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Special Edition

Application of constructal theory for the construction of an arrangement of heated blocks inserted in a channel subject to flows with forced convection

Aplicação da teoria construtal para a construção de um arranjo de blocos aquecidos inseridos em canal sujeito a escoamentos com convecção forçada

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ABSTRACT

This work shows an analysis of the construction of the geometric arrangement of blocks mounted on the surfaces of a channel subjected to a laminar, incompressible flow, with forced convection in a two-dimensional domain. The construction is carried out using a construction function based on the system's performance indicator, i.e., the heat transfer rate from the arrangement to the fluid flow. For the assembly of the arrangement, a methodology based on the principles of the Constructal Theory is employed. To solve the convection problem, the conservation equations for mass, momentum, and energy are solved using the Finite Volume Method, more precisely using the FLUENT software. The objective of this work is to understand how the construction of the initial blocks of the array (N = 3 blocks) occurs in an area occupied by the channel in flows with forced convection and Reynolds and Prandtl numbers of Re_H = 100 and Pr = 0.71. The best and worst cases for N = 2 led to an increase of 93.21% and 28.59%, respectively, compared to the N = 1 case. The results demonstrated that the construction leading to the best thermal performance is the configuration where there is the highest momentum between the blocks (enhancing the convective heat transfer coefficient) and the lowest interaction between the thermal boundary layers, which is in agreement with the principle of optimal distribution of imperfections.

Keywords: Constructal theory; Geometric investigation; Forced convection; Arrangement of blocks; Laminar flow

RESUMO

Este trabalho mostra uma análise da construção do arranjo geométrico de blocos montados nas superfícies de um canal sujeitas a um escoamento laminar incompressível com convecção forçada em um domínio bidimensional. A construção é realizada através de uma função de construção baseada no indicador de performance do sistema, ou seja, a taxa de transferência de calor do arranjo para o escoamento. Para a montagem do arranjo, foi empregada uma metodologia baseada nos princípios da Teoria Construtal. Para resolver o problema de convecção, as equações de conservação de massa, quantidade de movimento e energia foram resolvidas com o Método dos Volumes Finitos, mais precisamente empregando o software FLUENT. O trabalho tem por objetivo compreender como ocorre a construção dos blocos iniciais do arranjo (N = 3 blocos) em uma área de ocupação do canal em escoamentos com convecção forçada e números de Reynolds e Prandtl de Re_H = 100 e Pr = 0,71. O melhor e o pior caso para N = 2 conduziram a um aumento de 93,21% e 28,59%, respectivamente, em comparação com o caso N = 1. Os resultados demonstraram que a construção que conduziu ao melhor desempenho térmico foi a configuração em que há uma maior quantidade de movimento entre blocos (intensificando o coeficiente convectivo de transferência de calor) e com menor interação entre as camadas limites térmicas, o que está de acordo com o princípio da ótima distribuição das imperfeições.

Palavras-chave: Teoria construtal; Investigação geométrica; Convecção forçada; Arranjo de blocos; Escoamento laminar

1 INTRODUCTION

Many experiments and numerical studies are being carried out to improve the understanding of convective heat transfer in channels with heated bodies. This type of problem can represent many real engineering problems such as those found in electronic circuit packages and compact heat exchangers. Examples related to the cooling of electronic devices and strategic application in aerospace, defense and biomedical engineering are presented in the literature (Fontana; Capeletto; Silva; Mariani, 2015). In this sense, the development of cooling strategies to improve the heat removal performance of these systems is an important object of study.

Many works have been carried out to expand the understanding of the dynamics and thermal behavior of fluids in forced convection in a laminar regime with channels where the geometry arrangement is assembled. For example, Young and Vafai (1998) numerically investigated flows with forced convection with a block mounted on the surface of a channel considering heat conduction in the obstacle. The influence of the geometric parameters of the blocks such as height and width, as well as, the thermal conductivity of the solid and the fluid in the convection heat transfer process were investigated. The results showed that the geometry of the bodies and their material significantly influence the behavior of the flow and heat exchange. Korichi and Oufer (2005) carried out a similar study considering an arrangement of three blocks mounted alternately on the upper and lower borders of the channel under forced convective flows. The influences of the Reynolds number, sizes of obstacles and their conductivity on the heat exchange behavior were analyzed. Subsequently, Korichi and Oufer (2007) extended the study by Korichi and Oufer (2005) to oscillating flows in a channel over an alternating arrangement of square blocks mounted on the channel walls. In general, the results show that the insertion of upper obstacles caused the generation of vortices that increased the heat transfer rate between the blocks and the flow around them. Furthermore, it was found that larger obstacles led to an increase in heat transfer. Luviano-Ortiz, Hernandez-Guerrero, Rubio-Arana and Romero-Mendez (2008) numerically evaluated the insertion of curved baffles on the heated blocks in the rate of heat exchange between the flow by forced convection and the obstacles. To achieve this purpose, a comparison was made between convection flows with and without baffles. According to the authors, the use of deflectors was recommended for flows with higher Reynolds numbers. Recently, Durgam, Venkateshan and Sundararajan (2018) experimentally and numerically studied a flow with forced convection of air as working fluid in a vertical channel for cooling heat sources mounted on its surfaces. The main intention was to estimate an optimal distribution of the seven heat sources in order to minimize the temperature in the heat sources. As a result, a correlation between the temperature of the sources as a function of the Reynolds number and the ratio between the thermal conductivity of the sources and the air was obtained.

Constructal Theory is the mental view that every flow system has its design defined from a physical principle (Bejan, 2000; Bejan, 2016). This physical principle is called the Constructal Law of Design and Evolution, which states that for a finite size flow system to persist alive; its design must freely evolve in order to maximize the access to the internal currents flowing through it (Bejan, 2016). The method of application of the Constructal Theory, called Constructal Design, has also been used in the literature as a powerful tool to investigate the design of several flow systems, including those seem in nature and social dynamic (Bejan, 2016).

In the field of engineering, several works have been developed to better understand the design in several applications, from cavities and fins of refrigeration systems to problems of solid mechanics and renewable energy sources (Lorenzini *et al.*, 2013; Santos; Isoldi; Gomes; Rocha, 2017; Gomes *et al.*, 2018; Teixeira *et al.*, 2018; Gonzales *et al*., 2021; Lima *et al.*, 2020; Silveira *et al*., 2021). In the scope of flows over blocks in channels, recently, Feijó *et al*. (2018) presented an application of Constructal Design for the investigation of two rectangular blocks mounted on alternating surfaces (lower and upper) of channels subject to flows with forced convection in the laminar regime. Results indicated that the greater insertion of the blocks in the spanwise direction of the flow was beneficial for the heat transfer rates, while the smaller insertion led to the smallest pressure drops in the investigated domain. Later, Moreira *et al*. (2021) performed a similar study on corrugated channels with a trapezoidal cross-section, obtaining recommendations for the trapezoidal geometries that led to the highest heat transfer rates. Recently,

the use of construction functions for assembling cylinder arrays has been developed. In the work of Pedroti, Escobar, Santos and Souza (2020), an array of cylinders was constructed in an occupation area employing a construction function dependent on velocity and temperature field to define the position of each new cylinder assembled in the occupation area. Despite these important developments, the study of assembling blocks in channels using a construction function dependent on the performance indicator itself (heat transfer rate) and investigating all geometric possibilities has not been carried out in the literature.

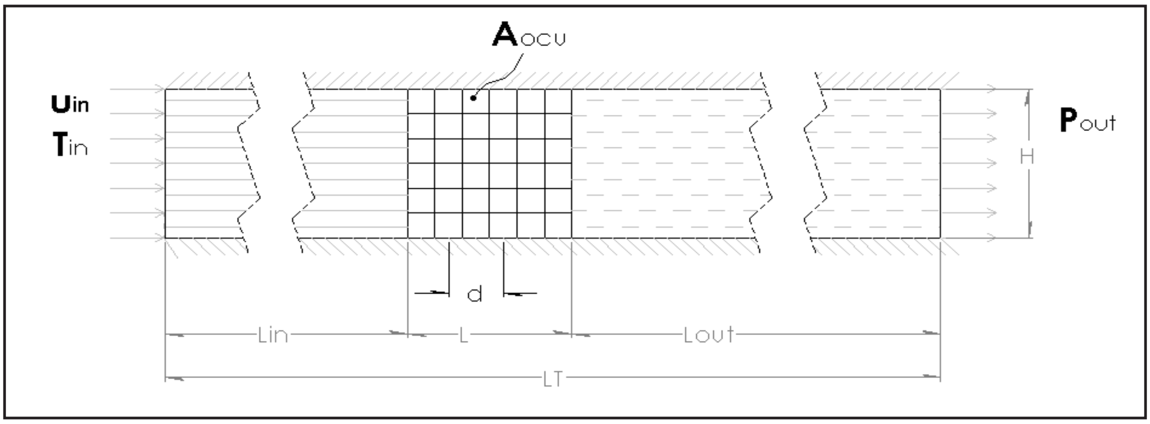
It is also worth highlighting that the present proposal follows ideas initially idealized in the work of Errera and Bejan (1998) who proposed the construction of empty channels in porous media that simulated the flow process between a volume and a point in the form of a tree.

In the present work, a methodology is developed for the construction of an array of blocks in an area occupied by channels subject to incompressible, laminar flows with forced convection, in the steady state in a two-dimensional domain. The construction is based on the Constructal Theory and carried out block by block, with the position of the new block being defined from the system performance indicator, the heat transfer rate, between the blocks and the flow. The main objective is to maximize the heat transfer rate between the heated bodies and the surrounding flow, as well as to investigate how the arrangement is built from the technique proposed here and the effect of the geometric arrangement of the heated bodies on the system performance.

2 MATHEMATICAL MODELING

In this work, incompressible, laminar flow with forced convection at the steady state is considered in a two-dimensional domain of a channel with an arrangement of heated blocks to be mounted in the positions of an occupation area, as illustrated in Fig. 1.

Figure 1 – Computational domain of the channel with construction of an array of heated blocks



Source: Authors (2023)

The working fluid is air, with constant thermophysical properties and a Prandtl number of Pr = 0.71. Fluid motion is caused by imposing a flow with constant velocity and temperature at the entrance to the domain that is represented by the left side of figure 1. More precisely, u_{in} = 4.87×10^{-2} m/s, so that the Reynolds number is Re_H = 100, and at an inlet temperature of T_{in} = 298 K. The channel and blocks surfaces have a boundary condition of non-slip and impermeability (u = v = 0 m/s). Furthermore, the channel surfaces are thermally insulated and thermal exchange occurs exclusively between the blocks, heated to a temperature T_S = 350 K, and the fresh stream of airflow in the channel. At the outlet of the channel, a zero gauge pressure condition is considered (P_{out} = 0 atm). For the computational domain illustrated in Fig. 1, the following dimensions are considered: H = 30 mm, L_T = 280 mm, L_{in} = 50 mm (distance between the input surface and the area occupied by the first solid).

The modeling of the forced convective flow studied here is given by the conservation equation of mass, balance of momentum equations in *x* and *y* directions and conservation of energy, as follows (Bejan, 2013):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_P}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

where x and y represent the spatial coordinates (m); u and v are the velocity components in the x and y directions (m/s); ρ is the density of the fluid (kg/m^3); P is the pressure (Pa); υ is the kinematic viscosity (m^2/s); CP is the specific heat at constant pressure (J/(kg · K)), k is the thermal conductivity of the fluid (W/(m · K)).

For the geometric evaluation of the arrangement of the blocks in the channel with forced convective flows, Constructal Theory is used (Bejan, 2000). In the present work, a construction technique is employed using the heat transfer rate as a construction function to define the position of each new block in an occupation area. For this, the following steps are followed:

1 – Define the physical problem and the dimensions of the channel and area of occupation;

2 – Divide the occupation area into Nx × Ny imaginary subareas where the heated blocks are mounted (in the present study Nx = Ny = 6) – see Figs. 1 and 2;

3 – Define the position where the first block is assembled respecting the mounting constraint that the block must be adjacent to some physical surface (in the present study, the first block was mounted in Position 1, as shown in Fig. 2);

4 – Perform the computational simulation to define the performance indicators of the problem (rate of heat transfer from the array of blocks to the fresh stream of flow and pressure drop in the channel);

5 – Perform the mounting of the second block in different positions of the occupation area, respecting the restriction of the assembly being adjacent to some physical surface (in the present study, the second block can be assembled in positions 2, 3, 4, 5, 6, 7, 31, 32, 33, 34, 35 and 36);

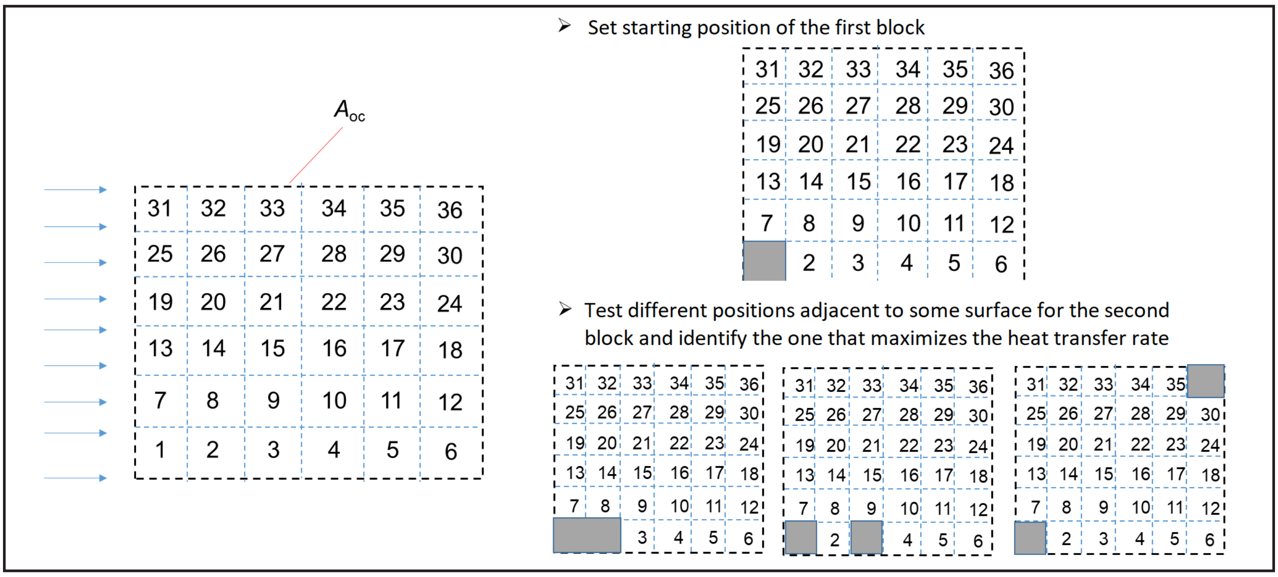
6 – Obtain the results by computational simulation of the cases with 2nd block for the different positions defined in Step 5 (12 different positions) and calculate the heat transfer rate between the blocks and the flow in the channel;

7 – Define the position for mounting the 2nd block for the configuration that maximized the heat transfer rate;

8 – Repeat steps 5 to 7 to assemble the subsequent blocks until the limit defined by the area fraction, φ, between the area of the arrangement of blocks and the occupation area is reached (in the present work 3 blocks were assembled, i.e., φ = 3/36 = 0.083).

In Figure 2, the construction scheme of the arrangement of blocks based on the Constructal Design and using the heat transfer rate to define each new position can be seen.

Figure 2 – Block arrangement construction scheme based on the Constructal Design and using the heat transfer rate to define each new position



Source: Authors (2023)

The main proposal here is to maximize the rate of heat transfer between heated obstacles and neighboring flow at lower temperatures in a channel, as in:

$$q = \sum_{i=1}^{N} \dot{m}\, C_P (T_{out} - T_{in}) = \sum_{i=1}^{N} \bar{h}_i A_{s,i} (T_{s,i} - T_{in}) \quad (5)$$

where is the mass flow rate in the channel (kg/s); *i* is an indicator of each block being inserted at constant temperature (T_s), T_{out} is the outlet temperature of the channel flow for each investigated configuration, $T_{s,i}$ is the temperature of the i-th heated block and $A_{s,i}$ the area of the i-th heated block, *h* i is the space-averaged heat transfer coefficient for the i-th block. It is worth mentioning that the heat transfer rate can be calculated in two different ways, as seen in Eq. (5), with the purpose of verifying whether the computation of *q* is adequate.

3 NUMERICAL MODELING

The equations of conservation of mass, momentum balance and conservation of energy, Eqs. (1)-(4), are solved using the Finite Volume Method (Versteeg; Malalasekera, 2007), more precisely using CFD software (Computational Fluid Dynamics) (Ansys, 2021). For the numerical modeling, a pressure-based solver is employed, the SIMPLE method is used to model the pressure-velocity coupling, SOU advection scheme (Second order upwind) is used for solving the advective terms and the Standard method for the spatial pressure discretization. The solutions are considered convergent when the residuals for the conservation equation of mass, balance of momentum equations and energy conservation equation are less than $R_{mass} < 1.0\times10^{-6}$, $R_{momentum} < 1.0\times10^{-6}$ and $R_{energy} < 1.0\times10^{-8}$, respectively. All simulations are performed using a computer with Intel® Core™ i7-3520M CPU@ 2.90 GHz 2.90 GHz and memory with 8 GB of RAM.

Regarding the spatial discretization, rectangular volumes with high refinement are used close to the surfaces of the bodies and channel. The mesh is considered independent when the relative deviation between the heat transfer rate predicted for the fine mesh and the coarse mesh of the heated blocks is less than $R = |((q^j - q^{j+1})/q^j)| < 5.0 \times 10^{-3}$. In the R expression, q_j represents the heat transfer rate obtained between a coarse mesh and q_{j+1} represents the value obtained for the successive refined mesh. The results of the mesh independence test for the case with $Re_H = 100$ and $Pr = 0.71$, and considering only one block inserted in the channel occupation area ($N = 1$), are shown in Table 1. Results indicate that a mesh with 56,153 volumes is adequate for the continuity of the study carried out here.

Verification of the computational code used here was previously performed in studies by Feijó *et al.* (2018) and Moreira *et al.* (2021) comparing the local Nusselt number over a block and comparing with literature results. For the sake of simplicity, the scan results will not be repeated here, please verify the works of Feijó *et al.* (2018) and Moreira *et al.* (2021).

Table 1 – Mesh independence test – Re_H = 100, Pr = 0.71 and *N* = 1

Mesh	Finite Volume Size (mm)	number of cells	$\bar{q}^i$(W)	$\left\lvert \frac{\bar{q}^{i+1}-\bar{q}^i}{q^i} \right\rvert \leq 5.0 \times 10^{-3}$
M1	1.0 x 10-3	16,943	6.2239	1.00 x 10-2
M2	8.0 x 10-4	25,980	6.1614	5.79 x 10-3
M3	5.5 x 10-4	56,153	6.1971	5.97 x 10-4
M4	5.0 x 10-4	67,358	6.1934	

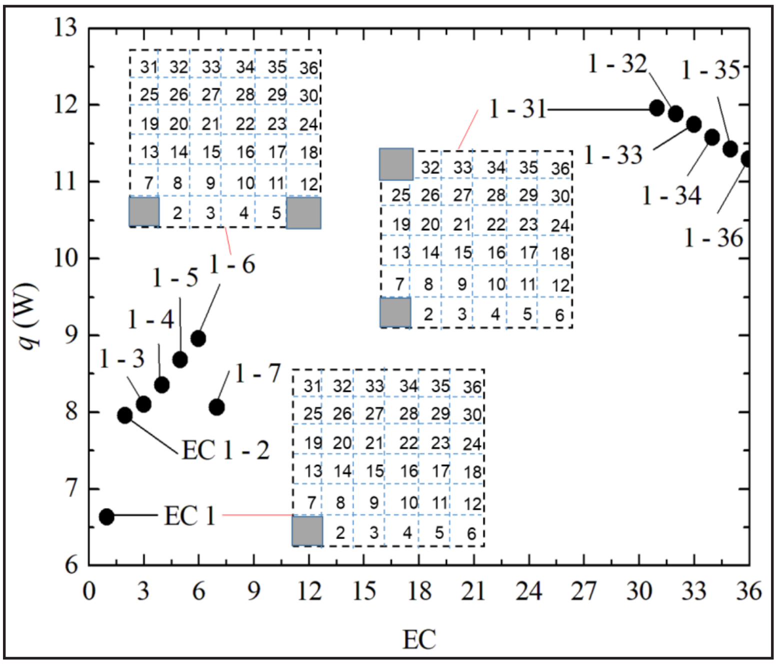
Source: Authors (2023)

4 RESULTS AND DISCUSSIONS

Results presented here correspond to the construction of the first 3 blocks in the channel occupation area. For all investigations, it is considered that the resolution of the blocks is *l* = 5.0 mm and the ratio between the minimum distance between the blocks and the resolution is *d/l* = 1.0.

As shown in Table 1, the heat transfer rate for *N* = 1, considering that the block is being mounted in the lower left corner of the occupation area, is given by *q* = 6.19 W. Figure 3 illustrates the heat transfer rate per unit of depth obtained for *N* = 2. The first block was mounted at position CE (Constructal Element) = 1 and the second block was simulated by testing the different positions in the search space, i.e., CE = 2, 3, 4, 5, 6, 7, 31, 32, 33, 34, 35 and 36. Results of Fig. 3 illustrate that the assembly of the block *N* = 2 is superior than the block with *N* = 1, regardless of the CE where the new block is mounted. The worst performance for *N* = 2 was obtained when the first block was assembled at CE = 1 and the second block at CE = 2 (CE 1 – 2) where a heat transfer rate of *q* = 7.96 W was obtained and the best performance was obtained when CE = 31 (CE 1 – 31) where *q* = 11.96 W was obtained. The best and worst case for *N* = 2 led to an increase of 93.21 % and 28.59 %, respectively, in comparison with the case *N* = 1. Thus, the results indicate that the construction of a new CE is recommended to improve the system's performance, regardless of the position where it is being mounted. The worst performance was obtained when the second block is mounted adjacent and downstream of the first block, probably due to the formation of the thermal boundary layer in the first block leading to the second block a heated portion of fluid. The best performance was obtained when the second block was constructed in the same *x*-position as the first block, but on the top surface of the channel. This behavior is related to the increase in the momentum between blocks 1 and 31 caused by the insertion of the second block in the same position *x* (see scheme shown in Fig. 3).

Figure 3 – Effect of assembling blocks for *N* = 1 and *N* = 2 on the heat transfer rate of arrangements with 1 and 2 blocks



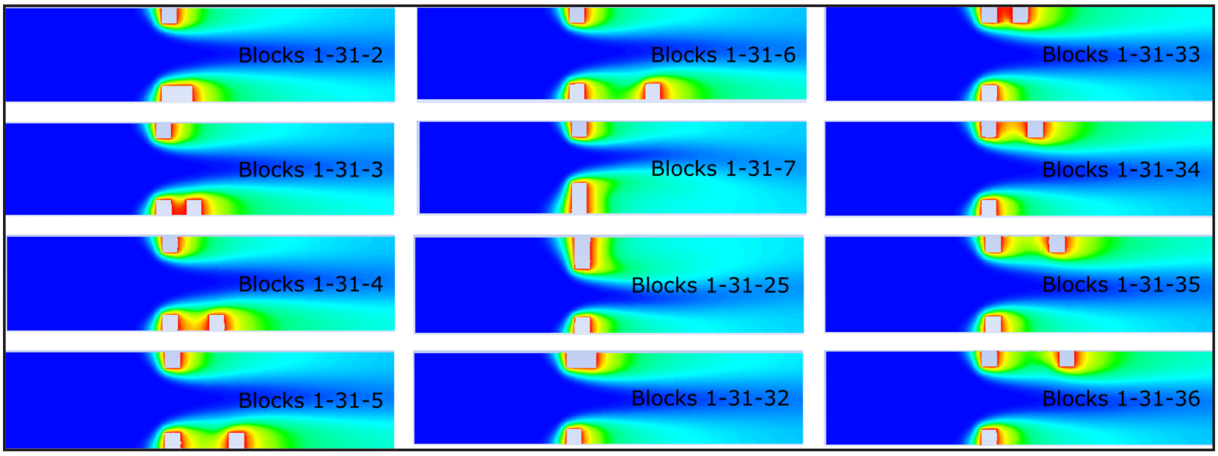
Source: Authors (2023)

For the next construction step, i.e., *N* = 3, all CE assembly possibilities are tested, considering that *N* = 1 is assembled on CE = 1 and *N* = 2 is assembled on CE = 31, that is, every construction step is considered a system with memory. Then, for *N* = 3, new blocks are tested in positions CE = 2, 3, 4, 5, 6, 7, 25, 32, 33, 34, 35 and 36. Figure 4 illustrates the temperature fields obtained for the simulations carried out with each of the configurations tested. It can be observed that the temperature gradients are more intense when the third block is as far away as possible from the front blocks assembled for *N* = 1 and *N* = 2. This is also reflected in the heat transfer rate, where the highest rates are obtained for CE = 6 and

CE = 36, with a slight advantage for CE = 6. For *N* = 3 the blocks were fitted with CE = 1 – 31 – 6 and the heat transfer rate obtained was *q* = 15.48 W, which shows that the assembly of the third block is still advantageous in the position that leads to the best thermal performance. Figure 4 also illustrates that the assembly of block *N* = 3 on the same line as blocks *N* = 1 and 2 and close to them, causes a heating region in both blocks, which is detrimental to thermal exchange. As the blocks move apart, along the same lines as blocks *N* = 1 and 2, there is an increase in temperature gradients around the blocks, benefiting the heat exchange.

The assembly of the blocks in positions CE = 7 and 25 was also presented as an interesting possibility, due to the increase in the momentum. However, there is a larger portion of the block area that is heated due to thermal boundary layer formation, which tends to lead to lower heat transfer rates than the cases where the third block was assembled at CE = 6 and 36. Thus, the best configuration for the arrangement with *N* = 3 was obtained when the blocks were mounted in the corners of the occupation area.

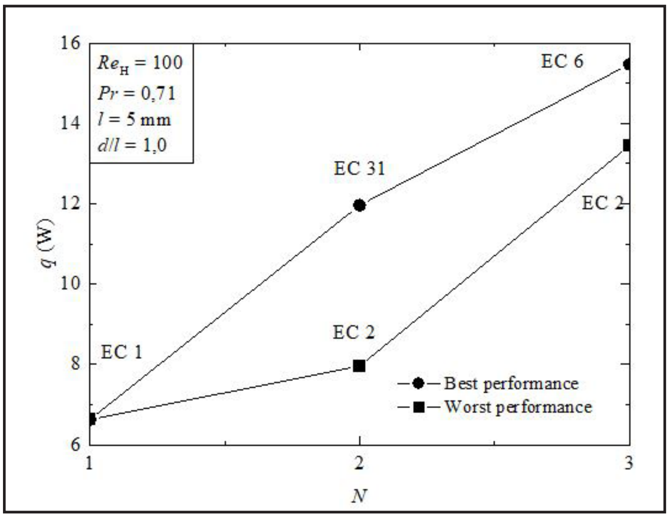
Figure 4 – Illustration of the temperature fields for assembling the third block (*N* = 3) for all possible CE



Source: Authors (2023)

In order to evaluate the influence of the number of blocks on the heat transfer rate, Fig. 5 shows the effect of *N* on *q* for the configurations that led to the best and worst performances. The elementary block (*N* = 1) presented a heat transfer rate of *q* = 6.19 W. As this block is imposed in the problem, there is no variation between minimum and maximum. For the construction of the second block (*N* = 2), CE = 31 led to a heat transfer rate of *q* = 11.96 W while CE = 2 led to *q* = 7.96 W. For *N* = 3, the worst case was obtained for CE = 2 with a rate of *q* = 13.45 W and the best case was obtained for CE = 6, where *q* = 15.47 W to *N* = 3 that, regardless of the position of the new block, the condition with *N* = 3 leads to a performance superior to *N* = 2. Despite this, the growth rate between *N* = 2 and *N* = 3 is reduced compared to first construction (from *N* = 1 to *N* = 2) which can indicate that the increase on the number of blocks may stabilize the heat transfer rate in the arrangement due to the saturation of the occupation area. Results also indicate that the difference in performance between the best and the worst arrangement showed a decreasing trend, which may indicate that, in the next assembly steps, the position of the new blocks can have limited influence on the performance of the arrangement.

Figure 5 – Effect of the number of blocks (N) on the maximum and minimum heat transfer rate (*q*) obtained for the block arrangement

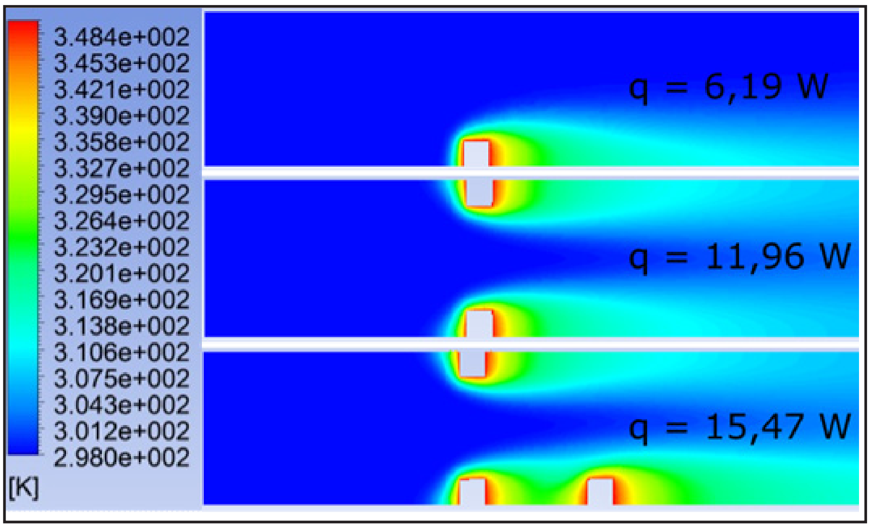


Source: Authors (2023)

The temperature fields obtained for the optimal configurations with *N* = 1, 2 and 3 are presented in Fig. 6. It is possible to observe that between *N* = 1 and *N* = 2 there is a low temperature jet between the heated blocks, intensifying the heat exchangers by the increase of momentum between the blocks. Furthermore, the thermal boundary layer around the obstacles is not influenced by the presence of the other block. For *N* = 3, the third block had to be mounted in a region under the influence of the thermal boundary layer formed by the previous block, in this case the block positioned at CE = 1. This behavior explains why there is a drop in the growth rate of q between N = 2 and 3 compared to N = 1 and 2. In general, the constructive technique proved to be very promising for the construction of an arrangement of blocks in channels subject to heat transfer by forced convection.

Results indicated that the constructive technique was very promising to indicate the new positions of the blocks that led to the best thermal performance, allowing a growth of up to 1.5 times between the best configuration with N = 3 and the elementary configuration (N = 1). Results also indicated that, for the construction of the three blocks, the performance increased with the insertion of each new block mounted in the arrangement. Despite this, between N = 2 and N = 3, the growth rate of q was not as significant compared to that obtained between N = 1 and N = 2, which shows a tendency towards saturation of the area occupied by the channel with the assembly of new blocks. The best configurations were obtained when the distribution of the blocks led to the highest momentum on the blocks and the highest temperature gradients, which is in accordance with the Constructal principle of the optimal distribution of imperfections.

Figure 6 – Temperature fields that led to q max for each assembly step N



Source: Authors (2023)

5 CONCLUSIONS

The present work presented the proposition of a methodology for the construction of arrangements of heated blocks in channels subjected to forced convection flows based on Constructal Theory. Results indicated that the proposed methodology conducted to promising results about the mechanism of growth of the heated blocks arrangement. Results of heat transfer rate demonstrated the importance of investigation of the design in the construction of the arrangement of blocks, which can be attested in differences of nearly 40% and 15% when the best and worst configurations were found for N = 2 and N = 3, respectively. In this sense, the proposed methodology can be employed to guide the design of channels and micro-channels used in heat exchangers and encapsulation of electronic circuits, having as main advantage the construction based on a physical principle of maximization of internal currents.

As future works, a larger number of blocks must be assembled to evaluate the behavior of the array configurations and its thermal performance.

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