Flow Analysis through Porous Media with Deterministic Distributions using Computational Fluid Dynamics (CFD) method

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Abstract:- The paper aims to study and evaluate the porous flow to determine the effect of these media on the behaviour of the heat exchanger. The digital method (CFD) was used to achieve this goal. The simulated procedure was using ANSYS software. The obtained results show that there is a great tendency to add porous medium to heat exchangers to increase heat transfer efficiency. This case was studied by pressure, velocity, and wall shear stress of heat exchangers. Also, when a porous material was placed in the pipe, the pressure values were affected, the pressure values differed along the length of the pipe, and its value was observed to decrease through the porous medium, the reason for this is that the wall of the porous area resists the flow, which works to reduce the liquid near the wall and from it, the force acting on it decreases. As the number of pores increases, the pressure value decreases. The velocity decreases through the porous media, this is due to the nature of the pores as they act as an obstacle in front of the liquid particles and collide with them. This collision leads to a loss of some momentum and the speed decreases due to the stability of the volume. Finally, the pressure gradients increase due to the porous media during the heat exchange. There will be seepage from the pipe if a pressure dispenser is placed or pressure relief is used.

Keywords;- *CFD, ANSYS, Heat Exchanger, Porous media***,** *Heat Transfer Efficiency* **,***Velocity, Pressure, Porous Flow, Wall Shear Stress.*

I. INTRODUCTION

For many areas, the flow through porous media is important. In 1856 Darcy performed a one-dimensional experiment, which is considered a preliminary point. Flow-through a porous medium is defined as a way that fluids behave as they flow through a porous medium. During fluid flow in a porous medium, a portion of it is stored in the pores in this medium (Whitaker, 2014). On the other hand, there is a heat exchanger, which is known as a regulator that transfers heat between two or more liquids. The heat exchanger transfers the heat from the high-temperature liquid to a solid wall, and the heat is transferred through the wall by the conduction feature, and then the heat arrives from the wall to the low-temperature liquid (Von and Ahlinder, 2006). Several studies have been conducted that will also be conducted to find new sources of energy production that ultimately lead to enhancing the overall production and overall material efficiency. It has been observed that there is an improvement in the thermal conductivity matrix when using porous media when changing heat as it enhances the overall heat capacity through the effective flow (Amanifard et al., 2007).

When using porous media for heat exchange, it does not lead to a change in the conditions in the flow field, making the layers thin, while the coefficient of thermal conductivity was observed to become larger when compared to the heat exchanger evaluated by Favai, (2005). CFD numerical methods will be used in this project to model and quantify the effect that affects the behaviour of fluid flow through the porous media used. Also, to perform the project simulation, the ANSYS program will be used.

II. AIMS AND OBJECTIVES

The aim of this study is to define the effect of porous media on the heat exchanger performance by evaluating heat exchanger porous flow. These objectives will be conducted to achieve the aim of study:

1. To determine the advantages and disadvantages of using porous media generally and in heat exchangers.
2. To evaluate the models' flow characteristics using porous media for several types of porous mediums in the heat exchanger.
3. To make a CFD simulation to evaluate the effect of the deterministic distribution on the porous materials flow behaviour.
4. To simulate heat exchanger with and without porous media using ANSYS design and compare the results.

III. LITERATURE REVIEW

A. Heat exchanger definitions and types

Heat exchangers are devices used to transfer thermal energy. The fluids are separated by a solid-state wall. The wall aims to be sure that the thermal energy can be transferred without external intercessions and no direct contact between the fluids. Two types of heat exchangers are existing which are:

- Counter flow, fluids enter the opposite ends and pass the opposite direction as shown in Figure 1.

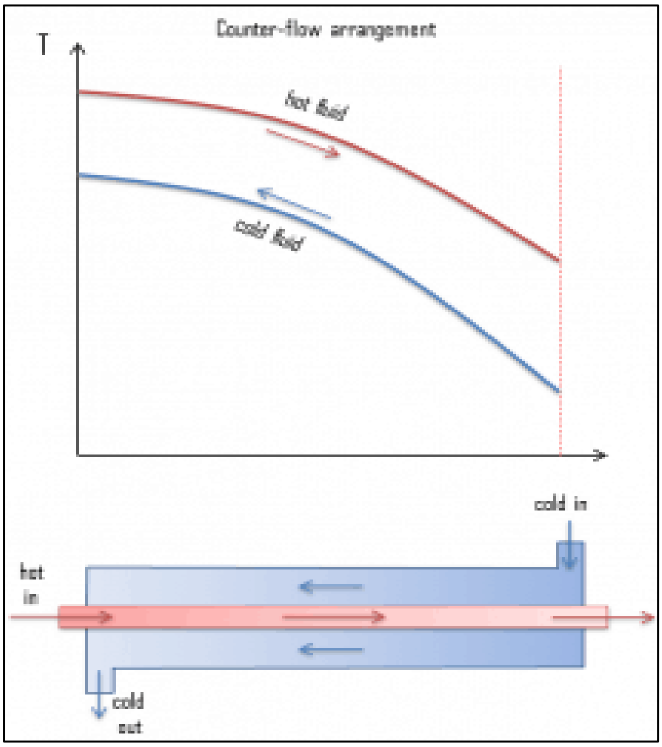

Figure 1: Counter flow illustration.

- Parallel flow, hot and cold fluid end at the same time for the same end with the same orientation.

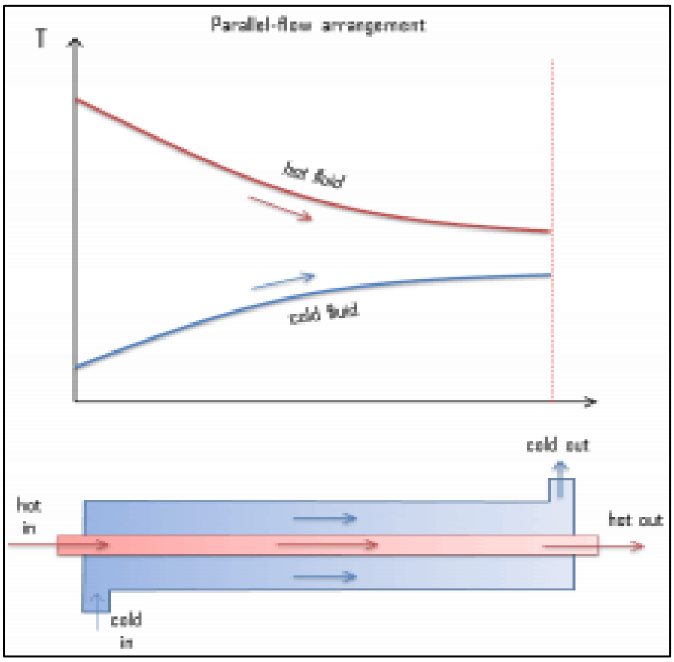

Figure 2: Parallel flow illustration

More heat can be exchanged for a counter-flow type, and the temperature has an impact on the heat exchanging process (Beavers, et al, 1969).

B. Porous Media Definition, Application, and Types.

The porous medium is used for combustion purposes; it is considered as a network for space that can be used in heat exchanging. This medium consists of voids or pores. The skeletal portion represents a matrix or a frame. In heat conduction, the empty spaces are filled with a fluid which can be either a gaseous or a liquid (Boomsma, et al, 2003). The main features of porous are permeability, conductivity, and tortuosity.

It is frequently that the solid matrix and the pore network is a continuous process to create an interpenetrating continuum. Many porous mediums can be existing in the environment, which presents in the environment like the rocks, wood, and the soil.

There are different types of porous medium, such as reservoir rocks which are distinguished based on their pore spaces that may exist among the rocks. Also, the porosity for the sandstones can differ according to the porosity which is between its sand grains. A second example is a limestone where the crystals can be noticed to disappear in the groundwater to make a special type of porosity. Large channels for the mediums create a hollow type for the porosity that can be stretched for a few meters.

C. Characteristics of porous media

The main characteristics for the porous media are porosity, as well as infiltration coefficient, as shown below:

- **Porosity:**

By the porosity, the porous media refers to the overall capacity that it can provide into the fluid. It could be represented as the blank porosity ratio with respect t the total volume. The limitation of the porosity is not to exceed .6%. Although the Nevertheless, if porosity is measured between the spheroid solids, it ranges between 0.2595 and 0.4644. For certain human porous materials including metal foam, porosity equals 1. η

- **Infiltration Coefficient:**

The infiltration coefficient is another important porous medium characteristic, and it is known as the permeability of η, which signifies the potential of the substance to move into the fluid. The researchers confirmed that the infiltration coefficient is primarily determined by various factors including porosity coefficient and the shape of the porous media bed.

D. The porous media advantages in the Heat Exchanger

Heat transfer using porous media is a common method that has been used for many years. Thermal conductivity depends on temperatures which are generally measured by the laser flash method or GHM method. Several studies have demonstrated the generation of the convection currents from the circulation patterns for the inundating fluid. It was

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also stressed that the layers using essentially tend to optimize the thermal conduction mechanism.

Generally, the porous medium is not utilised as a heat transfer medium, it helps to improve the whole process. The porous material utilised as a heat exchanger is interconnected voids (empty spaces) network located in fluids for heat exchange applications (Diao, et al, 2004).

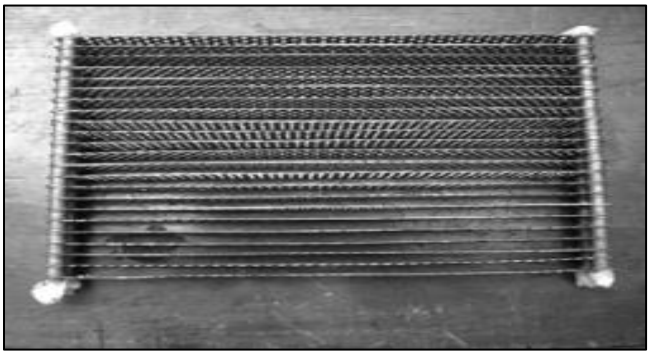
Figure 3: Porous Heat Exchanger.

E. The characteristics of flow using porous media.

There is a growing interest in porous media in the field of flow characteristics. This is attributed to the fact it can happen regularly in the natural industry environment. The characteristics of the fluid flow in such systems depend on the material's geometric structure and physical characteristics, and its physical details which provide a suitable strategy for underground water systems and oil recovery. A different procedure utilising melted material and membrane can be used in this system.

Studying various fluid layers' flow has demonstrated recent advances in the field of fluid mechanics. The problems between the boundaries situation between layers appear when utilising the Navier stroke equation for the flow in the fluid layer as well as Darcy's law in porous media; also, there is a risk of utilising the Brinkman equation in the no-slip situation. Because the fluid flows to the well from all directions, fluid flow in the well can be signified by using radial flow. Optimal radial flow in the wellbore is shown in Figure 4.

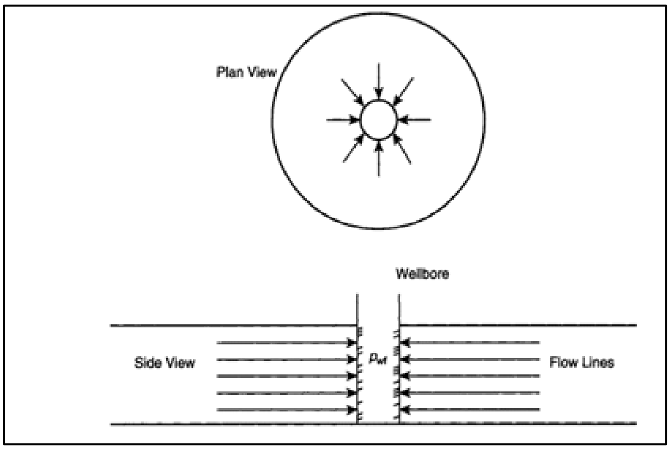

Figure 4: Optimal radial flow in the wellbore.

F. The porous media effect on the heat exchanger performance

Because of the human energy usage demands and the alleviation of energy waste, experts are making significant efforts to improve the productivity of energy production and its conversion. To raise the efficiency of heat transfer, a particle with smaller diameters should be used (Tarawneh et al., 2013).

In recent times, various experiments have been conducted to enhance the heat transfer, to find approaches that, together with enhancing the heat transfer, are more effective. These strategies directly decrease energy consumption, minimize costs, and the need for expensive tools and machines to have higher thermal efficiency. As growing efficiency in improving energy consumption in the sector has been relevant for experts where optimizing heat transfer in both cooling and heating systems is not excluded from their concerns (Hanspal, et al, 2006).

IV. METHODOLOGY

A. Study Preparation

- Assume the pipe dimensions, characteristics, and solids, and fluid properties.
- Select the heat exchanger type.
- Present the heat exchanger initial model in ANSYS.

B. Methodology Steps

- Perform a typical heat exchanger of non-porous media and obtain the flow characteristics using the simple rules for non-dimensional measurement and energy calculations.
- Make a 3D analysis using ANSYS to simulate the normal heat exchanger noting the flow and velocity distribution.
- Depending on the simulation the initial parameters will be updated if required.
- Model the heat exchanger with a porous material (calculations of the velocity will be conducted as basic criteria).
- Simulate the heat exchanger with porous media.
- Compare the mean velocity, rate of heat transfer, pressure drop, and heat transfer coefficients of normal flow and porous media flow.
- Select various porous media types with several porosities sizes and ranges.
- Determine the minimum and maximum rate of heat transfer, velocity, and pressure drop to determine the appropriate heat exchanger type for real applications, the limitations of the application of each type.
- Improve the CFD analysis to obtain a closer and accurate solution depending on the mesh generation and updating.
- Compare the different porous media types and determine the most and least effective porous media heat exchanger, in addition to the most and least stable porous heat exchanger.

C. Calculations

- The assumed initial solid parameters of the non-porous medium heat exchanger:

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Heat exchanger length (L) = 1 m, Shell diameter (D_s) = 0.75 m, Tube diameter (Dp) = 0.5 m, Shell and tube thickness (t) = 5 mm.

- The assumed initial fluid parameters:
  The inner and outer fluid type is freshwater, the water mass flow rate = 1 Kg/s.

- The fluid temperature:
  The outer fluid temperature (TH) = 70^0 C, the inner fluid temperature (TL) = 30^0 C.

Table 1: The water Isobaric specific heat at selected temperatures

Temperature (C)	Isobaric specific heat C_p (KJ/Kg. K)
30	4.1801
70	4.1902

The heat transfer rate (q) can be obtained from the energy conservation equation:

$q = Cp \times m^0 \times (TH - TL)$ Eq.1

Another form of energy conservation equation:

$q = As \times h \times \Delta Tm$ Eq.2

Where:

As: The exposed surface area to heat transfer and can be obtained from Eq. 3

$As = 2\,\pi\, r$ Eq.3

$As = 2 \times \pi \times 0.25 = 1.570$ m^2

h: coefficient of heat transfer.

ΔTm: The logarithmic temperature difference.

$\Delta Tm = \frac{(T1-t2)-(T2-t1)}{\ln(\frac{T1-t2}{T2-t1})}$ Eq.4

Where:

T1: Inlet fluid temperature in tube side = 50°C (assumed).
T2: Outlet fluid temperature in tube side = 70°C (assumed).
t1 = Inlet fluid temperature in shell-side = 40°C (assumed).
t2: Outlet fluid temperature in shell-side = 30°C (assumed).
Then:

$\Delta Tm =$ 24.66 ^{0}C.

After substituting in Eq.1:

$$q = 167.608\, W$$

By equating Eq.1 and Eq.2:

$$167.608 = h \times 1.57 \times 24.66$$

$$h = 4.329 \frac{W}{m^2.C}$$

Now, for this flow the Nusselt number (Nu) and Reynolds's number (Re) can be obtained from Eq. 5 and Eq. 6:

$Nu = \frac{d \times h}{K}$ Eq. 5

d: Characteristic length = 1 m, K= Water thermal conductivity = 0.659 $W/m.K$

$$h = 4.329 \frac{W}{m^2.C}$$

Then:

$$Nu = 6.569$$

Now,

$Re = \frac{\rho \times d \times u}{\mu}$ Eq. 6

Where:

ρ: Water density (kg/m^3), d: Diameter of flow area (m) = Dp = 0.5 m, u: Average velocity (m/s), μ: Water viscosity (N.s/m^2) = 0.0004660 $N.s/m^2$. Firstly, the Prantdl number will be calculated to obtain u value:

$$\mathrm{Pr} = \frac{Cp\,\mu}{K} = 3.431 \times 10^{-3}$$

The relation between the Nu, Re and Pr is:

$Nu = 0.664\, Re^{0.5} Pr^{1/3}$ Eq. 7

Nu = 6.569, and Pr = 3.431×10^{-3}. Thus, Re = 4302.44 > 4000 (turbulent flow).

Now,

$$u = \frac{Re\,\mu}{\rho\, d}$$

$$u = 5.7951 \times 10^{-3} \frac{m}{s}$$

This calculation is conducted for the non-porous media, the same calculation steps will be followed on the porous media, with some assumptions and dimensions of the no porosities heat exchanger.

V. RESULTS AND DISCUSSION

In this section, the results obtained in the four cases will explain the basic differences of heat exchange through the porous medium. Such settings and models refer to both turbulence flow and laminar. Brief research on the distribution of shear stress has been developed.

A. Results of the sensitivity and mesh information

For applying the solution to the part, solid pipes and geometries have meshed. The first step is to create the mesh. Improvements have been made in the properties such as size, shape, and part number of the mesh. Figure 5 represents the mesh that was created. It was finer during the area between the wide and the narrow area, as it is considered sensitive and the main factor in selecting the part shape of the mesh.

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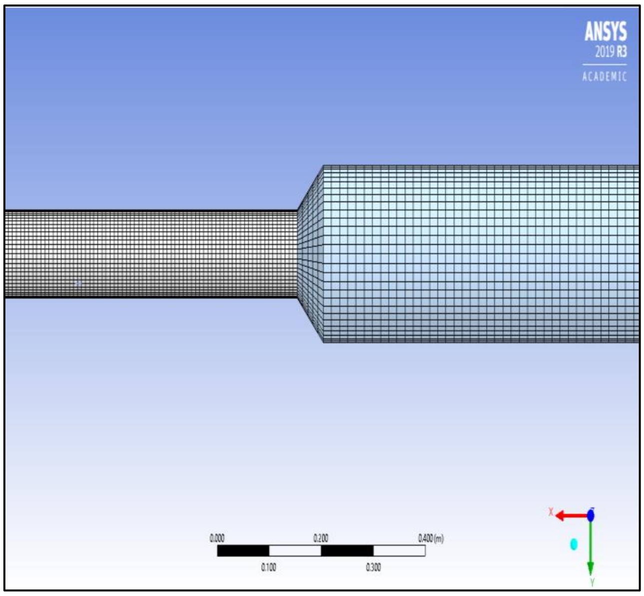

Figure 5: The part of the meshed in ANSYS.

Table 2 shows the network information and characteristics obtained from the Mesh Calculator tab.

Table 2: The Mesh Information.

Mesh information	Connectivity Number
Mesh Information for Case FFF **Number of Nodes: 251516** **Number of Elements: 238579** **Tetrahedra: 0** **Wedges: 5412** **Pyramids: 0** **Hexahedra: 233167** **Polyhedra: 0**	Connectivity Number for Case FFF Min: 2 Max: 12 Global range of Variable Connectivity Number has been updated.

It was concluded that the accuracy of the obtained solution depends largely on the mesh. As for the ideal shape and the standard mesh, it was accepted in addition to the mesh.

B. Velocity profile/ flow behaviour for turbulent and laminar flow results

By observations along the inlet for each flow and boundary layers, a comparison between turbulent and laminar flow was conducted during the simulation. The settings were validated in ANSYS by performing this operation. Figure 6 and 7 shows the velocity profile that was obtained.

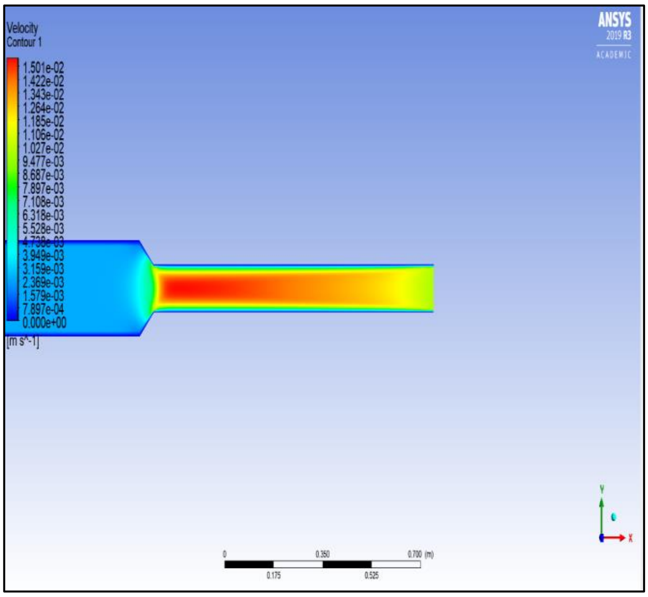

Figure 6: Laminar Velocity profile

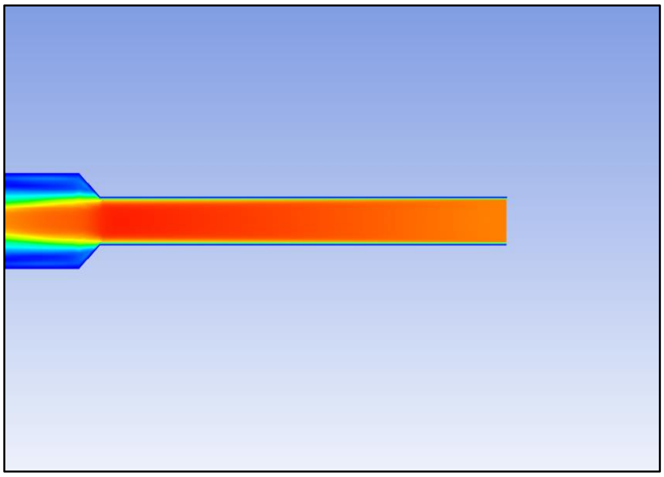
Figure 7: Turbulent Velocity profile

It has been observed from Figure 6 that laminar flow takes more time to develop compared to turbulent flow, while turbulent flow has less inlet length compared to laminar flow as shown in Figure 7, this is consistent with the boundary layer theory.

The turbulent flow requires less time to be fully developed than the laminar flow and has a shorter entrance length because the turbulent flow has more momentum than the laminar in the same pipe. The turbulent flow increases the heat transfer process in the pipe because its particles do more collisions. Though the turbulent flow has more heat transfer efficiency it influences the wall mechanical properties, because the high speeds increase the mechanical vibration waves intensity and can lead to wall failure. Thus, there is a need for further fittings and bearings.

Another difference between the two types of flow is that the laminar flow has a noticeable boundary layer with a significant thickness. This because of the fluid viscosity that performs a boundary layer. While the turbulent flow has no significant boundary layer, this because of the collisions and turbulences between the wall and fluid particles, thus, the boundary layer will disappear. These findings are consistent with the boundary layers principle, which also explains the length of the entrance. From these variations, porous media heat exchangers will be examined for turbulent and laminar flow.

C. Laminar flow Results

In this section, the results of both pressure and pressure are presented. They should be studied together with the effects of the porous medium. Laminar flow is created by choosing a small value for the velocity of the inlet. From the region's setting, the areas that will be laminated have been selected. The ability to add a porous medium without choosing the shape or size of the pores was provided by Fluent. To obtain a suitable measure, repeatability and then simulation is used. The settings are not changed in the case of a turbulent flow study so that there is an accurate comparison between them.

Results of total pressure distribution

The pressure distribution in non-porous and porous media was studied to find the difference between them and their effect in the case of laminar flow.

Pressure distribution in the Non- porous media:

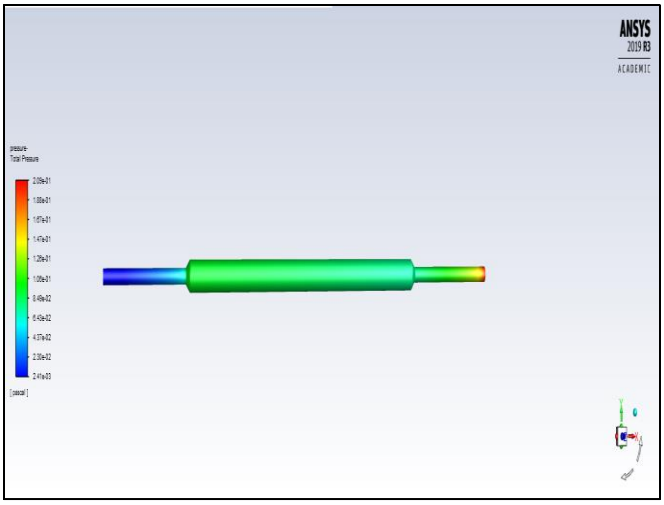

Figure 8: Pressure distribution through non-porous media.

The decrease in the pressure was observed over a small distance, despite its large value at the entrance, then it suddenly decreased after the distributor due to the larger area. Up to the nozzle, the distribution of the pipe is fixed and then enlarged. The pressure decreases at the outlet with the distance.

Pressure distribution in porous media:

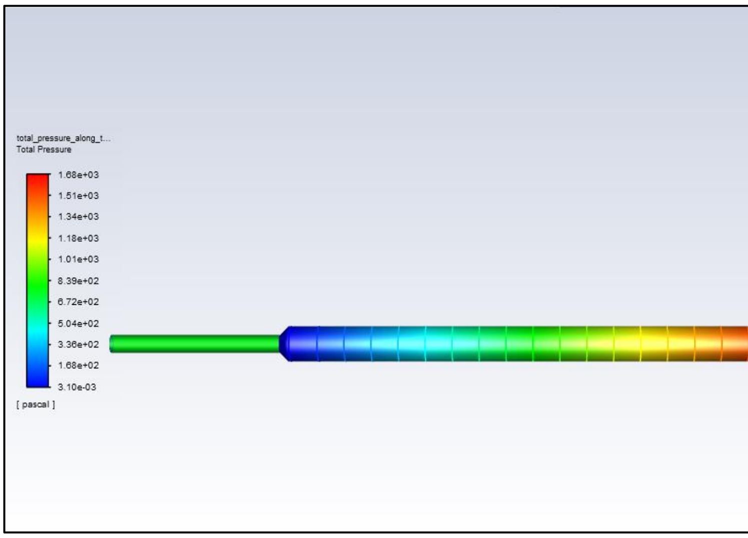

Figure 9: Pressure distribution in porous media.

The pressure is constant through the inlet and the outlet because it is nonporous. After the entrance, the laminar flow starts to decrease at the diffuser. The pressure decreases slowly to reach the lowest value in the porous part in the middle section.

Results of velocity for laminar flow

- **Results of velocity for non-porous media:**

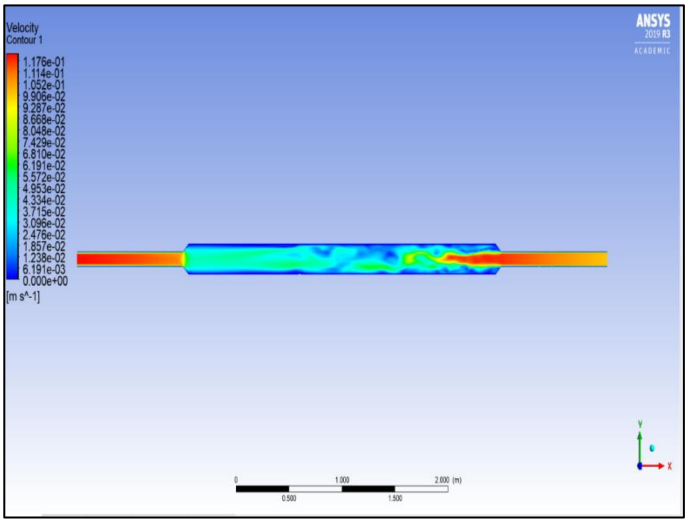

Figure 10: Velocity values with the non-porous media

The velocity decreases at the diffuser due to the increase in the area. The velocity decreases when moving from a small cross-section to a large cross-section.

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- **Results of velocity for porous media:**

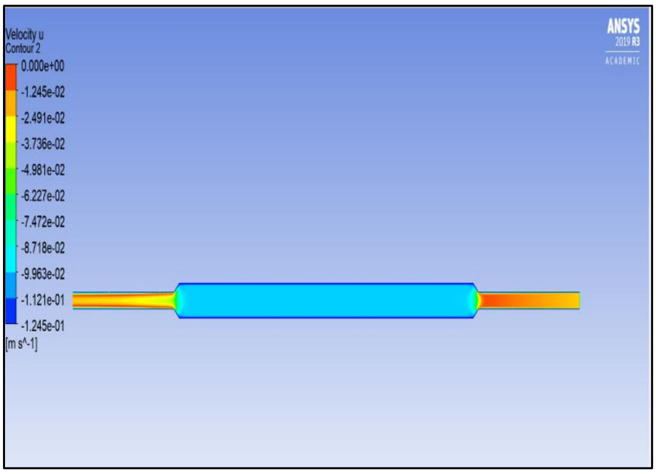

Figure 11: Velocity values for the porous media.

The velocity of the pore part decreases because the pores are obstacles to the movement of liquids. The mass of the fluid is constant, the momentum depends on the mass and the velocity and collisions affect the momentum, so the velocity will decrease for this reason.

The results showed that the pressure starts with a high value, it becomes lower in a short distance, and then has a sudden reduction after the diffuser. The inside middle pipe distribution is constant, till entering the nozzle, which is a pressure redistributor system that lowers pressure and increases velocity. The pressure within the outlet would reduce with the distance.

These findings are the normal behaviour of the laminar flow through the pipe. It is also consistent with the principle of pressure distribution instruments including diffuser and nozzle. In comparison, the primary definition of pressure as a divided force is observed; as the area increases, the pressure is reduced.

The decrease in the laminar flow value after reaching the diffuser, while the pressure is supposed to be higher in the porous portion due to an increase in the surface area, it is reducing. This because the simulation process analyses the outer wall, and as there are more surfaces in the inner area, the interactions between the outer wall and fluid are getting smaller, which reduces the exerted pressure on the outer wall.

Furthermore, the fluid velocity is influenced by field changes. At the diffuser, the velocity is decreased because of the area difference, and the movement of the fluid from a thin cross-section to the wider cross-section decreases the velocity as per the continuity equation.

The velocity profile demonstrates unsteady behaviour when going from the lower to the wider cross-section. It has the typical form of the laminar flow. This demonstrates that the software configuration is implemented properly. Moreover, the fluid velocity in the porous pipe reduces, which is due to the porosities that are barriers facing the fluid. The interactions between the porosities and fluid particles absorb some of the momenta. Thus, the velocity and mass are the only quantities that regulate the momentum value. As the mass is unchanged, the velocity will decrease due to the collisions.

The previous results indicate that the porous medium decreases the velocity of the fluid because of the barriers along its direction. This needs to be examined in a heat exchanger with a multi-pipe, which needs to maintain the fluid velocity high to continue the flow through the next pipes.

A relevant comment about the relation between the velocity and pressure, the pressure in this analysis is measured only on the outer wall while the velocity is measured within the pipe. The general relationship between pressure and velocity is therefore not implemented.

D. Results of turbulent flow

High velocity is selected from the zone setting at the entrance to create turbulent flow. The turbulent flow is well executed although the initial state is not very compatible as turbulent flows are the most common. The values of velocity and pressure of turbulent flow through porous and non-porous tubes were used for comparison.

Results of total pressure values

In this section, the values of pressure distribution through porous and non-porous tubes are found. Figure 12 shows results of pressure distribution in non-porous media:

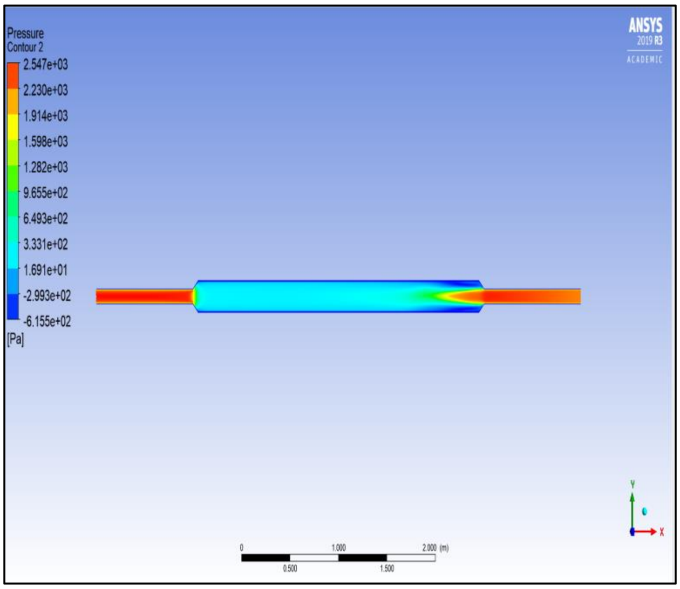

Figure 12: Pressure distribution in non-porous media

At the diffuser, the total pressure of the liquid decreased. Pressure does not change at the diffuser to a uniform distribution, and this is one of the differences between the laminar and turbulent flow. Total pressure distribution in porous media results is shown in Figure 13.

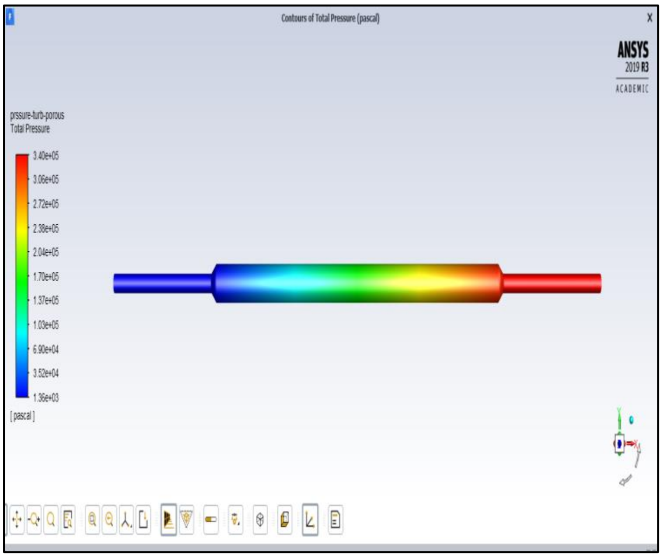

Figure 13: Pressure distribution in porous media.

By simulating turbulent flow, the pressure is obtained through the pipe with the porous area in the middle part of the tube. The pressure changes through the pore section, in the same way that the pressure changes through the pore section of the laminar flow.

Results of velocity values for turbulent flow

- **Results of velocity values for non-porous zone:**

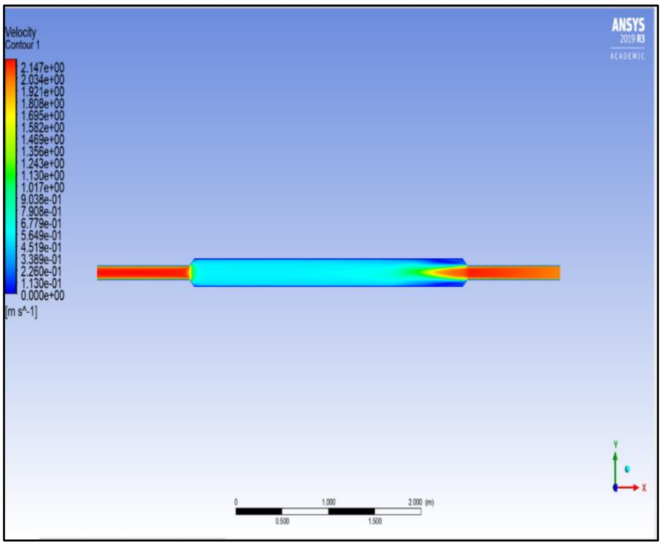

Figure 14: Velocity values in the non-porous pipe.

At the inlet to the diffuser the local velocity is high, it has been observed that there is the instability of the flow when moving between two different cross-sections.

- **Results of velocity values for porous zone:**

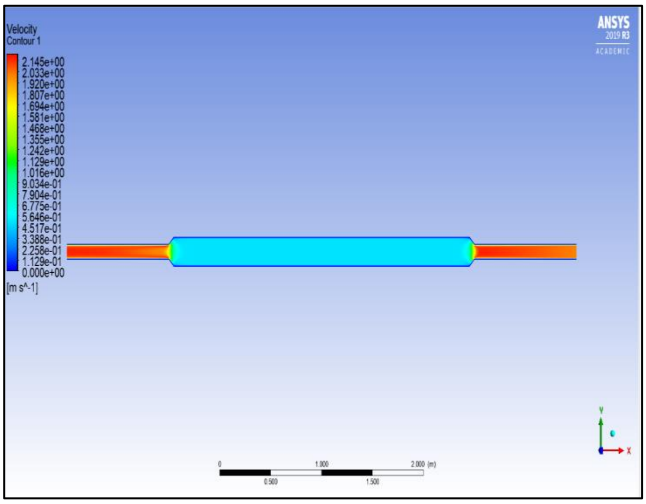

Figure 15: Velocity values in the porous pipe.

Note that the velocity profile in turbulent flow is like the velocity profile in laminar flow in the case of porous media. But there is some difference, the inlet length and the velocity profile are smaller compared to the laminar flow. Another difference is that the maximum velocity value of turbulent flow through the porous medium is 2 m / s, while the maximum velocity of laminar flow through the porous medium is equal to zero m / s as it decreases its energy through the flow, while the velocity is 0.1 m / s at the inlet.

The turbulent pressure does not shift its profile to a uniform distribution after going through the diffuser. It requires time and length to be more stable after a shift in the cross-section region, which is consistent with that the turbulent flow has more energy and momentum than the laminar flow and does not change its characteristics with the area or geometry change. Moreover, the turbulence flow enhances the heat transferring, because of the high velocity and momentum. The maximum pressure is 2.5 KPa, while the maximum pressure of laminar flow in the same case is 200 Pa.

The pressure in the porous zone also differs, as the maximum value in the porous area is 3.4×10^5, and in the non-porous region is 2.5 kPa. This supports that the pressure rises in the porous region. It is obvious that there is a high-pressure differential inside the porous medium, the change in pressure within the pipe can lead to pipe crack or failure, and this can be solved by using the nozzle. Furthermore, there is a local high velocity in the diffuser inlet and unstable flow is noted when transferring between the two separate cross-sections.

At the inlet of the nozzle, another high local velocity happened, with the transfer region nearly disappearing. The turbulence theory justifies this behaviour. Because of the energy magnitude it has, it can be easily accelerated as heavy turbulence reaches a limited cross-section. These local high-velocity values should be identified in the heat exchanger pipes design phase. The high speeds are transformed into pressures that are added to the walls.

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E. Results of wall shear stress "Brief study"

As a secondary study, the wall shear stress affected by the porous area was studied in this section. Only laminar flow was studied and examined because the laminar and turbulent flow values in porous media were compatible.

- **Results of wall shear stress in the porous pipe and non-porous:**

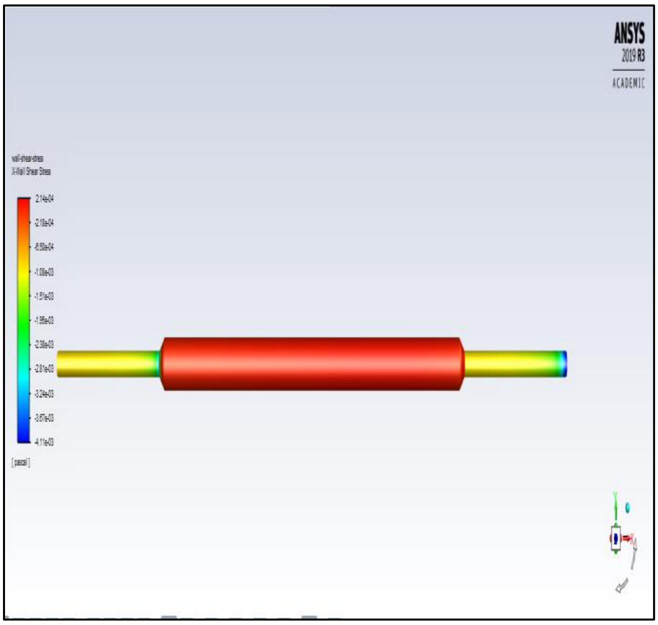

Figure 16: Wall shear stress with non-porous pipe

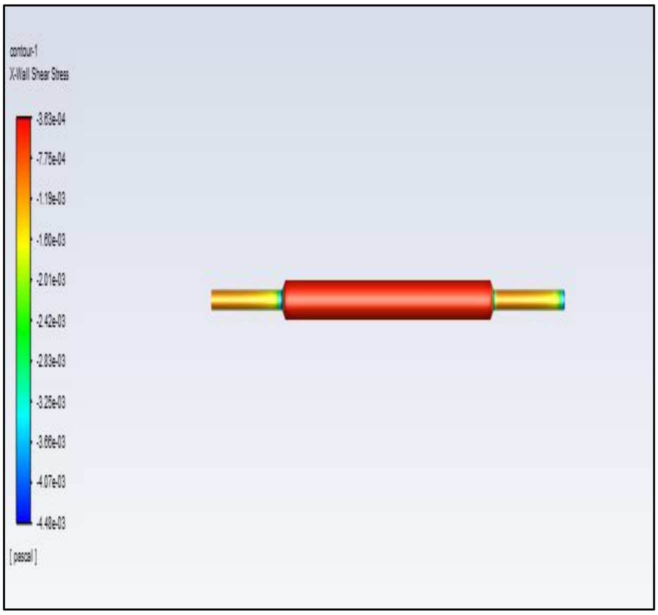

Figure 17: Wall shear stress with porous pipe

The value of wall shear stress is greater in the case of the porous medium. A negative or positive signal indicates the direction of the wall shear stress.

As a secondary analysis, the effects of the porous region on the values of the wall shear stress were examined. Where the findings showed that porous medium wall shear stress is greater than the non-porous situation. The negative value only shows the shear stress' direction, but the porous medium has larger wall shear stress by comparing the magnitudes. Understandably, the sheer pressure often becomes higher as the surface area becomes bigger, the distribution shear stress is studied because the higher shear stress values make the flow stick to the heat exchanger wall, and it will interrupt the fluid if it became big values.

VI. CONCLUSION

The use of fluids to transfer heat is known as a heat exchanger. Several systems work according to conduction and convection to transfer heat. To find new sources to produce energy and to enhance its overall production, there has been numerous research work has done to achieve this. To increase the thermal transfer process, porous materials are used in the heat exchanger, this helps to ensure an efficient flow to improve the heat capacity and develop the thermal conductivity matrix, and the porous media provides a larger area, which leads to more heat transfer.

The project aims to study and evaluate the pore flow to determine the effect of these media on the behaviour of the heat exchanger. The digital method (CFD) was used to achieve this goal. The simulated procedure was using ANSYS software. A summary of the results was as follows:

- There is a great tendency to add porous medium to heat exchangers to increase heat transfer efficiency. This case was studied by pressure, velocity, and wall shear stress of heat exchangers.
- When a porous material was placed in the pipe, the pressure values were affected, the pressure values differed along the length of the pipe, and its value was observed to decrease through the porous medium, the reason for this is that the wall of the porous area resists the flow, which works to reduce the liquid near the wall and from it, the force acting on it decreases. As the number of pores increases, the pressure value decreases.
- Know the necessary distance that the flow needs to develop and fill the tube along is the inlet length. The inlet length of turbulent flow is less than the laminar for the same material and diameter of the tube due to the momentum associated with the velocity of turbulent flow as the velocity is greater than the turbulent flow.
- The turbulence develops heat transfer, through the collision that takes place between the wall and the particles. Therefore, it is preferable to establish a turbulent flow heat exchanger. On the other hand, turbulence cause problems, so pipes must be chosen carefully.
- The velocity decreases through the porous media, this is due to the nature of the pores as they act as an obstacle in front of the liquid particles and collide with them. This collision leads to a loss of some momentum and the speed decreases due to the stability of the volume.
- The pressure gradients increase due to the porous media during the heat exchange. There will be seepage from the pipe if a pressure dispenser is placed or pressure relief is used.

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