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NUMERICAL ANALYSIS OF HEAT EXCHANGER BASED ON CONSTRUCTAL THEORY

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ABSTRACT

In this work, analytical and numerical methods are used to analyze the performance of constructal heat exchangers (CHEs). The flow of the liquid stream reaches the branches from the trunk, i.e., the diameter and length of the structure continues to decrease at each subsequent divider level. In the analysis method, the constructal and normal (conventional) heat exchangers (NHEs) were compared according to entropy generation numbers, NTUs, efficiency and thermal economic costs. In numerical methods (simulated methods), the constant temperature flow conditions were considered. The analytical results are first validated for the CHE at the constructal level, i=3. Subsequently, comparison of NHE and CHE was performed by comparing them according to various performance parameters such as effectiveness, number of entropy-generation and heat transfer rate. The variation in heat transfer, pressure drop and velocity profile through the heat exchanger was obtained from numerical methods and validated from analytical methods. In addition, a detailed comparison was made for similar conditions to normal heat exchangers.

Keywords: Constructal theory, heat exchanger, numerical simulation, tree- shape, dendritic structure

INTRODUCTION

Heat exchangers are an important component and used in various equipments and processes possesses opportunities for energy-conservation . The losses caused by the irreversibilities of the process can be investigated using the second law of themodymamics. Constructal law is adopted for performance and optimization of different thermal and fluid systems. It explains the natural law of self organization and optimization based on natural phenomena which is used to generate geometry and flow structures. Bejan [1] stated that the constructal law as "in order for a finite-size system to exist over time, it must evolve in such a way as to facilitate access to the imposed (global) current that flows through it". The optimal system is obtained by shape optimization of volume at each scale length having sequence of steps. This sequence of steps will be hierarchical beginning with small structure and establishes to large structure [2]. Bejan [3] provided the constructal methodology for design of heat exchanger to achieve higher heat transfer per unit volume having tree like branching in construction.

The constructal design and operation of balanced two-stream counterflow heat exchangers, in which each stream travels through its designated place like a tree network, were explained by Silva et al. [4]. In counterflow, the two trees resemble two palms squeezed up against one another. For various tree-counterflow topologies, they established the correlations between the number of heat transfer units and effectiveness. Zimparov et al. [5] examined the performance of balanced two-stream parallel flow tree heat exchangers using the ideas of Silva et al. [4]. The performance of various classes of simple flow systems, which are made up of T- and Y-shaped assemblies of ducts, channels, and streams, was optimized by Zimparov et al. [6-7]. Reducing the amount of entropy produced within the assemblies allowed for the achievement of maximum thermodynamic performance.

Numerical analysis of constructal heat exchangers has been studied in a number of works. Chen and Peng investigated the thermal performance of spiral heat exchangers with various spiral designs and assessed whether altering the spiral design may enhance thermal performance [8]. For potential use in passive and low-energy building, Adrian el al.have investigated numerical models of thermal pipelines in an effort to optimize highly efficient and smaller-sized thermal pipeline exchangers [9]. In order to investigate the impact of increasing the number of clusters on heat transfer and pressure decline, Sakamatapan et al. present a new liquid cooling heat tank based on constructal theory [10]. Reducing the irreversibility of heat allowed Feng et al. to build a shell-tube heat exchanger for the organic liquid evaporation process and increase overall performance.Reducing the irreversibility of heat transfer allowed Feng et al. to build a shell-tube heat exchanger for the organic liquid evaporation process and increase overall performance [11]. As an alternative to conventional geothermal heat exchangers, Popovici and Hudişteanu examined the novel heat exchangers and the consistent heat flux of heating and air conditioning systems [12].

Based on constructal theory, Manjunath and Kaushik developed an equation for a tree-shaped anti-flow-imbalanced heat exchanger [13]. examined rational efficiency, efficiency behaviors, and entropy creation for various factors. The research presents a thermodynamic analysis of a constructed heat exchanger with an emphasis on the efficiency of the second law and the minimizing of entropy creation. Manjunath and Kaushik examined the building heat exchanger's thermodynamic analysis and contrasted it with a typical heat exchanger [14]. It examines qualities that are irreversible as a result of material synthesis, pressure decrease, and heat transfer. The entropy generation minimization method was applied in order to examine the differences between the two types of heat exchangers. Furthermore, consideration is given to the thermoeconomic characteristics of the heat exchanger. Thermodynamic analysis is not explained in full in this study.

Mardani et al. analyzed and optimized triangular microchannels to achieve maximum heat removal [15]. The numerical results show that microchannels with a contact angle of 60° have the highest heat transfer rate. The most important contribution is the optimization of triangular microchannels that is independent of arrangement and number. Microchannels with 60° contact angles have the highest heat transfer rate. Ochende and Meyer discussed geometric optimization of three-dimensional microchannel heat sinks [16]. Geometry optimization of the microchannel heat spherical to maximize thermal conductivity was performed as well as the effects of the solid volume and pressure reduction on peak temperature being investigated. Tunde et al. performed numerical optimization of microchannel heat tanks with water as cooling fluid. [17]. The main contributions are geometric optimization to minimize overall maximum temperature and maximize thermal conductivity, and the optimal allocation of solid volume fractions for fixed pressure reductions.

The study was carried out by Kai and others. [18] to reduce pressure drop in microchannels with the help of constructal theory. Two construction theory-based models were developed and tested to demonstrate the performance of heat transmission. The main result is that microchannels increase heat transfer but also increase pressure drop. Therefore, constructal theory is used to reduce pressure drop while maintaining heat transfer. Rong et al. developed a 3D model of a unified rectangular microchannel heat sink and a static microchannel heat sink. [19]. The constructal design was carried out to minimize the entropy generation rate and improve temperature uniformity. Thin and high fins reduce temperature differences and entropy production rates. Staggered fins with appropriate spacing reduce the rate of entropy generation further.

Constructal theory was utilized by Ruiping et al. to enhance the thermal efficiency of microchannel heat sinks. [20] Thermal performance is effectively improved by the entrance bifurcation design. The thermal performance is significantly enhanced by the design of one or two bifurcations in the entrance area. The microchannel heat sinks' total thermal resistance is contrasted with the pump power. Gongnan et al. use the constructal law optimization and the minimization of entropy generation to optimize the pin-fin for better heat transmission in a heat exchanger. [21]. The 10.2% increase in stored thermal energy is achieved by the optimized pin-fin heat exchanger.

Plates-fin heat exchangers are designed, engineered, and optimized by Amir et al. using the idea of constructal theory [22]. The usefulness and possible applications of this methodology are demonstrated in a case study. Compared to a typical plate-fin heat exchanger, the constructal heat exchanger offers a better thermal recovery. Constructal theory is a useful idea in heat exchanger design, and Bejan et al. [23] address the issue of heat exchanger sizing optimality. The power requirements are affected in the opposite way by changes in the heat exchanger's size. The equilibrium between energy loss and energy destruction dictates the heat exchanger's size. El Mosharaf et al. Applied Bejan constructal theory to air-cooled heat exchanger optimization[24]. Parameter effects on heat exchanger optimization and heat transmission. The technique of optimization produced a 6.2% enhancement of in heat transfer.

Dense heat transfer packing is provided by constructal heat exchangers, which also maintain pressure below the minimal threshold. Reducing the area under which heat transfer occurs and increasing compactness are necessary to raise the overall efficiency of heat exchangers. As a result, the maximum transport density, or increased compactness and thermal transfer capacity, is achieved. More heat transfer over a unit area is made possible by increased transport density, which enhances the heat exchanger's total thermal performance (efficiency).Investigating and contrasting the performance of constructal heat exchangers with that of conventional heat exchangers is the aim of this study. The primary goals of this project are to perform an analytical analysis of the constructal heat exchanger and to modify the flow direction, input and output pressure, temperature, and other variables using engineering problem solver software and the formulas provided by Bejan. Under conditions of steady heat flow, compare the constructal heat exchanger with the conventional heat exchanger that has the same surface area and volume. Utilizing numerical techniques and a range of Reynolds values, examine the behavior of both constructal and standard heat exchangers.

ANALYSIS

In Figure 1, the counter-flow heat exchanger comprises two identical trees, one for hot liquids and one for cold liquids, in accordance with the protocols outlined by Silva et al. [5]. The hot tree tube is parallel to and in perfect thermal contact with the equivalent cold tree tube because the two trees work perfectly together. To stop heat leakage from the outside, insulation is given, as seen in the figure.

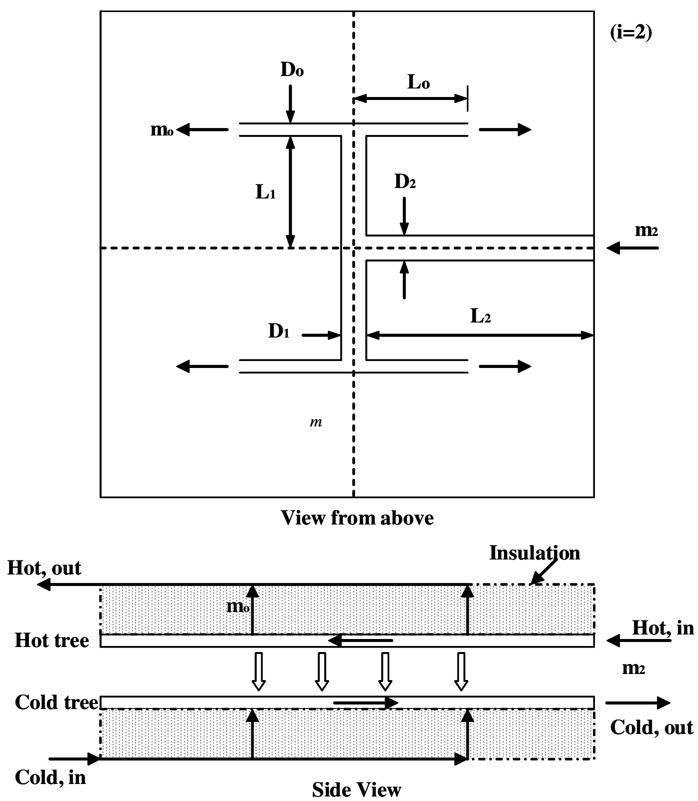

Figure 1: Counter flow of tree shaped streams distributed over a square area [5].

ANALYTICAL ANALYSIS

In the analysis given in [5, 14], the following presumptions were made: (i). When fully grown, the flow is laminar (ii). Friction along the heat exchanger's straight cross section is the primary cause of the pressure drop (iii). It is ignored that tube joints cause localized pressure dips (iv). There is good thermal contact between the hot and cold stream tree tubes, one of which is next to the other. In both currents, the identical kind of fluid flows, (v). There is equilibrium in both heat exchanger fluids. The formula and process for analytical modeling are used in accordance with Manjunath and Kaushik [14]. It is essential to take into account the same surface as well as additional factors derived in the manner outlined in in order to compare CHE and NHE.

NUMERICAL ANALYSIS

Ansys Fluent 16 is used to simulate both normal (NHE) and constructal (CHE) heat exchangers [25]. The heat exchanger's shape is the only region that can be computed. Beyond the input and output ports, it is not extended. The analysis is done by considering a balanced design of the heat exchanger and a constant heat flux condition is assumed. Though a number of angle of bifurcations are possible, however in order to reduce the complexity of the geometry only 90^0 bifurcation angle is used. The number of bifurcations at each constructal level is equal to two. Increasing the value of bifurcation levels it leads to complexity during mesh generation in simulation. Constructal and normal heat exchangers are simulated by considering the Reynolds number as 1500.

GEOMETRIC MODELING:

For simulating CHE in Ansys, a 2-D model of CHE is first drawn in Ansys geometric modeler. Following constraints are taken into consideration while finalizing the dimensions of CHE:

a. Number of branching level is equal to 3.

b. Diameter of thinnest branch of CHE should not be less then 3 mm otherwise channel will become micro channel.

c. Length to diameter ratio ($L_n/D_n = 120$)

d. Initial diameter (D0 = 6 mm)

Dimensions of different branches considered for CHE is given in Table 1. Length of NHE in case of equal surface area found to be 3453.6 mm Diameter in both of these cases is taken to be 6 mm.

Table 1: Dimensions of various branches of CHE

Branch number n	Diameter (D_n)	Length (L_n)
0	6mm	720mm
1	4.7622mm	509.1168mm
2	3.7797mm	360mm
3	3mm	254.5584mm

Meshing

After constructing the geometry in the Ansys workbench design modeler it was imported to Ansys ICEM meshing software [25]. To generate a fine and structured mesh to capture the flow near boundary walls and at intersections face meshing and edge sizing were used as shown in Fig. 2. Table 2 provides the information of meshing for CHE, while Table 3, provides same information for NHE.

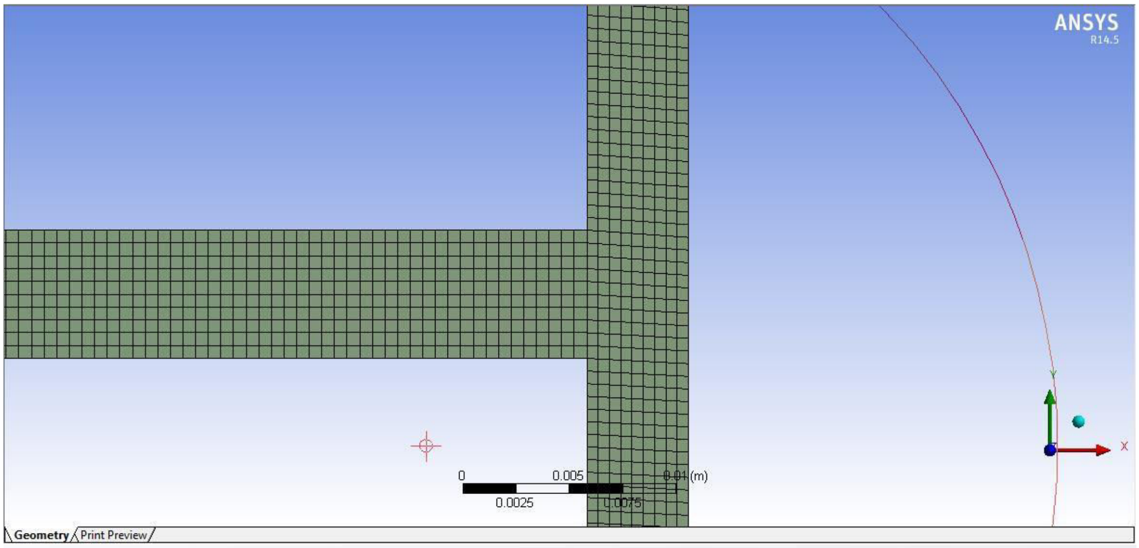

Fig: 2 Meshing at first intersection

Table 2: Information of mesh generated for CHE

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra	Polyhedra
Flow domain	82284	36127	0	0	0	36127	0

Table 3: Information of mesh generated for NHE

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra	Polyhedra
Flow domain	214334	103680	0	0	0	103680	0

Boundary Conditions and Setup

After meshing the geometry and the mesh have been set up to solve the problem using FLUENT. Laminar viscosity model is used for flow with Reynolds number 1500.

The material used for fluid is air while the material used for heat exchanger material is copper. The thermodynamic properties of air taken from Ref. no. [14]

Boundary Conditions Taken for Simulation Are:

1. Inlet in all the cases is taken as velocity inlet as the velocity for the inlet is derived using Reynolds number.
2. Outlet is taken to be be pressure outlet as only pressure is known as the outlet i.e. 1 atmosphere. Gauge pressure equal to 0 pascal is used.
3. The heat flux considered to constant and for all cases it is equal to 500 W/m^2.

Numerical Details for Simulation of Heat Exchanger.

a. Simple algorithm is adopted for pressure velocity coupling as provided in Fig. 3

b. For the solution method upwind scheme of second order is adopted.

c. Convergence criterion for momentum is 1xe^{-06} and for energy it is 1xe^{-09} as provided in Fig. 4.

Standard Initialization technique is used and solution is initialized from inlet in all the cases.

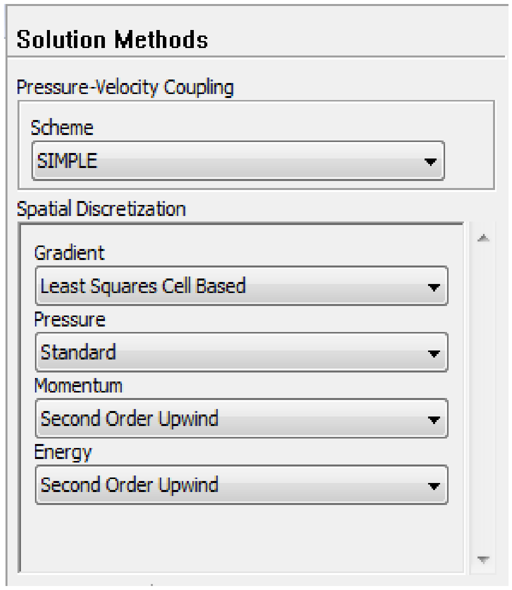

Fig: 3 Numerical details used

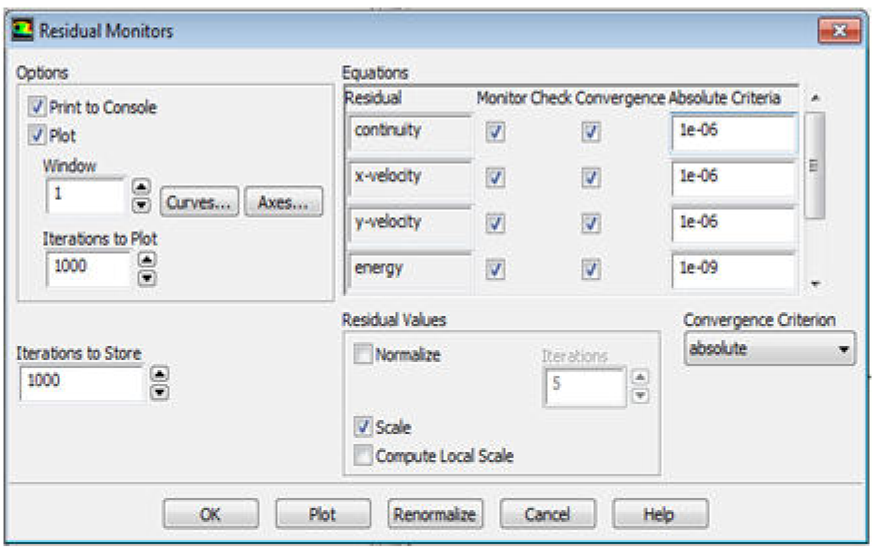

Fig: 4 Convergence criteria

Similar procedure is followed for case of NHE with similar boundary conditions and numerical details. Length of NHE in case of equal surface area is 3453.6mm

RESULTS AND DISCUSSION

In order to establish a detailed comparison for heat transfer, effectiveness, and entropy production numbers, and to aid in validation with analytical solutions, the laminar region's Reynolds number is 1500 [14]. On the walls of CHE, constant heat-flux equal to 500 W/m^2 is applied. CHE temperature of the fluid keeps on decreasing constantly as it moves along its paths as shown in Fig. 5. Spikes in the temperature graph are there at the intersection points of different branches as shown in Fig. 6. This temperature spikes is justified by the fact that at the intersection the velocity of the fluid drops down. Hence, the temperature spikes up instantaneously.

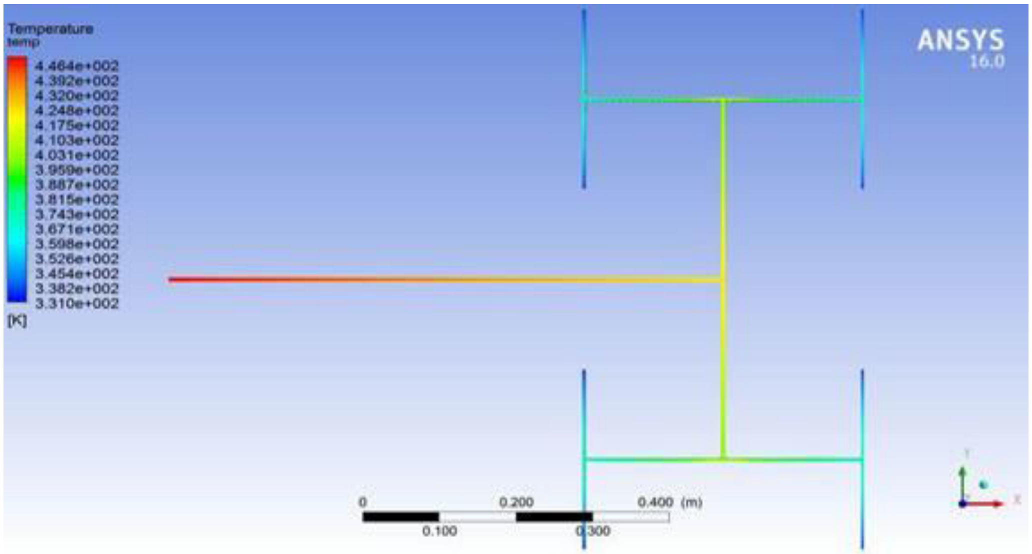

Fig: 5 Temperature profile in Kelvin for hot stream in CHE

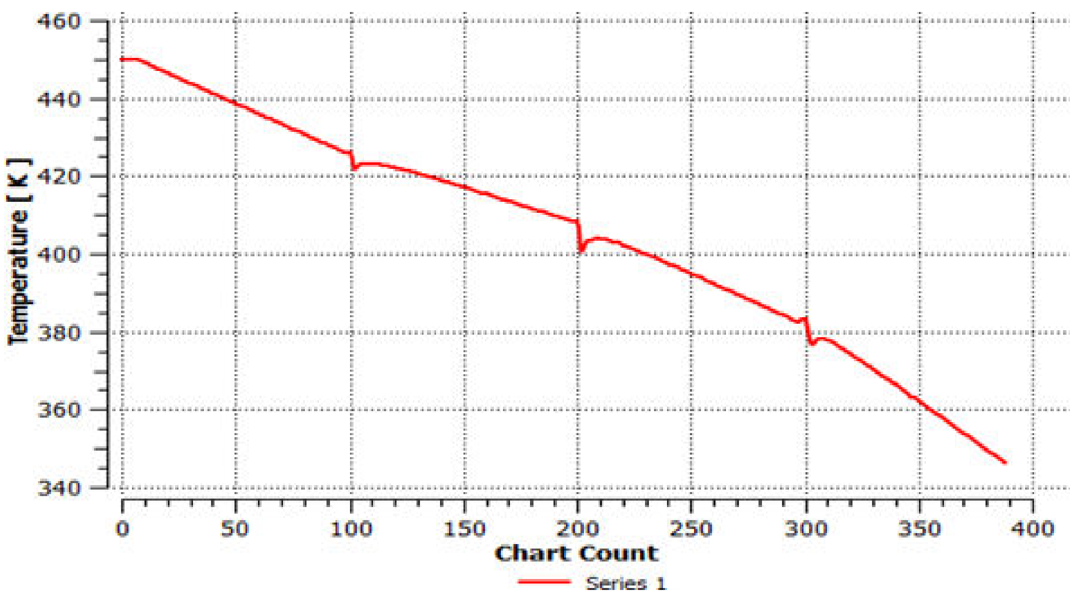

Fig: 6 variation of temperature along the chart count for hot stream in CHE

The inlet of the hot stream takes place from the left and moves on till the first branching level as shown in Fig. 7. As the fluid starts flowing in CHE its pressure constantly keeps on falling due to friction losses that occurs, however at intersections of branching level sudden decrease in the pressure takes place because of fluid impact on joints of the heat exchanger which can be seen in Fig. 8.

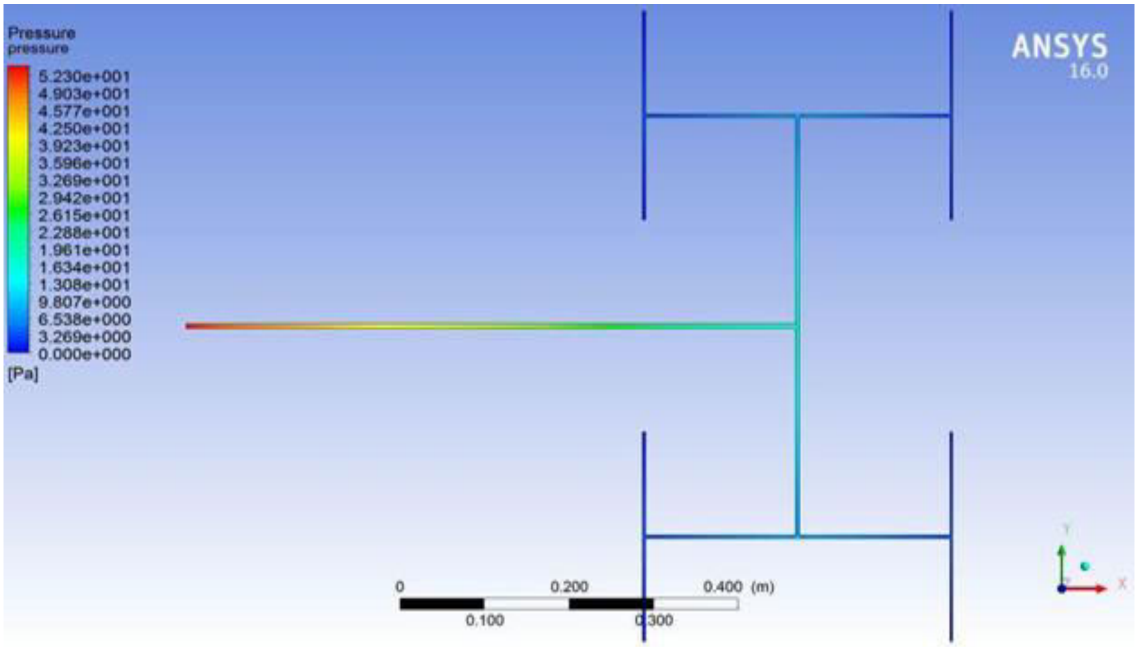

Fig: 7 Pressure profile in Pascal for hot stream in CHE

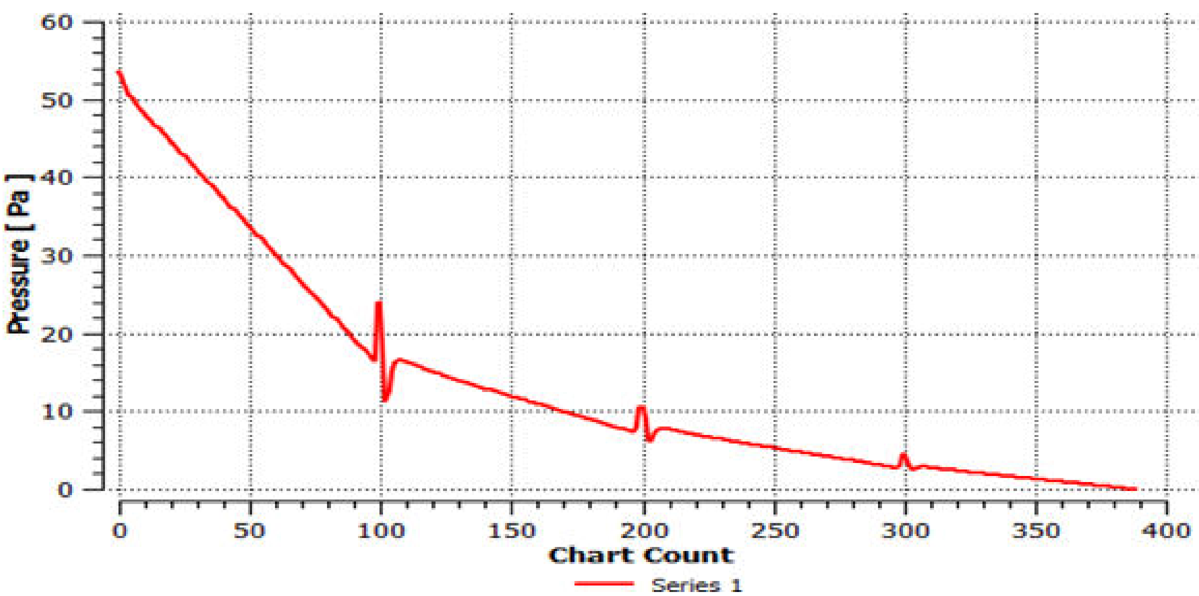

Fig: 8 variation of pressure along the chart count for hot stream in CHE

As it can be clearly seen velocity in all four branches increases from an initial value to a constant value as the fluid flow becomes fully developed as shown in Fig. 9. However at the intersection points of the branches there is a sudden drop in velocity due to change in direction after the impact with the wall as shown in Fig. 10. After the impact fluid flow again become fully developed and attains a constant velocity however as the mass flow rate in divided into half at every intersection velocity of fluid decreases at subsequent stages.

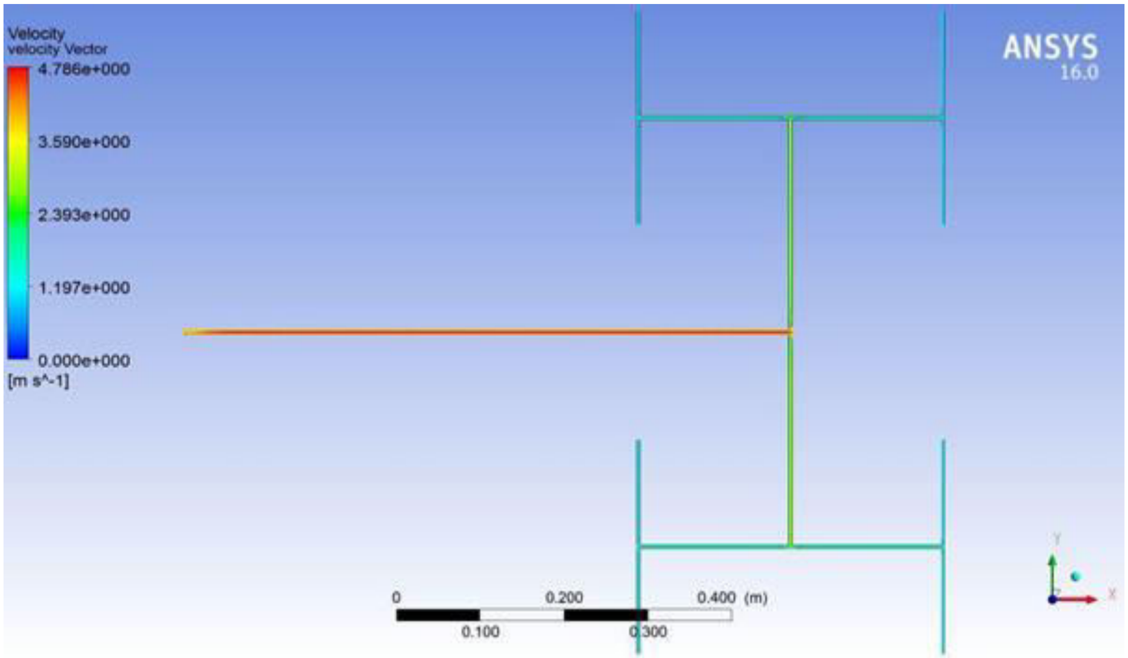

Fig: 9 Velocity profile in m/s for hot stream in CHE

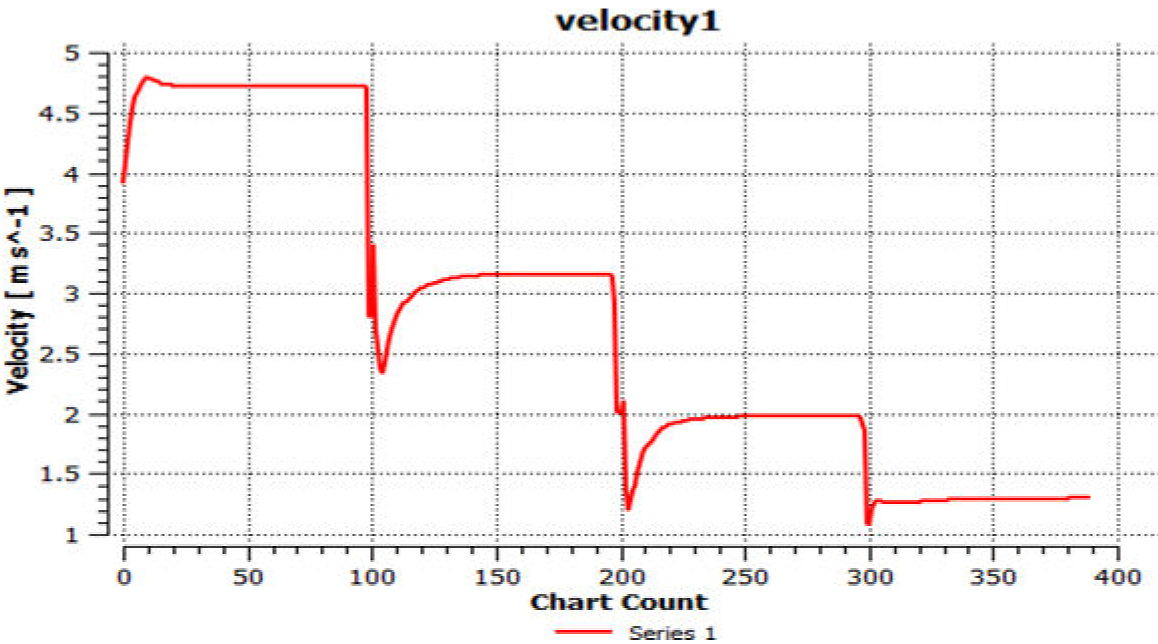

Fig: 10 variation of velocity along the chart count for hot stream in CHE

For the case of NHE, which is having contant dimension tube both diameter and length of cold and hot stream. The analysis is carried out with same inlet and boundary conditions as CHE.

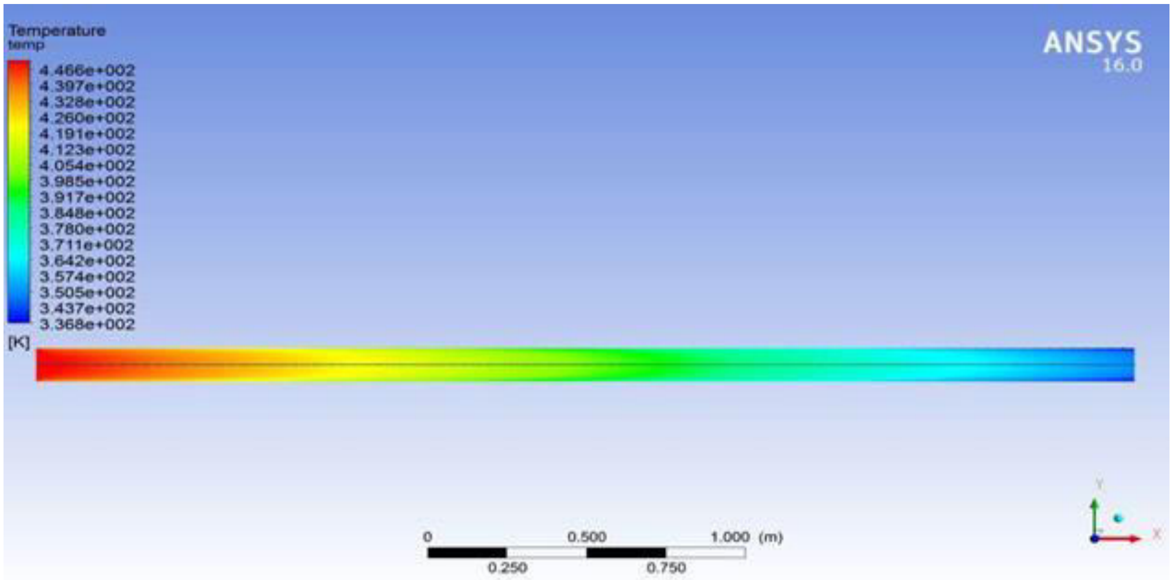

Fig: 11 temperature profile in kelvin for hot stream in NHE for constant surface area

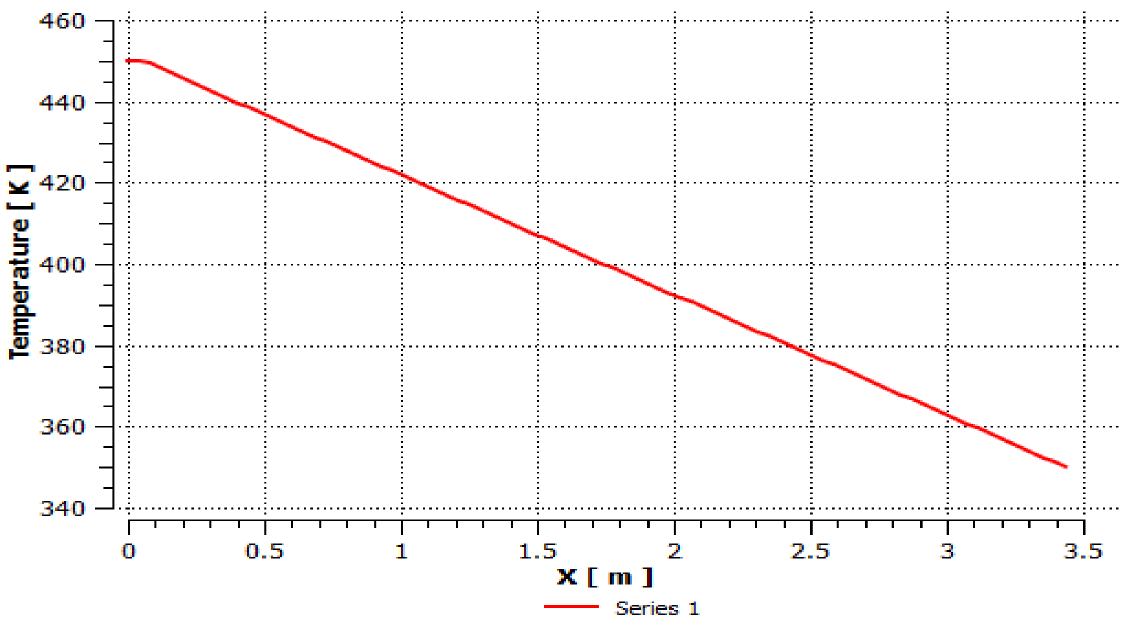

Fig: 12 Variation of temperature along length for hot stream in NHE for constant surface area

In the case of NHE the temperature of hot fluid keeps reducing constantly as it proceeds with the length of heat exchangers as shown in Fig. 11. The temperature of the hot stream keeps on reducing without spikes as the flow progresses towards the outlet because of the constant flux condition as shown in Fig. 12.

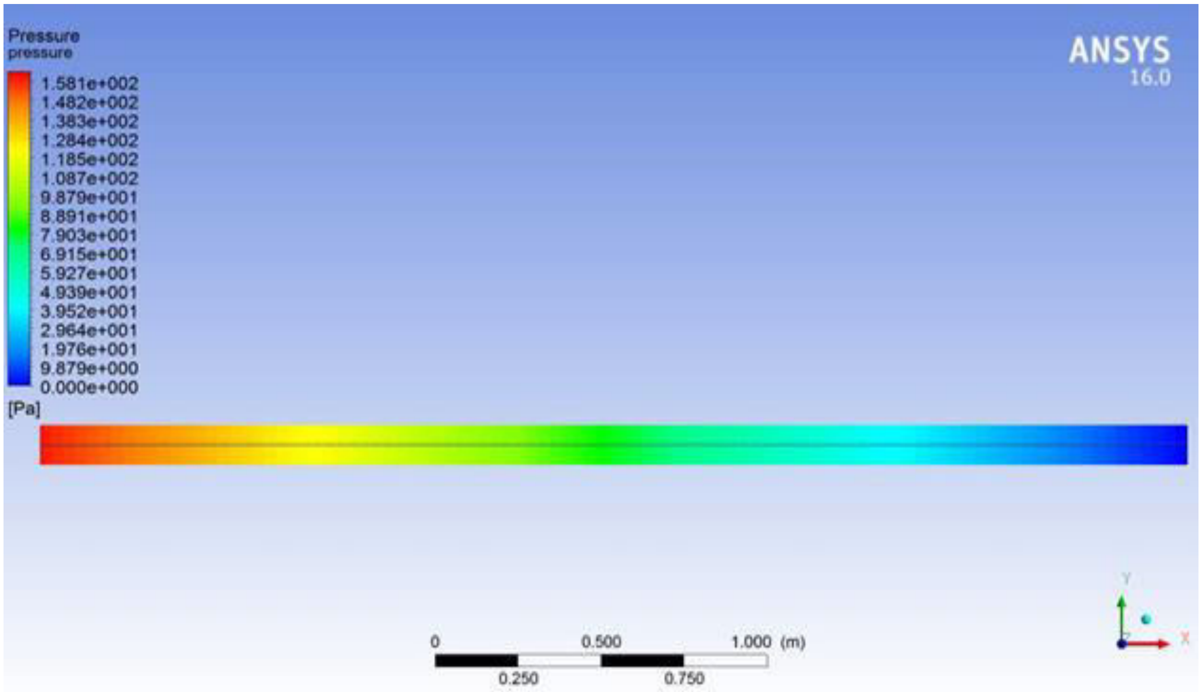

Fig: 13 Pressure profile in Pascal for hot stream in NHE for constant surface area

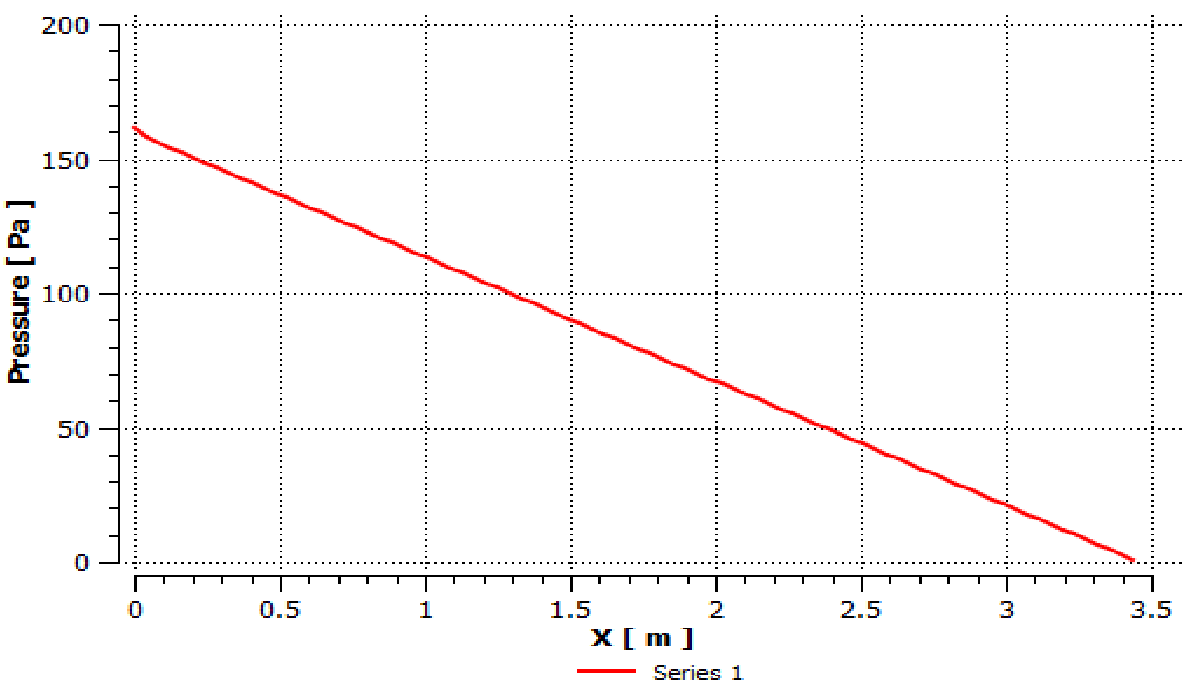

Fig: 14 variation of pressure along the length for hot stream in NHE for constant surface area

As the fluid flow becomes fully developed, pressure inside the NHE keeps of falling constantly due to friction losses as shown in Fig. 13. The pressure losses are the only factor that is responsible for the drop in pressure in NHE as indicated in Fig. 14.

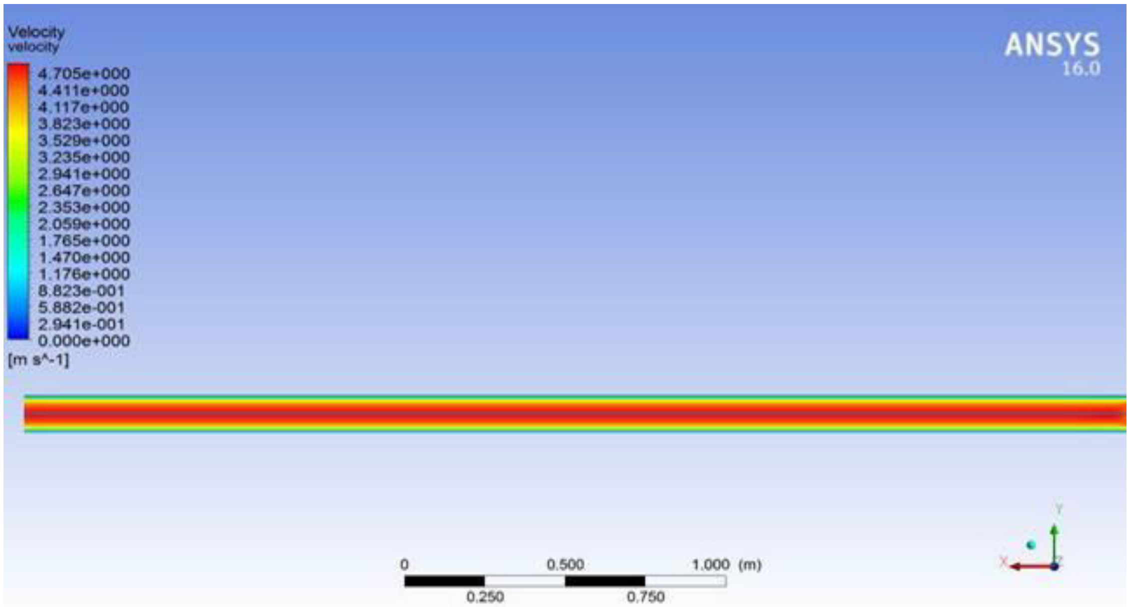

Fig: 15 Velocity profile in m/s for hot stream in NHE for constant surface area

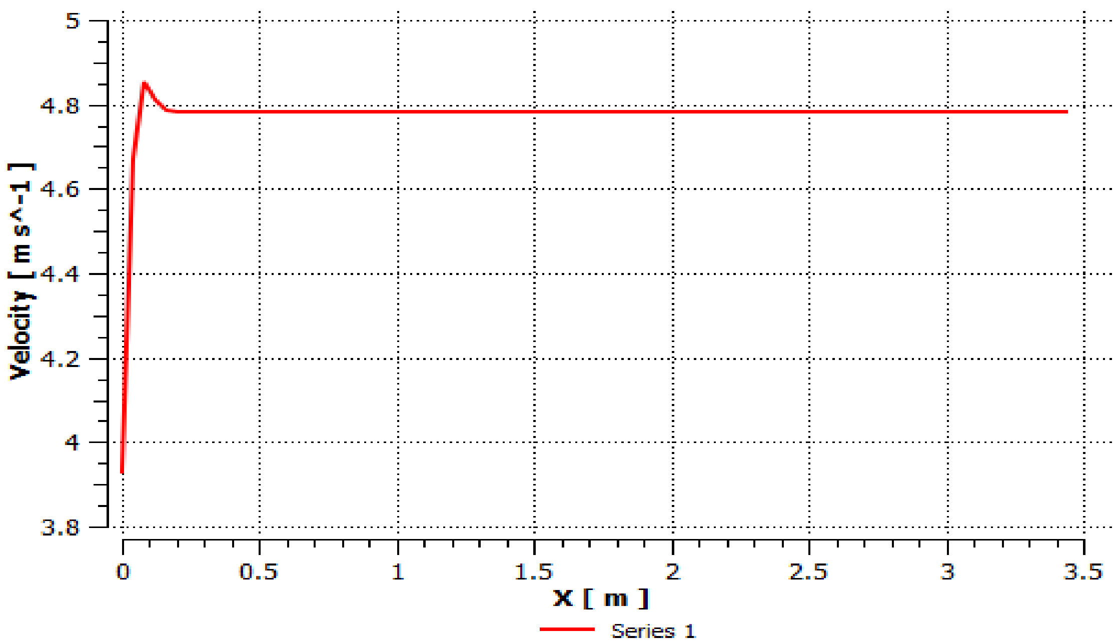

Fig: 16 Velocity variation along the NHE length for hot stream for constant surface area

Velocity at the inlet is 3.93m/s and after flow becomes fully developed it increases to a certain value and then becomes constant at 4.85m/s as shown in Fig. 15. Velocity variation along the NHE length for hot stream for constant surface area is shown in the Fig. 16. Initially at the entrance, the increase in velocity can be observed. Thereafter, the velocity remains constant due to NHE constant diameter tube.

Validation of Analytical Results

Comparison between analytical and numerical solutions are carried out in respect of three parameters [14] namely heat transfer, effectiveness and entropy generation numbers. The validation of numerical results of both CHE and NHE is presented in the Table 4. As mentioned earlier, for analytical procedure and results the reference [14] is followed. As seen in the Table 4, there is less than 10% variations between numerical and analytical results for both CHE and NHE. This validates the numerical procedure and results followed for the analysis of heat exchanger designed with the constructal law.

Table 4: Validation of numerical results with analytical results

Sl. No.	Parameters	Constructal Heat Exchanger (CHE) Results		Normal Heat Exchanger (NHE) Results	
		Analytical [14]	Numerical	Analytical [14]	Numerical
1	Heat transfer (W)	11.92	13.72	8.62	8.29
2	Effectiveness	0.85	0.806	0.77	0.75
3	Entropy Generation Number	0.00396	0.0027	0.00605	0.00385

CONCLUSIONS

Numerical and analytical anlaysis are carried out for constructal heat exchanger (CHE) to compare its perfomance with the normal heat exchanger (NHE). The following are some of the conclusions.

1. For CHE the entropy generation number results lower value in comparison to NHE for third level of pairing i.e. i=3 and these values are almost equal to results of the analytical method. This validates the results of the numerical method.
2. The effectiveness of the CHE for third pairing level is more than the NHE which shows that the CHE is more effective in transferring the heat. Also the CHE heat transfer is higher than NHE which provides higher performance. Moreover, similar results are obtained from the analytical method also.
3. As compared to NHE, the pressure drop is lower in the case of NHE for same surface area condition. This results in lower losses and improved performance of CHE over NHE .
4. In CHE velocity of fluid decreases in steps for each branching level. This also reduces the losses occurring during fluid flow in CHE in comparison with NHE which is having higher value of velocity profile.

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