixed Reynolds number ($Re = 50$). One can conclude finally that the elevation of Reynolds number and the Prandtl number enhances the heat transfer quality adequately with the participation of the four inclined partitions.

Table 2: Evolution of average Nusselt number.

Pr=0.71			
Re	50	120	
Nu (avg)	0.866	1.227	
Re=50			
Pr	0.71	1	3.8
Nu (avg)	0.866	0.990	1.595

REFERENCES

[1] Abu Talib, A. R., & Hilo, A. K. (2021). Fluid flow and heat transfer over corrugated backward-facing step channel. *Case Studies in Thermal Engineering*, *24*(December 2020), 100862. DOI: 10.1016/j.csite.2021.100862

[2] Moosavi, R., Moltafet, R., & Shekari, Y. (2021). Analysis of viscoelastic non-Newtonian fluid over a vertical forward-facing step using the Maxwell fractional model. *Applied Mathematics and Computation*, *401*, 126119. DOI: 10.1016/j.amc.2021.126119

[3] Pekmen Geridönmez, B., & Öztop, H. F. (2021). Effects of inlet velocity profiles of hybrid nanofluid flow on mixed convection through a backward-facing step channel under partial magnetic field. *Chemical Physics*, *540*(October 2020). DOI: 10.1016/j.chemphys.2020.111010

[4] Abuldrazzaq, T., Togun, H., Alsulami, H., Goodarzi, M., & Safaei, M. R. (2020). Heat transfer improvement in a double backward-facing expanding channel using different working fluids. *Symmetry*. DOI: 10.3390/sym12071088

[5] Abu Talib, A. R., & Hilo, A. K. (2021). Fluid flow and heat transfer over corrugated backward-facing step channel. *Case Studies in Thermal Engineering*, *24*(December 2020), 100862. DOI: 10.1016/j.csite.2021.100862

[6] Lahmer, E. B., Moussaoui, M. A., Mezrha, A., Botton, V., & Henry, D. (2019). Double constricted channel for laminar flow and heat transfer based on double MRT-LBM. *Double Constricted Channel for Laminar Flow and Heat Transfer Based on Double MRT-LBM.*, *August*, 16. Retrieved from https://cfm2019.sciencesconf.org/244844/document

[7] Lahmer, E. B., Moussaoui, M. A., & Mezrhab, A. (2019). Investigation of laminar flow and convective heat transfer in a constricted channel based on double

MRT-LBM. *2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems, WITS 2019*. DOI: 10.1109/WITS.2019.8723820

[8] Benhamou, J., Jami, M., Mezrhab, A., Botton, V., & Henry, D. (2020). Numerical study of natural convection and acoustic waves using the lattice Boltzmann method. *Heat Transfer*. DOI: 10.1002/htj.21800

[9] Admi, Y., Moussaoui, M. A., & Mezrhab, A. (2020). Effect of a flat plate on heat transfer and flow past three side-by-side square cylinders using double MRT-lattice Boltzmann method. *2020 IEEE 2nd International Conference on Electronics, Control, Optimization and Computer Science, ICECOCS 2020*. DOI: 10.1109/ICECOCS50124.2020.9314506

[10] Moussaoui, M. A., Lahmer, E. B., Admi, Y., & Mezrhab, A. (2019). Natural convection heat transfer in a square enclosure with an inside hot block. *2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems, WITS 2019*, 1–6. DOI: 10.1109/WITS.2019.8723863

[11] Mezrhab, A., Amine Moussaoui, M., Jami, M., Naji, H., & Bouzidi, M. (2010). Double MRT thermal lattice Boltzmann method for simulating convective flows. *Physics Letters, Section A: General, Atomic and Solid State Physics*. DOI: 10.1016/j.physleta.2010.06.059

[12] Zou, Q., & He, X. (1997). On pressure and velocity boundary conditions for the lattice Boltzmann BGK model. *Physics of Fluids*. DOI: 10.1063/1.869307

[13] Kondoh, T., Nagano, Y., & Tsuji, T. (1993). Computational study of laminar heat transfer downstream of a backward-facing step. *International Journal of Heat and Mass Transfer*. DOI: 10.1016/0017-9310(93)80033-Q

[14] ARMALY, B. F., DURSTS, F., PEREIRA, J. C. F., & SCHONUNG, B. (1983). Experimental and theoretical investigation of backward-facing step flow. *Journal of Fluid Mechanics, 127*, 473–496. DOI: 10.1017/S0022112083002839