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Numerical Investigation of Heat Transfer Enhancement in Micro-Channel Cooling Using Finite Element Analysis

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Abstract

Due to the enormous heat fluxes emitted by modern electronic chips, there is a persistent need to enhance the efficiency of cooling systems. This study's focus is on optimizing heat transfer in micro-channel heat sinks that use liquid cooling. Geometric changes and the use of nano-fluids as coolants in place of water are performed to achieve this goal with little energy consumption. Numerical analysis of pipe micro-channel fluid flow and heat transfer. is presented, along with a systematic and accurate methodology for doing such an analysis provided by this work. This study examines the temperature and velocity of water passing via a little conduit. In addition, the micro-channel within the pipe is discretized using Finite Element Method. Adding domain elements and nodes discretizes finer components. MATLAB codes are designed for this. The simulation results reveal that entrance velocity variations greatly affect fluid flow and temperature research. The temperature fields affect energy sources in the domain's midsection. The findings show that the fluid flow is upward and that the heat transfer mode is conductive. The investigation examines how adding a heat source to the temperature field changes things. This work supports the concept that our computation matches that of other academics who have studied similar fundamental geometries. FEM is effective for analyzing constant flow due to its simple measuring techniques.

Keywords: Heat transfer, Simulation, Finite Element Method, flow, temperature, entrance velocity.

INTRODUCTION

Solving partial differential equations with finite elements is common. Finite elements are used to discretize a complex continuous region in this research. At element corner, uncertain numbers represent material qualities and governing relationships. Consideration of assembly technique loads and limitations yields equations. Solving these equations approximates continuous behavior.

Thompson discusses finite element techniques (FEM) for partial differential equations in fluid mechanics, elastics, and electromagnetics [1]. Fluid mechanics and heat transfer problems may be solved in [2]. Winget and Hughes give a more advanced transitory heat conduction equation [3]. Compressible heuristic step size selection Jacob and Ebecken [5] and Johan et al. [4] give Navier-Stokes equations and structural dynamics issues [6]. Convection is fluid-based heat transmission. Partial differential equations are needed to solve thermodynamic and fluid mechanics problems for convective heat transport.

We solve the steady flow problem for an incompressible, non-viscous fluid in a two-

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dimensional channel using the finite element approach in this paper. Using this fluid's flow field, temperature flow partial differential equations are solved. Boundary conditions govern thermal and fluid fluxes. We attain this accuracy by discretizing the issue domain into many components. This issue is modeled with four-node isoparametric quadrilaterals. Internal heat sources are also examined in relation to regional temperature patterns. For each value of the entry velocity, the flow field and the temperature field are analyzed separately.

NUMERICAL SIMULATION

Partial differential equations are commonly solved using the finite element method. Here, a complicated continuous region is discretized with the help of finite elements. At element corner, uncertain numbers represent material qualities and governing relationships. Consideration of assembly technique loads and limitations yields equations. Solving these equations approximates continuous behavior (Figure 1).

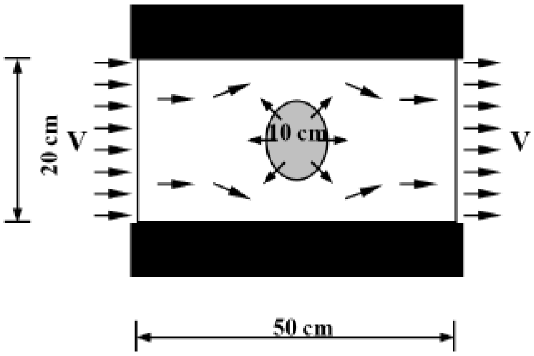

Figure 1. The Flow Micro-Channel System for Pipes.

The following relation yields the two-dimensional governing equation.

$$\frac{\partial}{\partial x}\left(R_x \frac{\partial \Phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(R_y \frac{\partial \Phi}{\partial y}\right)+B_x \frac{\partial \Phi}{\partial x}+B_y \frac{\partial \Phi}{\partial y}+G\Phi+H=0 \text{ in } \Omega$$
$$\Phi=\Phi^* \text{ on } S_1 \quad (1)$$
$$R_x \frac{\partial \Phi}{\partial x} n_x + R_y \frac{\partial \Phi}{\partial y} n_y = q^* \text{ on } S_2$$

The coefficients G and H provide x and y functions. Written symbols represent two-dimensional spaces. S_1 and S_2 are subsets of the domain border S. The boundary's outward normal unit vectors are also shown.

Based on the universal governing partial differential equation, Poisson's equation accurately represents ideal fluid flow and other situations. Perfect fluids move according to two equations:

$$\frac{\partial u_x}{\partial y}-\frac{\partial u_y}{\partial x}=0 \qquad \text{(Irrotational flow)} \qquad (2)$$

$$\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}=0 \qquad \text{(Incompressible flow)} \qquad (3)$$

We get if we define in such a way that it strictly satisfies the incompressible flow condition.

$$u_x=+\frac{\partial}{\partial y}\Psi \qquad \text{(x component of the velocity)} \qquad (4)$$

$$u_y=-\frac{\partial}{\partial x}\Psi \qquad \text{(y component of velocity)} \qquad (5)$$

When Equations (4) and (5) are substituted into Equation (2), the resulting stream function describes the flow of the fluid.

$$\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial y^2}=0 \tag{6}$$

The energy equation governing the steady-state two-dimensional convection through a constant-property homogeneous fluid can be found in reference 2.

$$\frac{\partial}{\partial x}\left(\rho C_p u_x\phi-k\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\rho C_p u_y\phi-k\frac{\partial\phi}{\partial y}\right)=0 \tag{7}$$

or in other form

$$\frac{\partial}{\partial x}\left(k\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial\phi}{\partial y}\right)-\rho C_p u_x\frac{\partial\phi}{\partial x}-\rho C_p u_y\frac{\partial\phi}{\partial y}=0 \tag{8}$$

The symbol k represents the thermal conductivity of the fluid, while C represents its heat capacity. Both of these variables are used to indicate the temperature. The symbols denote the x and y components of velocity. Time-dependency will not be assessed due to study limitations. Therefore, we will assume that the thermal conductivity of the fluid remains constant, with a value of k = 1.0. Furthermore, it is assumed that the heat capacity is equal to 1.

This study demonstrates the application of finite elements for the resolution of a two-dimensional steady flow issue. The partial differential equations governing the flow of temperature in the fluid's flow field are solved. Both fluid flow and temperature distribution exhibit boundaries. The problem's domain is divided into numerous pieces to guarantee accuracy in finding a solution. An extensive investigation analyzed the distribution of temperature and the movement of fluid at different entrance velocities.

FINITE ELEMENT MODELING

The energy functional is minimized in finite element analysis to find FEM temperatures, stresses, fluxes, and other unknown quantities. All FEM-related energies are included in the energy functional. Energy conservation requires the finite element energy functional to be zero. Mesh generators are used in MATLAB to numerically simulate pipes [7–10]. Figure 2 shows a discretized basic module diagram. The finite element approach divides the analytical domain into smaller parts. The areas are distinct and connected at their nodes. The geometric data for components and nodes is created during mesh generation. This entails computing coordinate nodes, connecting them, and generating elements. In this context, "mesh" refers to assemblages of elements, nodes, and lines that indicate their links. The mesh creation method greatly affects analysis domain modeling capabilities and comfort. The geometry of generated elements greatly affects finite element analysis efficiency and accuracy. Mesh creation is crucial to the Finite Element Method (FEM). The mesh generator takes as input the number of iterations and the geometric coordinates of specified locations on each side. In order to maintain degrees of freedom at the boundaries of the elements, the total number of elements is divided into discrete domain elements [11–12]. Figure 3 illustrates a trend where the size of components decreases as they approach the smaller pipe located in the middle. This ensures solution accuracy in this high-stress site. As mentioned in [13–14], mesh discretization applies to flow and temperature estimates [15]. Evaluating two-dimensional problems requires determining how to assign node numbers to minimize stiffness matrix storage. The stiffness matrix bandwidth relies on the node numbering method. A badly designed numbering system may use much more bandwidth. Finite element equations associated by common elements must be found to minimize bandwidth (Figure 4).

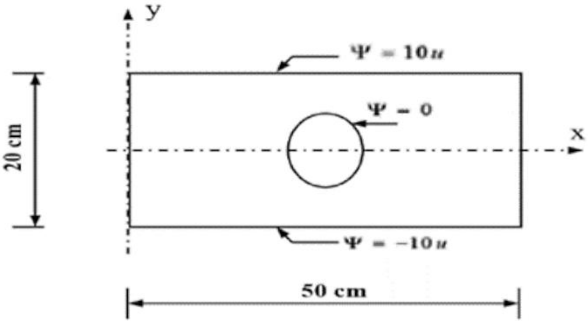

Figure 2. Conditions at the fluid's boundaries.

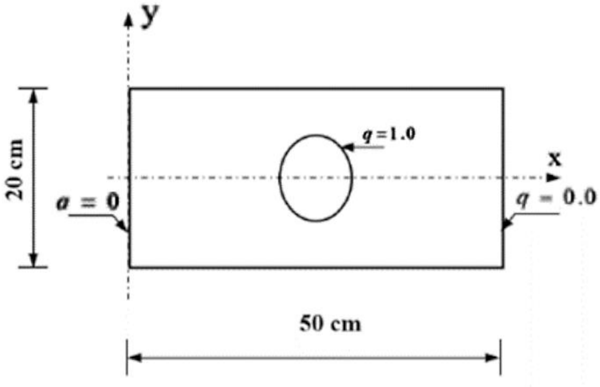

Figure 3. Conditions at the temperature field's boundaries.

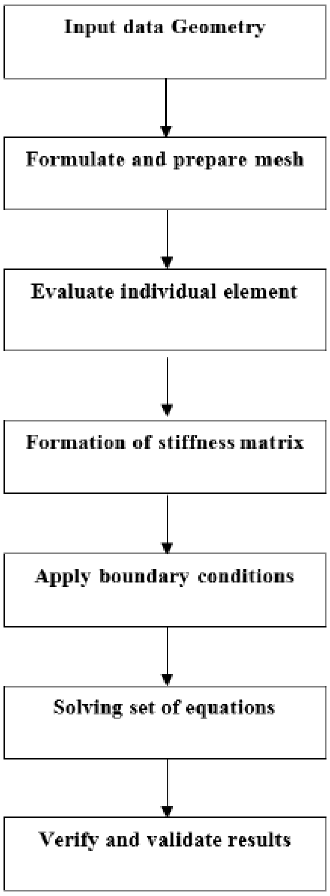

Figure 4. FEM flowchart.

Figure 5 shows the "initial wave of nodes." The second wave includes all nodes that share elements with the first. From the updated list, second-wave nodes get sequential numbers. This continues until all nodes have updated numbers[16-19]. All sub-assemblies must have node counts within two successive long waves, if not less. The new finite element analysis numbering scheme is output (Figure 6).

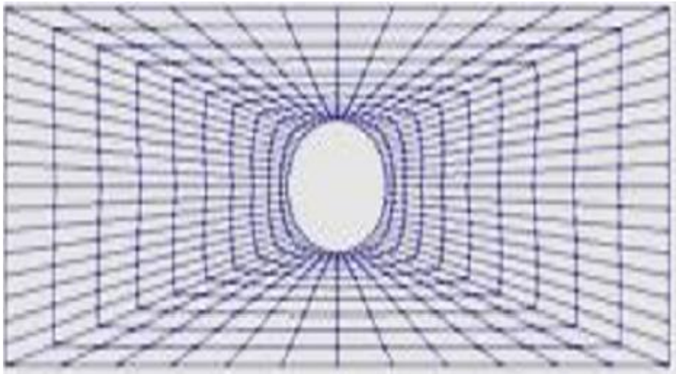

Figure 5. Discretization of Mesh.

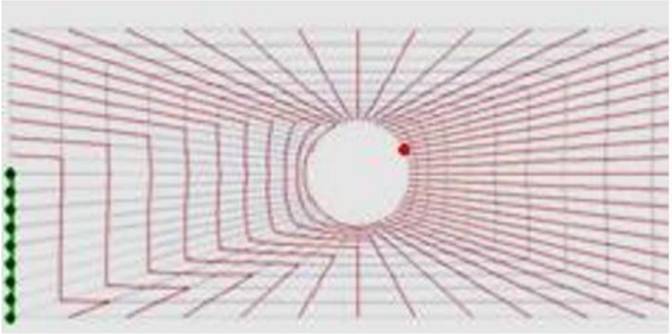

Figure 6. Wave of nodes.

FLOW ANALYSIS

Flow and temperature distribution can be included in the typical two-dimensional equation. However, equation (1)'s coefficients differ for the fluid flow and temperature field, meeting equations (6) and (8). Fluid flow is governed by Poisson's equation (6).

$$\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial y^2}=0$$

The general governing equation (1) coefficients, G and H, are 1.0, 1.0, 0.0, and 0.0, respectively.

$$\Psi = u_x\, y \tag{9}$$

V represents constant velocity and y represents border node y-coordinates. Non-viscous, incompressible flow retains x-component velocity at both upper and lower boundaries. Thus, the following equations describe maximum and minimum fluid movement:

$$\Psi = u_x\,(10) \qquad \text{(at upper boundary)} \tag{10}$$

$$\Psi = u_x\,(-10) \qquad \text{(at lower boundary)} \tag{11}$$

Y values of 10 and -10, respectively, mark the upper and lower boundary nodes. At both the beginning and end of the passage, the y-velocity is 0. To keep the fluid non-viscous and incompressible, the flow rate through the central circular pipe should be held constant[20]. By making the coefficients G and H

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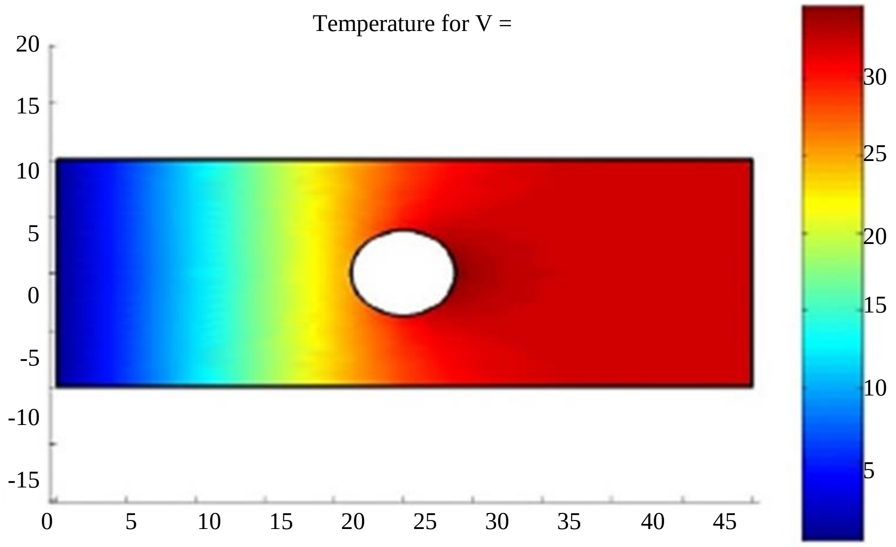
in the universal governing equation (1) equal to zero, the temperature flow is defined by the energy equation (8). The heat capacity and thermal conductivity of fluids are assumed to be same. The speeds of and depend on one another. Equations (4) and (5) demonstrate that the velocity components can be calculated using the derivative of the fluid flow with respect to x and y.

$$\frac{\partial}{\partial x}\left(k\frac{\partial \phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial \phi}{\partial y}\right)-\rho C_p u_x\frac{\partial \phi}{\partial x}-\rho C_p u_y\frac{\partial \phi}{\partial y}=0$$

The results are presented for entry velocities of 0.0, 0.3, 0.6, and 1.0. Temperature distribution at different entry velocities is seen in Figure 7. Data reveals that entrance velocity greatly decreases temperature field. This lends credence to the idea that convection is a more efficient heat transmission mechanism than conduction. Figure 8 adds further proof that speed amplifies local heat conduction.

Figure 8 demonstrates fluid movement at predefined entrance velocities. Observations demonstrate the flow field is constant regardless of velocity. Entry velocity strengthens flow. When ux is 0.0, the flow field remains immobile and the stream function remains constant across the domain, according to actual data. Energy (8) controls temperature flow. The coefficient values in the general governing equation (1) are Rx = k, Ry = k, Bx = -ρCPux, By = -ρCPuy, G = 0.0, and H = 0.0. Fluid heat capacity (ρCP) and thermal conductivity (k) are assumed to be identical. Ux and uy velocity components affect Bx and By. Equations (4) and (5) calculate the velocity components ux and uy from the fluid flow derivatives with respect to x and y.


Temperature for V =
20
15
10
5
0
-5
-10
-15
0
5
10
15
20
25
30
35
40
45
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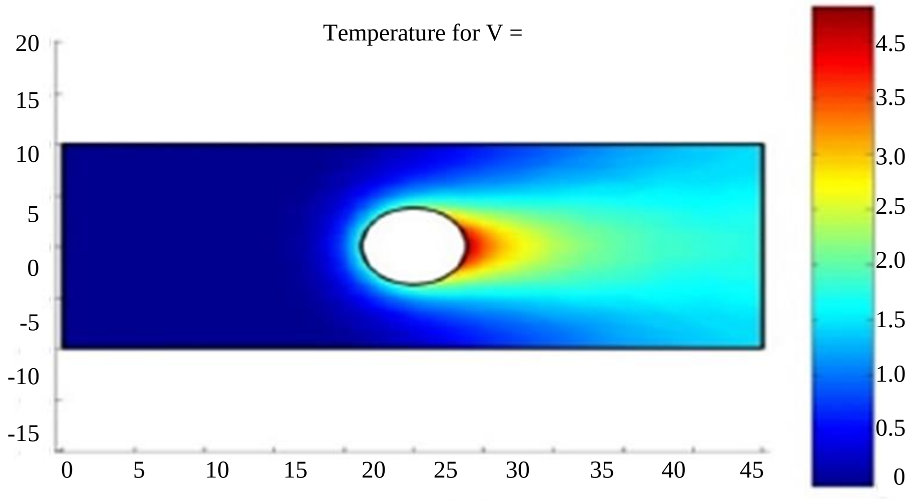
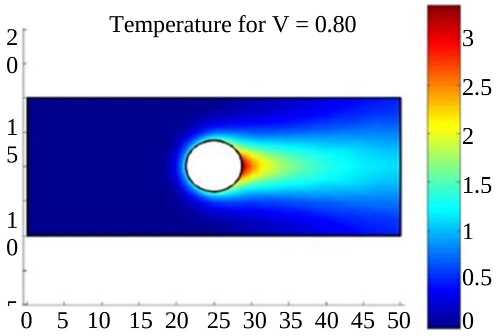
15
10
5


Temperature for V =
20
15
10
5
0
-5
-10
-15
0
5
10
15
20
25
30
35
40
45
4.5
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0


Temperature for V = 0.80
2
0
1
5
1
0
0
5
10
15
20
25
30
35
40
45
50
3
2.5
2
1.5
1
0.5
0

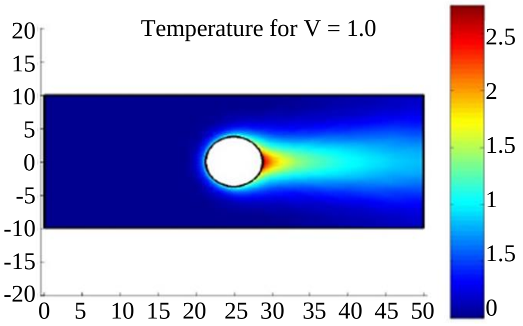
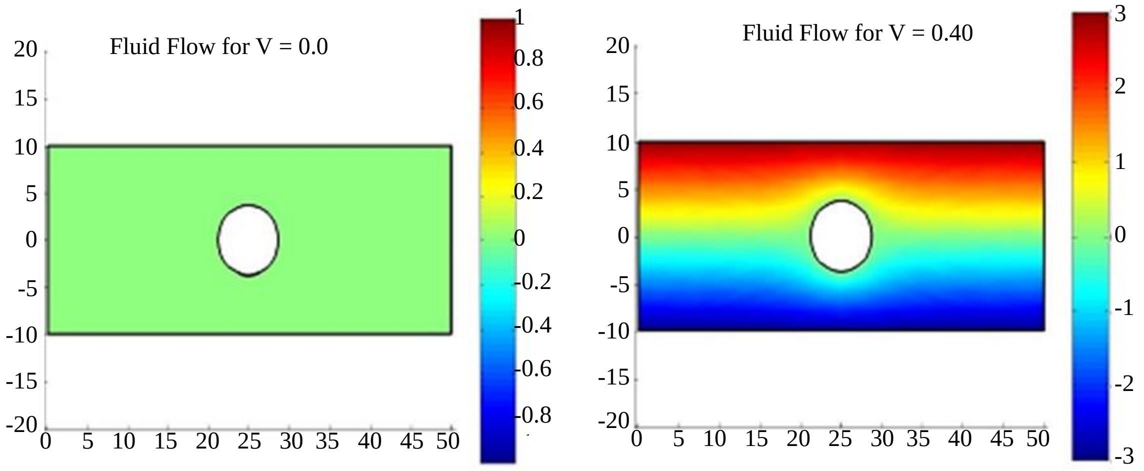

Temperature for V = 1.0
20
15
10
5
0
-5
-10
-15
-20
0
5
10
15
20
25
30
35
40
45
50
2.5
2
1.5
1
1.5
0

Figure 7. Temperature field for different values of entrance velocity.



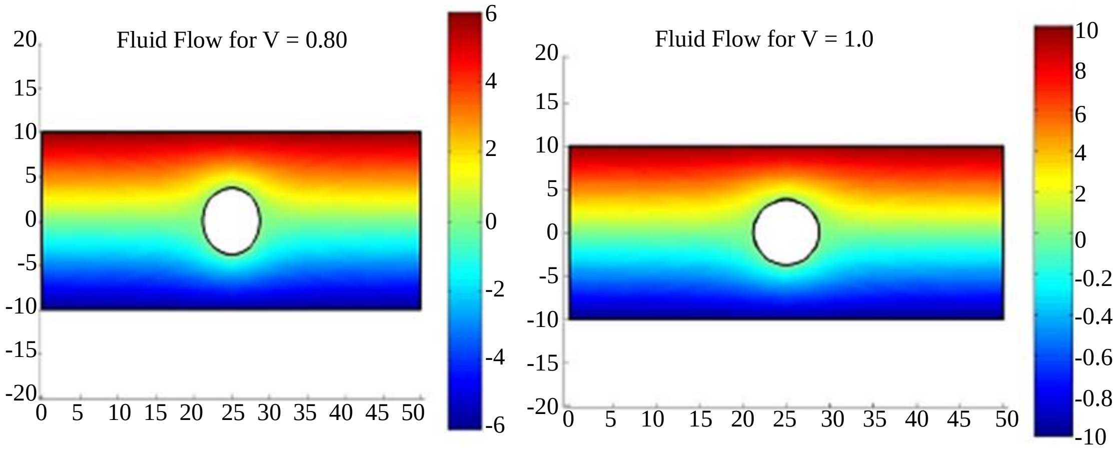


Figure 8. Variations in fluid flow with varying entrance velocities.

Temperature distribution analysis boundary conditions are in Figure 7. The central pipe may generate q units of energy per unit surface area per unit time. The exit, lower boundary, and higher boundary have 0 energy q, but the pipe input has 1. Assume zero entrance temperature flow φ. Define boundary conditions and coefficients, then analyze temperature distribution. Results are for ux=0.0, 0.40, 0.80, and 1.0 velocity. Figure 7 depicts flow field temperature distribution at different entrance velocities. With higher inlet velocity, temperature distribution reduces significantly. This supports the fact that convection transmits more heat than conduction. Figure 8 illustrates that heat transfer across the region is directly related to speed, lowering temperature near the middle heat source.

This study assumes two-dimensional flow without perpendicular direction changes. A partial differential equation represents flow domain. Fluid flow and temperature field effect pipe channel temperature dispersion in numerical simulations. The flow direction's broad pipe diameter makes local heat transfer less precise than the x and y directions. This resolution is excellent for industrial pipeline design and understanding fluid flow parameters in flow direction. The computer model shows that pipe intake and exit adiabatic barriers are challenging to build. Thus, low fluid flow loses a lot of heat to the surroundings. This means heat dissipation must be considered when analyzing heat transmission in a low-flow pipe.

CONCLUSIONS

The numerical simulation of fluid flow and temperature distribution in a pipe channel at varied entrance velocities is examined in this study. Finite Element Method (FEM) solves fluid flow partial differential equations. Fluid flow is depicted using a partial differential equation. Heat transfer is studied using the energy equation. Using the fluid's flow field, the temperature flow partial differential equations are solved. A thorough analysis of heat transmission flow structure and properties is conducted. The steady flow problem is solved using the fundamental and exact Finite Element Method (FEM). Differential equation and energy equation yield the formulation. The fluid flows upward, and heat transfer is solely conduction, according to the data. The study analyzes how a heat source affects temperature distribution. Our calculation matches basic geometries research in the literature, according to our examination. However, the simplicity of FEM measurements makes it suitable for assessing constant fluid movement.

FUTURE SCOPE

This research study suggests the following some future research:

In this research, we look at how different entrance velocities affect the fluid flow and temperature distribution in a simulated pipe channel using numerical simulation. The partial differential equations for fluid flow can be solved using the Finite Element Method (FEM). A partial differential equation is used to represent fluid motion. The energy equation is used to analyze heat transmission. The temperature flow partial differential equations are then solved using the flow field of the fluid. The nature and dynamics of the fluids involved in heat transmission are thoroughly analyzed. The standard and precise Finite Element Method (FEM) is used to resolve the steady flow problem. The formula is derived from the differential equation and the energy equation. According to the numbers, the fluid is moving upwards and the only mode of heat transfer is conduction. The effects of a heat source on local temperatures are investigated. Our analysis shows that our estimate agrees with basic geometry studies in the literature. Despite the ease with which FEM can be measured, it is best suited for evaluating steady flows.

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Data Availability

The authors affirm the presence of the study's data within the confines of this research paper.

Conflict of Interests

All of the authors made equal contributions to this paper and have no conflicts of interest.

Funding Statement

The present research paper is based on a B.Tech level investigation. The authors of the research paper affirm that no financial resources were utilized in the execution of this research paper.

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