Investigating Heating Transfer and Turbulent Flow in a Channel for Different Cross Sections Full-Filled of Glass Spheres as a Porous Media

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Abstract

In recent years various modern improvements have been used to raise the performance of heat systems in various engineering and industrial applications. One of these improvements is the use of porous material. This research focuses on conducting a theoretical study (numerical simulation) via forced convection heat transfer of three channels of various cross-sections (square, rectangular, and triangular) with an equal hydraulic diameter of (0.15 m) with glass spheres filled of a diameter (0.012 m) as a porous martial. The lower surface of the test section is subjected to a uniform heat flux along the fluid flow of (5000 W/m^2), while the upper surface is thermally insulated. The type of model used in this study (k- epsilon turbulent model) to simulate and analyze fluid flow inside three channels. This study aims to enhance the thermal properties of the fluid (water) and study its effect on the distribution of temperature, velocity, and pressure, respectively. The results showed that the channel with a triangular cross-section gives the highest distribution of temperature and pressure compared to the rest, and therefore it is considered the optimal design for the channels.

Keywords- Turbulent Flow, Full Filled, Channel, Porous Media, Different Cross Sections, Glass Spheres.

I. INTRODUCTION

Many improvements are made in the heat transfer process for engineering and industrial applications to increase its thermal efficiency and performance, including the addition of fins, mixing of hybrid nanofluids with the base fluid, adding surface roughness, the presence of porous materials, and others. This addition obstructs the flow of the fluid and thus gains heat, which leads to a raise in the heat transfer coefficient and a raise in the Nusselt number. Many researchers dealt in their research articles with forced convection heat transfer within channels of different cross-sections to improve the coefficient of heat transfer. **D. Poulikakos, and K. Renken. [1]** Studied a theoretical investigation (numerical simulation) of heat transfer via forced convection inside a channel in different shapes, the first between two parallel plates and the second in a circular tube, the channel is filled with a porous medium type of glass balls. **M.K. Alkam et al. [2]** The research deals with a theoretical (numerical) study of heat transfer by forced convection in the area of flow development for a channel with two parallel plates. The porous material was placed in the inner wall of one of the plates to improve the thermal properties of the fluid flow. Darcy Brinkman-Forchheimer's model was used to study this problem for several parameters, including (Darcy number, thickness, thermal conductivity ratio, and micro inertial coefficient). According to the findings, the influence of the microscopic inertial coefficient may be completely removed for Darcy numbers under 10,000, while the effect of the Darcy number is seen to be negligible for large microscopic inertial coefficients beyond 1000. **Yue-Tzu Yang and Ming-Lu Hwang [3]** This research focused on conducting a numerical simulation of a two-dimensional (2D) tube filled with porous media-type bronze balls using a model (k-epsilon turbulent model) to improve the flow properties. The most important parameters that have been studied are the Reynolds number for a range ($5*10^3 – 15* 15^3$) and a thermal flux of (8000 W/m^2). The research results recorded that the thickness of the boundary layer decreases in the presence of the porous material, which leads to an improvement in the heat transfer coefficient in the tube. **Amir S. Dawood and Osama Basil Hmood [4]** The research includes a numerical simulation of convective heat transfer in a rectangular space filled with porous medium, the walls of the space are exposed to a constant temperature. The governing equations (conservation of mass, conservation of momentum, conservation of energy) of the fluid flow have been solved using the method of finite differences for the range of the Rayleigh number (0 – 500). The study showed that the Nusselt number increases gradually with the increase of the Rayleigh number and decreases gradually with the increase in the length of the space. **Antonio Barletta et al. [5]** A fluid-saturated, horizontal porous channel with a rectangular cross-section is created for the stability investigation. A uniform flux is used to simulate the heating from below, and the top wall is considered to be isothermal.

The side borders are regarded as properly conducting and porous. The fundamental state's linear stability under perturbations of the normal mode is investigated. Since the exchange of stabilities concept is established, the stability analysis just needs to take into account stationary normal modes. **Falah Assi Abood. [6]** This research focused on studying the effect of the porous medium within a two-dimensional (2D) triangular space filled with the porous medium to improve the thermal properties of the flow for heat transfer of the free convection type. Use Darcy's model to solve the problem for several ranges of the Rayleigh number (100 – 1000). The results of this study showed that the Nusselt number gradually increases with an increase in the Rayleigh number and decreases gradually with an increase in length. **M. Layeghi, and A. Nouri-Borujerdi. [7]** This research deals with the study of forced convection heat transfer for a steady state of a circular cylinder filled with a porous medium. Darcy model was used to solve the problem and analyze heat transfer and fluid flow through the porous medium. To comprehend the impacts of porous media on the temperature, flow, and Nusselt number distributions around a cylinder, parametric simulations are carried out. The comparison of the findings with the quantitative data present in the literature reveals good agreement. **V. Prasad et al. [8]** This research conducts a numerical study of the heat transfer by forced convection of two parallel two-dimensional layers filled with porous medium and a constant wall temperature is applied to it from the bottom, but from the top, it is thermally insulated. The results of this study showed that the rate of heat transfer increases gradually with an increase in the Rayleigh number. **Ahmed Mohammad Saleh et al. [9]** This research deals with an experimental study of heat transfer by forced convection for three channels with variable cross-sections, including circular, triangular, and rectangular, with a fixed hydraulic diameter of (0.1 m). The bottom surface of these channels is exposed to a constant, uniform heat flow along the length of the channel by (1070 W / m^2). Air was used as a working fluid for this issue with a turbulent and non-compressive flow and for a range of Reynolds numbers (12461 - 2500). The results of this study showed that the temperature distribution increases with the length of the fluid flow axis, the average Nusselt number increases gradually with the Peclet number, and the local heat transfer coefficient decreases gradually with the increase in the length of the test model for all channels. **M.E. Nimvari et al. [10]** This research reviews a theoretical study of fluid flow and heat transfer by forced convection in a channel with a circular cross-section that is partially filled with the porous medium in two ways, the first in the middle of the channel and along the axis of the fluid flow, and the second in the upper and lower limits of the channel wall and also along the axis of the fluid flow. The change in the thickness of the porous medium layer inside the channel was studied, and the kinetic energy of the turbulent flow was taken into account for this issue. The channel is exposed to a uniform heat flow from the upper and lower walls. The research results showed that the local Nusselt number decreases gradually with increasing the length of the test section of the channel and the pressure drop across the test section increases gradually with the increase in the thickness of the porous medium layer. **Ahmed A. Mohammad Saleh et al. [11]** This research deals with the study of the effect of the porous medium (glass spheres with 0.012 m diameter)) on the process of heat transmission in a forced load of three channels with different cross sections (circular, rectangular, and triangular) and an equal hydraulic diameter (100 mm), and is filled with the porous medium and exposed to a uniform and constant heat flux along the flow axis. The results of this study showed the local temperature gradually increased with an increase in the length of the test section of channels and gradually decreased by increasing the number of Reynolds. The current research is a theoretical study (numerical simulation) that focuses on the investigation of heat transfer via forced convection of three channels with different cross-sections (square, rectangular, and triangular) filled with porous medium (glass spheres) to compare them and show the effect of the use of the porous medium on fluid behavior and the distribution of temperatures, velocity, and pressure.

II. DESCRIPTION OF THE PROBLEM

Figures (1 – 3) represent three models of different channels (square, rectangular, and triangle) in 3D designed by COMSOL Multiphysics 6.0 program with the same hydraulic diameter (0.15 m) and all filled with glass balls as a porous media. Tables (1 and 2) below show the details of the channels and the properties of the glass spheres. The lower surface of a test section is exposed to uniform heat flux along the fluid flow by (5000 W / m^2), while the other surfaces are thermally insulated. The lift side of a test section is exposed to a fluid flow velocity of (0.06 m/s), and the right surface represents the fluid exit area and is exposed to atmospheric pressure. All these conditions were used as boundary conditions to solve the problem for the three channels.

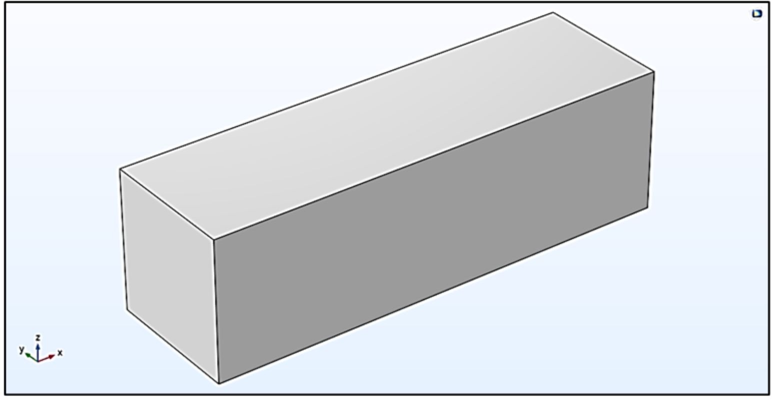

Figure 1: 3D model of a test section for the square channel.

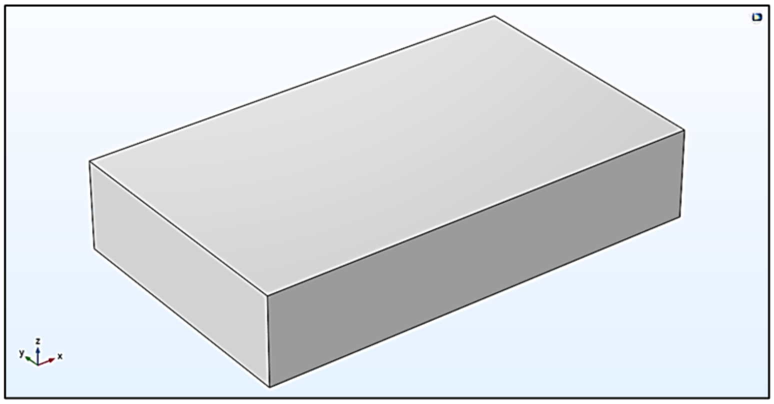

Figure 2: 3D model of a test section for the rectangular channel.

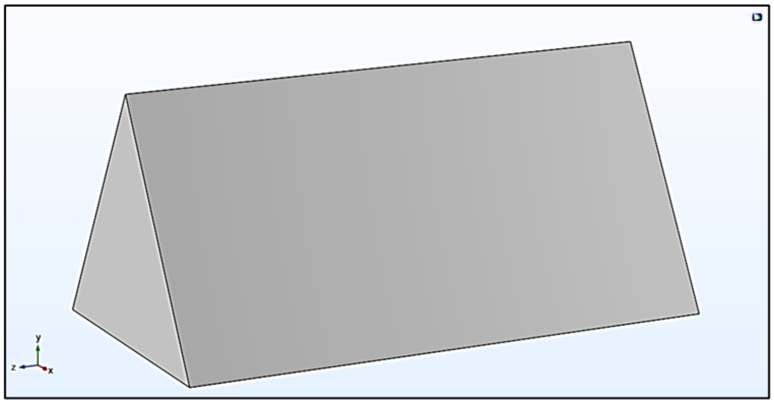

Figure 3: 3D model of a test section for the triangular channel.

Table 1: Dimensional of three channels.

Type of Channel	Length (m)	Width (m)	Height (m)	Aspect Ratio	Hydraulic Diameter (m)
Square	0.5	0.15	0.15	0.15: 0.15	0.15
Rectangular	0.5	0.3	0.1	0.3: 0.1	0.15
Triangular with ($\theta = 60^o$)	0.5	0.26	0.26	0.26: 0.26	0.15

Table 2: Thermo – physical properties of glass spheres.

Diameter (m)	Porosity	Thermal Conductivity (W/m^2. K)	Density (kg/m^3)	Specific Heat (J/kg. K)
0.012	0.4	0.78	2530	670

III. GOVERNING EQUATIONS OF THE K-EPSILON TURBULENT MODEL FOR A CHANNELS

The following equations below symbolize the conservation of (continuity, momentum, and energy) for the steady-state, 3D, turbulent flow, internal flow, and incompressible fluid flow in a saturated porous medium with negligible inertial effects [12]:

- Conservation Mass:

$$\nabla . V = 0 \rightarrow \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

- Momentum Conservation:

$$\rho(\frac{\partial V}{\partial t} + V.\nabla V) = -\nabla p + \mu \nabla^2 V + \rho g \beta (T - T_{ref}) \tag{2}$$

- Energy Conservation:

$$\rho Cp(\frac{\partial T}{\partial t} + V.\nabla T) = k \nabla^2 T \tag{3}$$

Where;

ρ : The density of the fluid (water) (kg/m^3);

V : The velocity of the fluid (water) (m/s);

g: Gravity acceleration (m/s^2);

μ : Dynamic viscosity of fluid (water) (Pa. s);

Cp: Specific heat at constant pressure (J/kg. K).

For modeling single-phase flows at high Reynolds numbers, utilize the turbulent flow, k- epsilon interface. Incompressible and compressible flows with low Mach numbers may both be handled via the physics interface (typically less than 0.3). The Navier-Stokes and continuity equations for momentum conservation and mass conservation are the equations that are resolved by the Turbulent Flow, k- epsilon interface. With realizability limitations, the traditional two-equation k- epsilon model is used to simulate the impacts of turbulence. Wall functions are used to simulate flow near walls [13]:

$$\rho(u.\nabla)u = \nabla.[-pI + K] + F \tag{4}$$

$$\rho \nabla . u = 0 \tag{5}$$

$$K = (\mu + \mu_T)(\nabla u + (\nabla u)^T) \tag{6}$$

$$\rho(u.\nabla)k = \nabla.[(\mu + \frac{\mu_T}{\sigma_k})\nabla k] + p_k - \rho\varepsilon \tag{7}$$

$$\rho(u.\nabla)\varepsilon = \nabla.[(\mu + \frac{\mu_T}{\sigma_\varepsilon})\nabla \varepsilon] + C_{\varepsilon 1}\frac{\varepsilon}{k}p_k - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \tag{8}$$

IV. CREATING MESH OF A TEST MODEL

Figures (4 – 6) below show the division of the mesh type (Normal) into the three channels, and Table (3) shows the amount of mesh for each of them. The highest value of the mesh appeared in the channel with a square cross-section. In addition to this, the edges were divided into small areas to obtain high accuracy of the results.

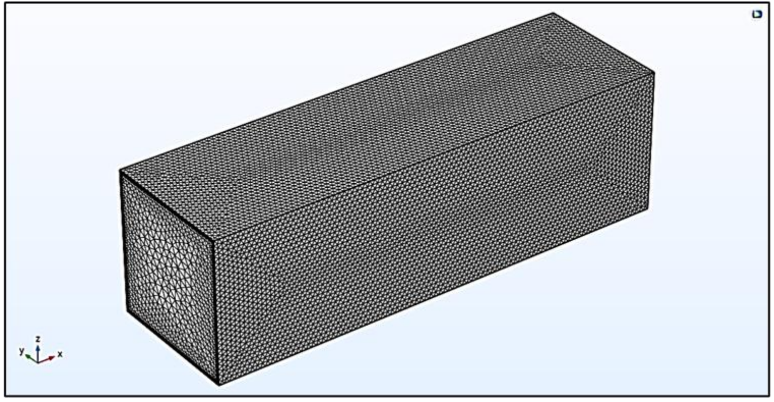

Figure 4: Normal mesh of a test section for a square channel.

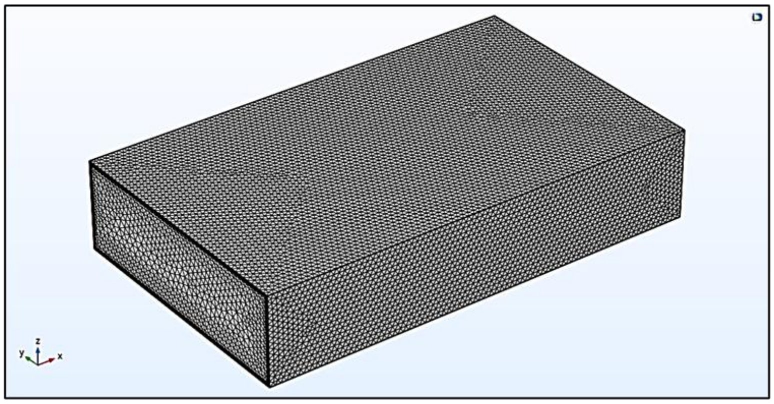

Figure 5: Normal mesh of a test section for a rectangular channel.

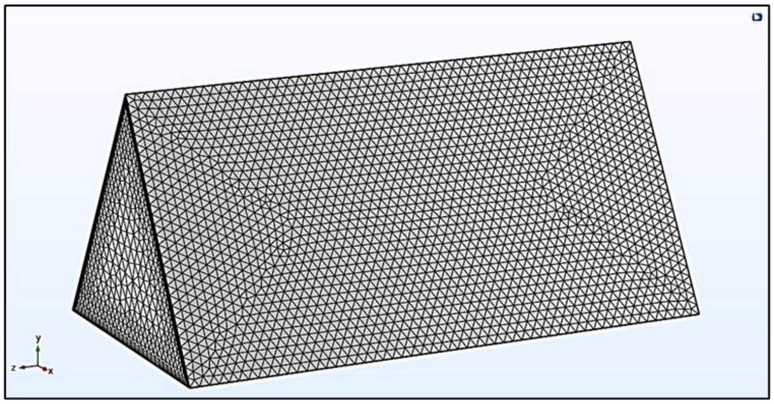

Figure 6: Normal mesh of a test section for a triangular channel.

Table 3: The number of normal mesh for different channels.

Type of Channel	Domain Element	Boundary Element	Edge Element
Square	491509	26366	576
Rectangular	466139	26622	564
Triangular	192629	13280	339

V. RESULTS AND DISCUSSION

- Temperatures and Velocity

Figures (7 – 12) below show the temperature and velocity distribution of the fluid flow through the test section for three channels with different cross-sections (square, rectangular, triangle) respectively. We notice the temperature distribution for the square and rectangular channels is almost similar, while the triangular channel has a higher value temperature distribution because the space filled with glass spheres is higher than in other square and rectangular channels, so the fluid acquired high temperatures. As for the fluid velocity distribution in all channels, it has the same gradient in values.

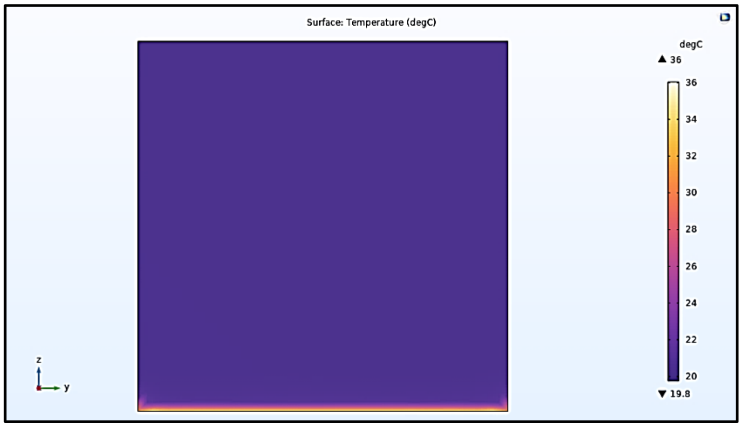

Figure 7: Temperatures of fluid (water) in a test section for a square channel.

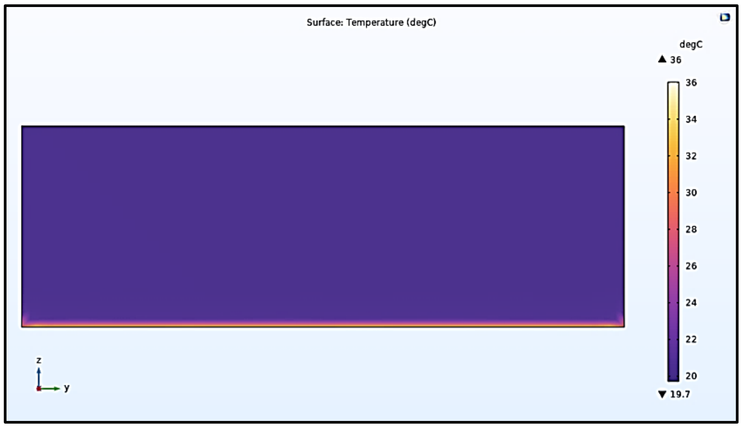

Figure 8: Temperatures of fluid (water) in a test section for a rectangular channel.

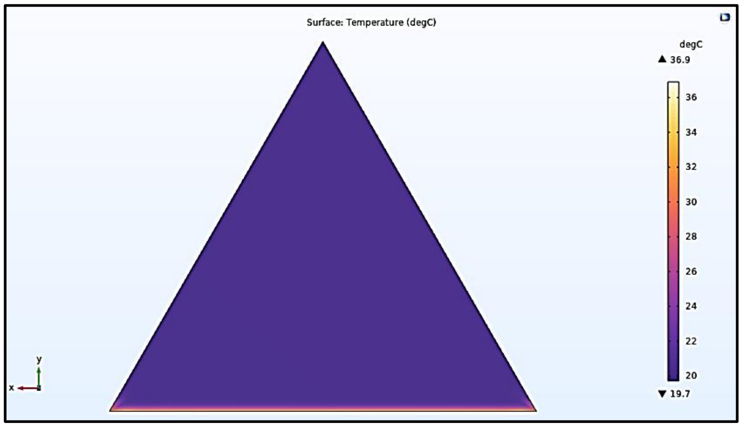

Figure 9: Temperatures of fluid (water) in a test section for a triangular channel.

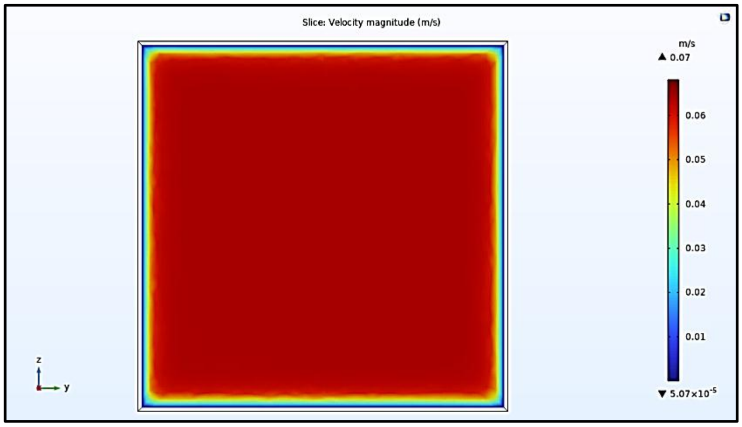

Figure 10: Velocity of fluid (water) in a test section for a square channel.

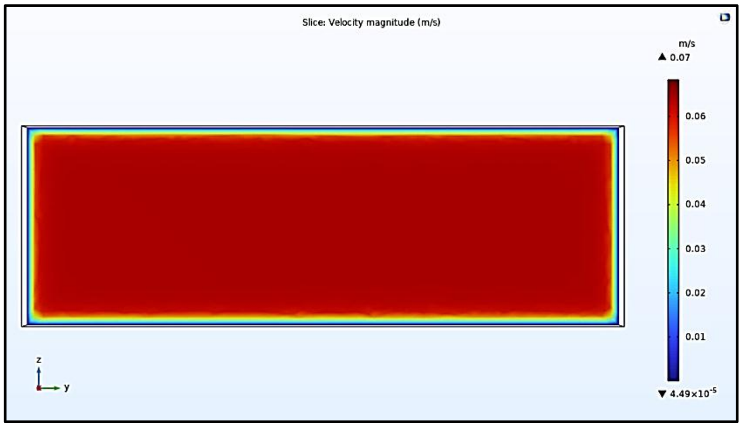

Figure 11: Velocity of fluid (water) in a test section for a rectangular channel.

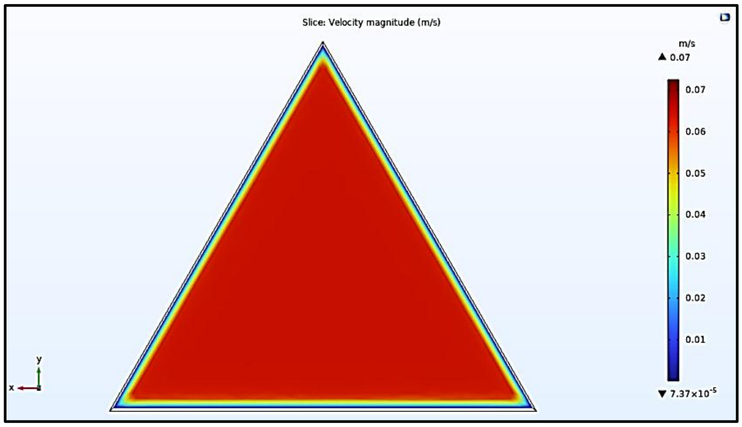

Figure 12: Velocity of fluid (water) in a test section for a triangular channel.

- Distribution of Pressure

The figures (13 – 15) below show the pressure distribution of the fluid flow within the three channels (square, rectangular, and triangle), respectively. We note that the pressure distribution of the square and rectangular channels is almost equal, while the triangular ducts give the highest distribution.

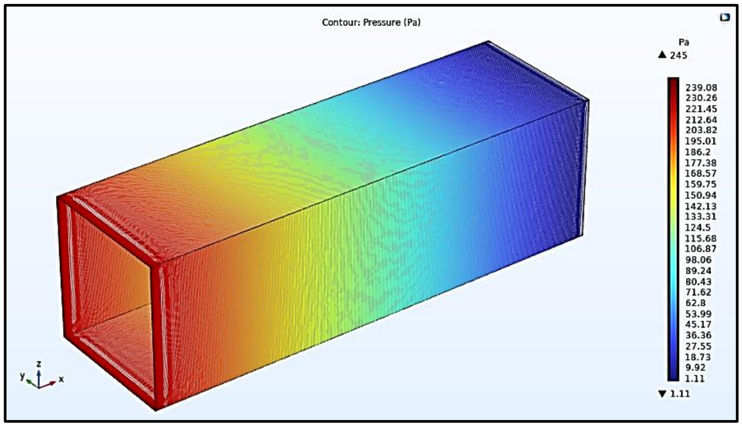

Figure 13: Pressure distribution of a fluid (water) in a test section for the square channel.

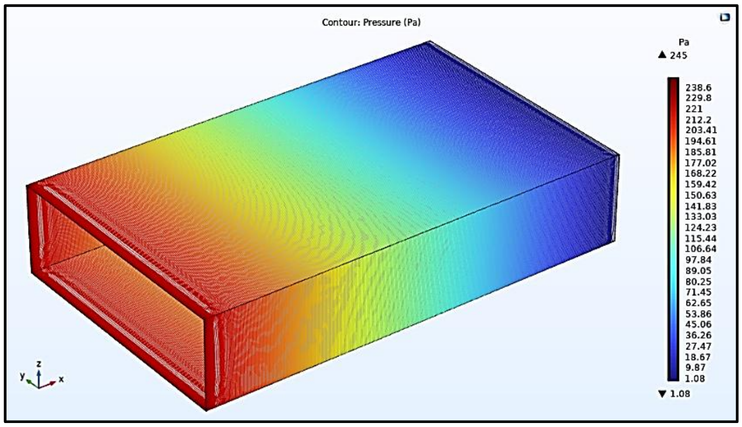

Figure 14: Pressure distribution of a fluid (water) in a test section for the rectangular channel.

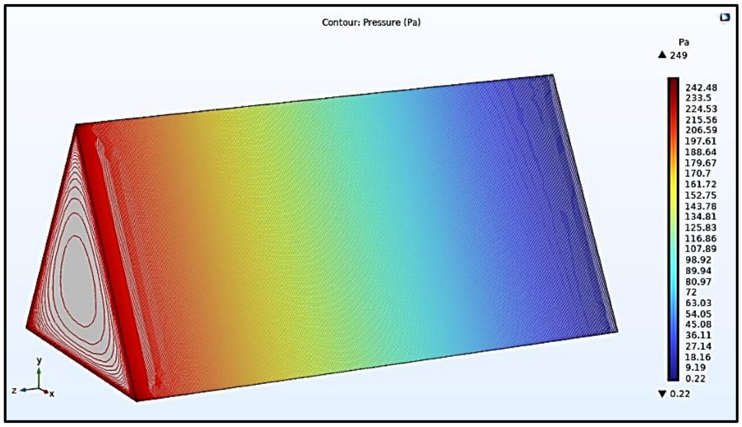

Figure 15: Pressure distribution of a fluid (water) in a test section for the triangular channel.

VI. COMPARING THE TEMPERATURE DISTRIBUTION OF THE CHANNELS

Table (4) below shows the calculation of the temperature distribution of the lower surface of the test model at different locations (0, 0.1, 0.2, 0.3, 0.4, and 0.5). In addition, the temperature distribution was compared between the three square, rectangular, and triangle channels, respectively, with the length of the test model (0.5m) for fluid flow. We notice a gradual increase in temperature as the fluid advances in flow, and the channel with a triangular cross-section gives the highest temperature distribution as shown in Figure (16) below.

Table 4: Values of lower surface temperatures for three channels at different locations.

Location (m)	0	0.1	0.2	0.3	0.4	0.5
	Lower Surface Temperature (°C)					
Square	20.163	28.502	30.869	32.517	33.761	34.242
Rectangular	20.170	28.568	30.88	32.585	33.971	34.419
Triangular	21	29	31	33	34	35

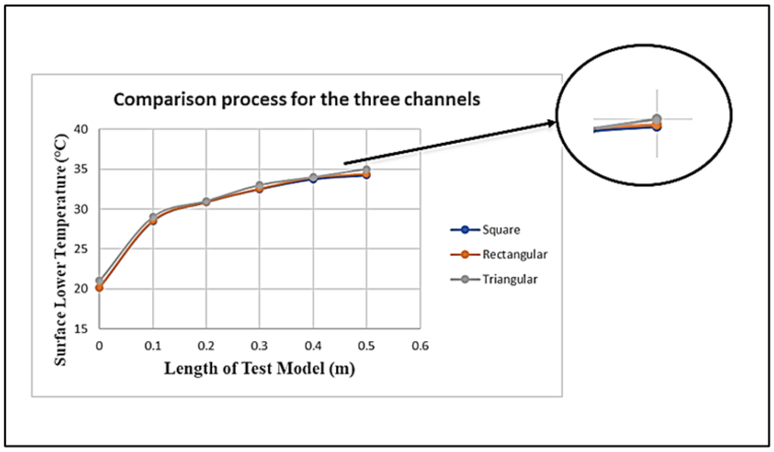

Figure 16: Lower surface temperatures against the length of the test model for three channels at various locations.

VII. VALIDATION OF PRESENT WORK

Figure (17) below shows the comparison process to distribute local temperatures against the length of the test section between the current study and a previous study [11] of the same phenomenon. Table (5) below shows the comparison details, as the distribution of temperatures is gradually increasing with the progress of the fluid flow through the test section, and therefore the behavior is identical between the current study and the previous study.

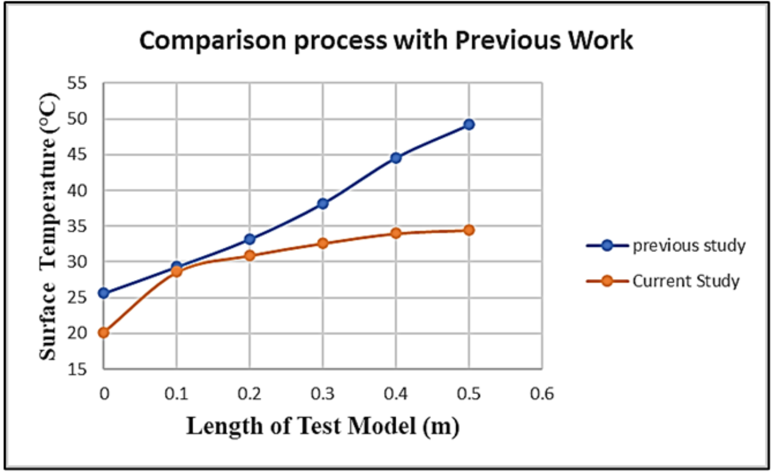

Figure 17: Local surface temperature vs length of test model between previous and current studies.

Table 5: Validation process with the previous study.

Author	Cross Section of a Channel	Type of Porous Media	Working Fluid	Type of Study
Current Study	Rectangular	Glass Spheres	Water	Numerical
Ahmed A. Mohammad Saleh et al. [11]	Rectangular	Glass Spheres	Air	Experimental

VIII. CONCLUSION

Some marks are recorded below for the current study:

1- The thickness of the boundary layers reduces due to using the porous material and thus raises the heat gain during the fluid flow through the channels.
2- The best temperature distribution was recorded in the triangular cross-section channel, although the hydraulic diameter is equal to the rest of the designed channels.
3- The temperatures increase gradually with the length of the test segment for all channels (square, rectangular, and triangular) respectively.
4- The pressure values gradually decrease with the increase in the length of the test section for all channels (square, rectangular, and triangular) respectively.

IX. RECOMMENDATIONS

Some points below can be made for the current study to know the behavior of the fluid:

1- Changing the type of fluid and studying its effect on the distribution of temperature, pressure, and velocity, for example using oil or air.
2- Changing the angles of the three channels and knowing their effect on the fluid behavior by increasing or decreasing the pressure, velocity, and temperature distribution.
3- Studying the impact of laminar flow on improving the heat transfer coefficient of the three channels.

ACKNOWLEDGMENT

I extend my thanks to my supervisor, **Asst. Prof. Dr. Suhad Abdel-Hamid Rashid**, a lecturer at the University of Technology, Department of Mechanical Engineering. I would like to thank **Prof. Dr. Salam Hadi Hussein**, a lecturer at the College of Engineering, University of Babylon, for his continuous support through the completion of this research paper.

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