

FLUID FLOW AND HEAT TRANSFER ANALYSIS IN A CONVERGING PIPE USING AL₂O₃-WATER NANOFLUID

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Abstract— With the demand for energy continuous to grow globally, there is a need to make heat transfer equipment more energy efficient. At one hand, the exponential growth of electronics, communication and computer technology and their choice to go for miniaturization has put added pressure on the designer to create efficient thermal management devices for the systems. Particularly thermal conductivity of a fluid plays a vital role in development of energy efficient heat transfer equipment. An innovative idea is to suspend nano-sized solid particles in the fluid to improve heat transfer characteristics of the fluid. Nano fluids are the suspension of nano meter sized particles in base fluids as such as water. In convective heat transfer, number of other factors along with thermal conductivity effects heat transfer performance, so careful examination of convective heat transfer using nanofluid is required. The CFD simulation of heat transfer characteristics of a nanofluid in a converging pipe under constant heat flux was considered using Fluent software in the laminar flow. Al₂O₃ nanoparticles in water with concentrations of 5%, 10%, 15%, 20%, 25% and 30% are used in this simulation.

IndexTerms— Nanofluid, Heat transfer, Simulation, Laminar flow

I. INTRODUCTION

Convective heat transfer can be enhanced passively by changing flow geometry, boundary conditions, or by enhancing thermal conductivity of the fluid. Various techniques have been proposed to enhance the heat transfer performance of fluids. Researchers have also tried to increase the thermal conductivity of the base fluids by suspending micro or larger-sized solid particles in fluids, since the thermal conductivity of the solid is typically higher than that of liquids.

Modern nanotechnology provides new opportunities to process and produce materials with average crystallite sizes below 100nm. Fluids with nano particles suspended in them are called nanofluids. Nanofluids can be considered to be the next generation heat transfer fluids because they offer exciting new possibilities to enhance heat transfer performance compared to pure liquids. They are expected to have superior properties compared to conventional heat transfer fluids, as well as fluids containing micro-sized metallic particles. The much larger relative surface area of nano particles, compared to those of conventional particles, should not only significantly improve heat transfer capabilities, but also should increase the stability of the suspensions. Also, nanofluids can improve abrasion related properties as compared to the conventional solid/fluid mixtures. The development of nanofluids is still hindered by several factors such as the lack of agreement between results, poor characterization of suspensions, and the lack of theoretical understanding of the mechanisms.

The recent advance in material technology has made it possible to produce innovative heat transfer fluids by suspending nanometer-sized particles in base fluids which can change the transport and thermal properties of the base fluid. Suspended nano particles in various base fluids can alter the fluid flow and heat transfer characteristics of the base fluids. The conventional understanding of the effective thermal conductivity of mixtures originates from continuum formulations which typically involve only the particle size/shape and volume fraction and assume diffusive heat transfer in both fluid and solid phase. This method can give a good prediction for micrometer or larger-size solid/fluid systems, but it fails to explain the unusual heat transfer characteristics of nanofluids.

Mobile electronic devices, such as wearable computers, mobile phones, personal digital assistants, mini-laptops, and others are becoming increasingly common and also getting smaller in sizes, but packed with higher power dissipation from their electronics components. Various cooling methods are available for keeping electronic devices within their operating temperature specifications. The methods are venting, enclosure fans, passive heat sinks, active heat sinks, heat pipes, thermal interfaces and metal back planes.

II. CFD THEORY AND EQUATIONS

The CFD approach uses a numerical technique for solving governing equations for a given flow geometry and boundary conditions. In this paper flow pattern and temperature distribution through a pipe are simulated using the FLUENT software.

2.1 GOVERNING EQUATIONS FOR NANOFLUID HEAT TRANSFER:

To simulate laminar forced convection of nanofluids through a pipe, the coupled continuity, X and Y momentum and energy equations are solved. The corresponding governing equations are given as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$\frac{u\partial v}{\partial x} + \frac{v\partial v}{\partial y} = \frac{\partial}{\partial x} \left(\mu \frac{\partial v}{\rho \partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial v}{\rho \partial y} \right) + g\beta(T - T_{\infty})$$

$$\frac{u\partial T}{\partial x} + \frac{v\partial T}{\partial y} = \frac{\partial}{\partial x} \left(\frac{k\partial T}{\rho c_p \partial x} \right) + \frac{\partial}{\partial y} \left(\frac{k\partial T}{\rho c_p \partial y} \right)$$

Where u,v are components of velocity vectors, T is the temperature, P is the pressure, ρ is the fluid density, μ is the effective viscosity of nanofluid, C_p is the heat capacity, β is the coefficient of thermal expansion and k is the effective heat conductivity of nanofluid.

2.2 DENSITY AND SPECIFIC HEAT:

The calculation of the effective density ρ_{eff} and the effective specific heat $C_{p,eff}$ of a nanofluid is straight forward. This can be estimated based on the physical principle of the mixture rule as

$$\rho_{eff} = \left(\frac{m}{V}\right)_{eff} = (m_b + m_p)/(V_b + V_p)$$

$$= \frac{(\rho_b V_b) + (\rho_p V_p)}{V_b + V_p} = (1 - \phi_p)\rho_b + \phi_p \rho_p$$

$$(\rho C_p)_{eff} = \rho_{eff} \left(\frac{Q}{m \Delta t}\right)_{eff} = \frac{\rho_{eff} (Q_b + Q_p)}{(m_b + m_p) \Delta t}$$

Which can be rewritten as

$$C_{p,eff} = \frac{(1 - \phi_p)(\rho C_p)_b + \phi_p(\rho C_p)_p}{((1 - \phi_p)\rho_b) + (\phi_p \rho_p)}$$

2.3 THERMAL CONDUCTIVITY:

Currently, there is no reliable theory to predict the anomalous thermal conductivity of nanofluids. It is known that thermal conductivity of nanofluids depends on parameters including the thermal conductivities of the base fluid and nano particles, the volume fraction, the surface area and the shape of the nano particles and the temperature. There are no theoretical formulae currently available to predict the thermal conductivity of nano fluids satisfactorily.

However, there exist several semi-empirical correlations for calculating the apparent conductivity of two-phase mixtures. They are mainly based on the following definition of the effective thermal conductivity of a two-component mixture.

$$k_{eff} = \left(\left(k_p \phi_p \left(\frac{dT}{dX} \right)_p \right) \right) + \left((k_b \phi_b) \left(\frac{dT}{dX} \right)_b \right) / \left(\left(\phi_p \left(\frac{dT}{dX} \right)_p \right) + \left(\phi_b \left(\frac{dT}{dX} \right)_b \right) \right)$$

According to Maxwell model the effective thermal conductivity is given by

$$k_{eff} = \frac{((k_p) + (2k_b) + 2(k_p - k_b)\phi)k_b}{(k_p) + (2k_b) - (k_p - k_b)\phi}$$

2.4.THERMO-PHYSICAL PROPERTIES OF BASE FLUIDS:

The base-fluid considered in this article is water. Thermo-physical properties of water are obtained as polynomial functions of temperature:

The water density is defined by

$$\rho_w = (-3.570 * 10^{-3} T^2) + 1.88T + 753.2$$

While the water viscosity is given by

$$\mu_w = 2.591 * 10^{-5} * 10^{\frac{283}{T-143.2}}$$

The thermal conductivity of water is calculated from

$$k_w = (-8.354 * 10^{-6} T^2) + (6.53 * 10^{-3} T) - 0.5981$$

The specific heat of water is considered constant as

$$C_{p,w}=4200$$

III. FLUENT ANALYSIS

SIMULATION OF SINGLE PHASE FLUID FLOW IN A CONVERGING PIPE:

It is well known that nano particles have very high thermal conductivity compared to commonly used coolant. Thus, the thermal conductivity and other fluid properties are changed by mixing the particle in fluid. The changed properties of the nanofluids determine the heat transfer performance of the pipe with nano fluids. This point is illustrated in this chapter by doing computational fluid dynamics (CFD) analysis of the hydrodynamics and thermal behavior of the pipe.

MODELING PROCEDURE:

The first step is to represent a two dimensional geometry of the pipe. It is divided into several cells.

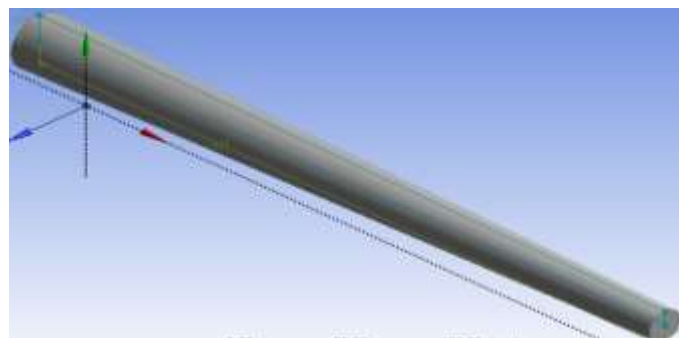


Figure.1.Pipe Geometry

Below figure shows the optimum grid of pipe. It is 400mm in pipe length direction (X) and radii for the converging pipe is 18mm, 10mm respectively. And a constant heat flux of 2670W/m² is applied over the wall. The range of Reynolds number and velocity of inlet flow are extracted from the experiment

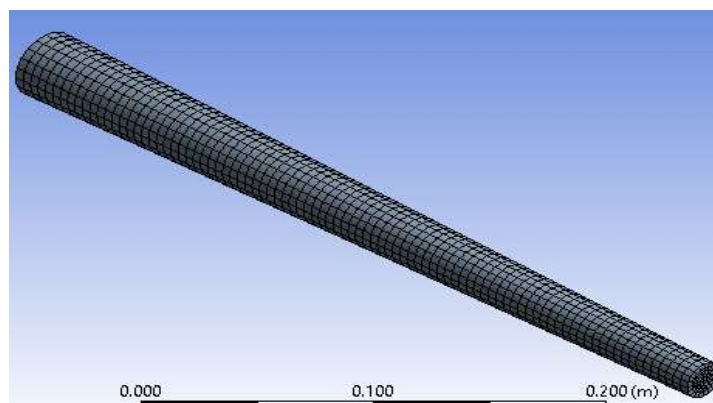


Figure.2.Pipe grid

PHYSICAL MODELS:

Based on the Reynolds number either viscous laminar model or standard k- ϵ model is used for laminar and turbulent flow respectively. The choice of the model is shown in table. choice of model based on Reynolds number

Table.1.Selection of model corresponding Reynolds number

REYNOLDS NUMBER	FLOW(MODEL)
<2000	Laminar
>2000	K- ϵ model

BOUNDARY CONDITIONS:

The boundary conditions for the inside the channel are prescribed as follows

- Inlet At the inlet, we prescribe velocity inlet and inlet temperature
 $V_x = V_{inlet}$, $V_y = 0$, $V_z = 0$, $T_{inlet} = 300K$
- Outlet At the outlet we set the pressure outlet for the tube outlet boundary condition and streamwise gradient of temperature is set to zero as the outlet velocity is not known a priori but needs to be iterated from the neighboring computational cells. This pressure is assumed to be in atmospheric pressure in outlet flow.
- The wall is in stationary state and no slip is applied to shear condition. And a heat flux of $2670W/m^2$ is applied

MATERIAL PROPERTIES:

Pure water is used as base working fluid and alumina(Al_2O_3) is taken as nano particles. The density, heat capacity and thermal conductivity of the alumina are $3600 kg/m^3$, $785J/kgK$ and $38W/mK$ respectively. The properties of nano fluid are given in table at 30 temperature and 100 kPa pressure. Water based fluid properties with different concentrations of alumina particles are

Table.2.Fluid properties

$Al_2O_3 - H_2O$				
VOLUME FRACTION	$\rho(kg/m^3)$	$C_p(J/kgK)$	$k(W/mK)$	$\mu(kg/ms)$
5%	4370	945.375	0.68989	0.00188
10%	4136.31	978.43	0.7895	0.003603
15%	3910	1021.45	0.899	0.00688
20%	3680	1066.3	1.022	0.013166
25%	3450	1117.826	1.161	0.02516
30%	3220	1176.33	1.3191	0.04811

METHOD OF SOLUTIONS:

The computational domains are created and meshed by using ANSYS WORKBENCH. An appropriate boundary conditions and constitutive relations comprising of five dependent variables. u , v , w , p and T are solved using the finite volume solver FLUENT. User-defined functions (UDF) are written in C language to account for particle volume concentration and temperature – dependence of the thermo – physical properties of the nanofluid.

The pressure based solver is used for the calculation. Second-order upwind interpolation scheme is applied for the momentum and energy calculations. The COUPLED algorithm is chosen for the pressure velocity coupling. Fluent solves the linear system resulting from discretization scheme using a point implicit(Gauss Seidel) linear equation solver in conjunction with an algebraic multigrid method. During the iterative process, the residuals are carefully monitored. The laminar model is used during the calculations. Convergence of the numerical solution is assured by monitoring the scaled residuals to a constant level below 10^{-6} for each variable. The default values of under-relaxation factor as shown in table are used in simulation work.

Table.3.Relaxation factor

PARAMETERS	UNDER-RELAXATION FACTOR
MOMENTUM	0.75
PRESSURE	0.75
ENERGY	1
DENSITY	1
BODY FORCES	1

IV. RESULTS AND DISCUSSIONS

The numerical simulations are carried out for a converging pipe with Al₂O₃/water nano fluid with different volume fractions. The physical parameters for the simulation are listed below

Table.4.Physical Parameters of Nanofluid

PARAMETERS	VOLUME FRACTION OF NANOFLUID						
	WATER	5%	10%	15%	20%	25%	30%
Pressure drop (Pa)	0.3225	0.3225	0.3744	0.688	1.278	2.4014	4.5624
Outlet velocity (m/s)	0.0225	0.0225	0.02265	0.0226	0.0226	0.0225	0.0225
Outlet temperature (K)	304.2	304.2	314.48	312.951	311.55	310.325	309.208
Surface heat transfer coefficient (W/m ² K)	211.88	211.88	147.638	164.527	183.716	205.434	230.423
Thermal conductivity (W/mK)	0.6	0.6	0.72	0.822	0.933	1.0568	1.1956
Skin friction coefficient	0.00095	0.00095	0.001139	0.002	0.0038	0.0071	0.0135

From the table it has been concluded that by increasing the volume fraction of the nano particles the heat transfer coefficient increases with increase in pressure drop and the main reason for increase is that increase in thermal conductivity.

PRESSURE GRAPH:

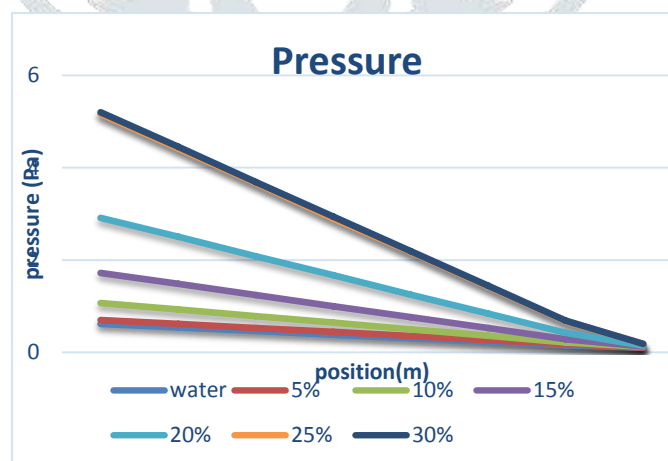


Figure.3.pressure contours between position vs Pressure

The pressure variation across the pipe with various fluids is shown above.

TEMPERATURE GRAPHS:

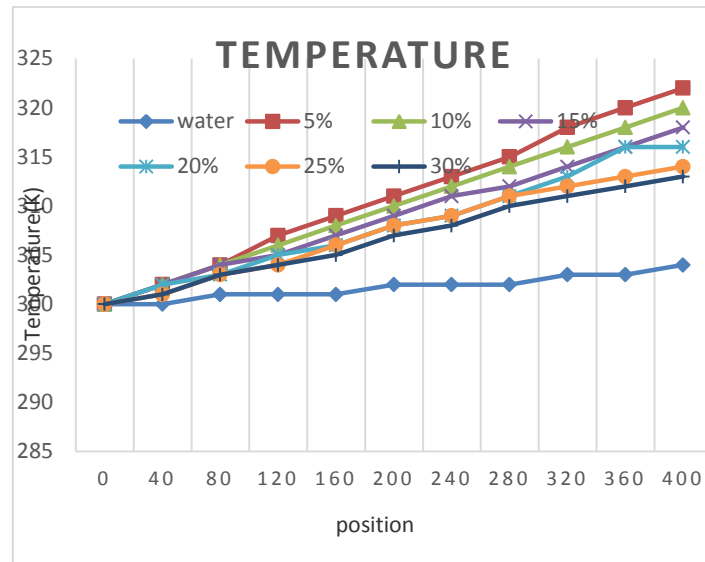


Figure.4. Temperature contour in between position vs temperature

HEAT TRANSFER COEFFICIENT GRAPH:

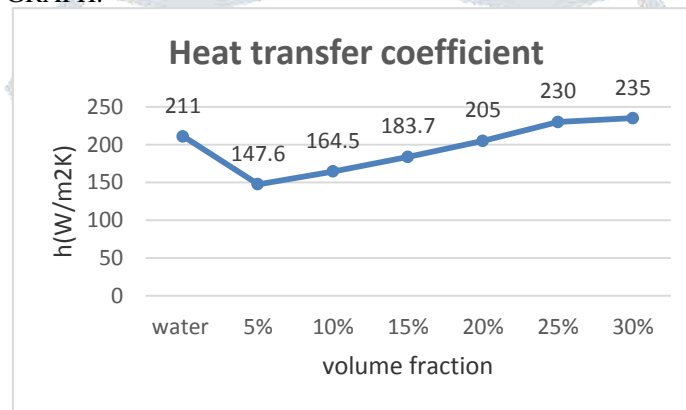


Figure.5. Heat Transfer coefficient plot between volume fraction vs heat transfer coefficient

THERMAL CONDUCTIVITY GRAPH:

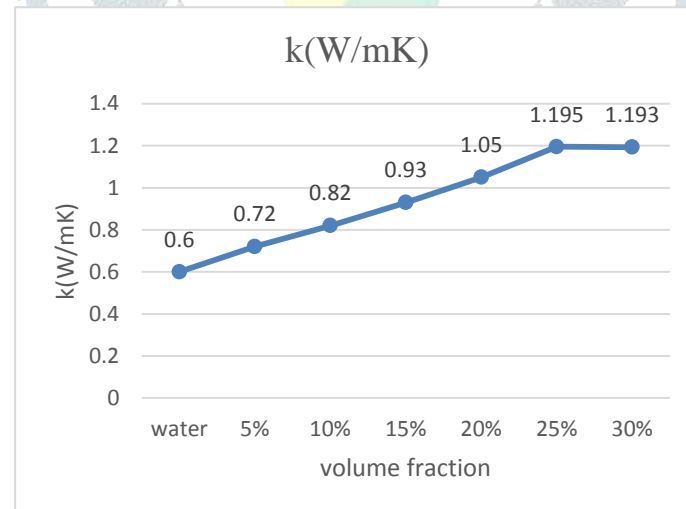


Figure.6. Thermal conductivity graph between volume fraction vs Thermal conductivity

TEMPERATURE CONTOUR OF NANOFLUID:

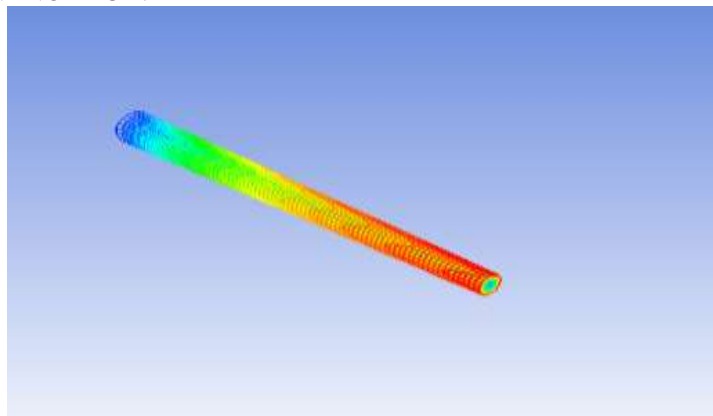


Figure.7.Temperatre Contour of Nanofluid

TEMPERATURE CONTOUR OF WATER:

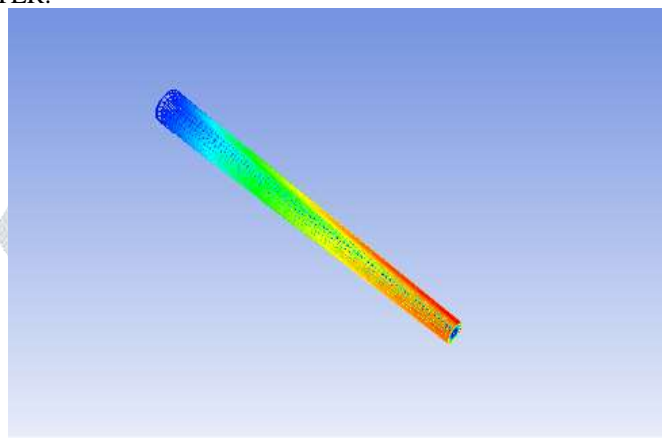


Figure.8.Temperature contour of water

From the above temperature contours, it has been clearly observed that the heat transfer takes place from the center of the pipe while using the nanofluid bit in the case of water the heat transfer takes place from the end of the pipe

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