

CFD ANALYSIS OF FUEL CELL

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE AWARD OF THE DEGREE OF
MASTER OF TECHNOLOGY
IN
THERMAL ENGINEERING

Submitted by:

MOHIT KUMAR SINGH
(2K21/THE/11)

Under the supervision of

PROF. RAJ KUMAR SINGH



DEPARTMENT OF MECHANICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

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CANDIDATE'S DECLARATION

I, Mohit Kumar Singh (2K21/THE/11) student of M.Tech (Thermal Engineering), hereby declare that the Project Dissertation titled — “CFD Analysis of Fuel Cell” which is submitted by me to the Department of Mechanical Engineering, DTU, Delhi in fulfillment of the requirement for awarding of the Master of Technology degree, is not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Fellowship or other similar title or recognition.

Place: New Delhi

Date: 31/05/2023

Mohit Kumar Singh

(2K21/THE/11)

CERTIFICATE

I hereby certify that the Project titled “CFD Analysis of Fuel Cell” which is submitted by Mohit Kumar Singh (2K21/THE/11) for fulfillment of the requirements for awarding of the degree of Master of Technology (M.Tech) is a record of the project work carried out by the student under my guidance & supervision. To the best of my knowledge, this work has not been submitted in any part or fulfillment for any Degree or Diploma to this University or Elsewhere.

Place: New Delhi

Date: 31/5/2023

Prof. Raj Kumar Singh

(SUPERVISOR)

Professor

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Delhi Technological University

ABSTRACT

PEM fuel cells are a promising alternative to fossil fuels in automotive applications and sustainable power-generating technology. One of the major obstacles to the commercialization of these cells is their thermal management. A thermal management system's main task is to keep the required temperature constant, ensuring that the stack and each of its component membranes gets heated uniformly. This work presents a numerical analysis of thermal enhancement for a single cooling plate for a proton exchange membrane fuel cell (PEMFC). A uniformly distributed parallel channel cooling plate measuring 210 x 220 mm and equipped with 19 parallel microchannel of 1 x 4 x 112 mm was utilized to cool PEMFC. The cooling plate was made of carbon graphite material. The SiO_2 , Al_2O_3 and ZnO were used as a cooling agent. Simple geometry and modified geometry is used for simulation. The 0.5% volume concentration of SiO_2 , Al_2O_3 and ZnO based on water is the study's main topic. The heating pad was chosen as the source term, which has a single energy source with the value of $1298701 W/m^3$ and is taken to be constant. Regarding the boundary conditions, the input velocity of water was adjusted between a 400–2000 Reynold Number range. The result showed that when compared to another nanofluid, the ZnO nanofluid's (with modified geometry) thermal performance was found to be better at 2000 Reynold Number. The favorable thermal outcomes suggested that ZnO nanofluid with modified geometry could be a better choice for upcoming uses in PEM fuel cell as coolant.

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The successful completion of any task is incomplete and meaningless without giving any due credit to the people who made it possible without which the project would not have been successful and would have existed in theory.

First and foremost, I am grateful to **Dr. S K Garg**, HOD, Department of Mechanical Engineering, Delhi Technological University, and all other faculty members of our department for their constant guidance and support, constant motivation and sincere support and gratitude for this project work. I owe a lot of thanks to our supervisor, **Prof. Raj Kumar Singh**, Professor, Department of Mechanical Engineering, Delhi Technological University for igniting and constantly motivating us and guiding us in the idea of a creatively and amazingly performed Major Project in undertaking this endeavor and challenge and also for being there whenever I needed his guidance or assistance.

I would like to thank **Gaurav Kumar (2K17/PhD/ME/57)** (PhD Scholar, Delhi Technological University) for his help in this work from Design Centre Lab, DTU Delhi. His valuable guidance is useful for me throughout this work.

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Mohit Kumar Singh
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LIST OF SYMBOLS AND ABBREVIATIONS

φ	Particle Volume Fraction
ρ_{nf}	Density of nanofluid
ρ_{bf}	Density of base particle
ρ_{np}	Density of nanoparticle
$C_{p_{nf}}$	Specific heat of nanofluid
K_{nf}	Thermal conductivity of nanofluid
K_{bf}	Thermal conductivity of base fluid
K_{np}	Thermal conductivity of nano particle
nf	Nanofluid
bf	Base fluid
np	Nano particle
Al_2O_3	Aluminum Oxide
SiO_2	Silicon Dioxide
ZnO	Zinc Oxide
H_2O	Water
CO_2	Carbon Dioxide
h	Heat transfer coefficient
$T_{avgplate}$	Average plate temperature
$T_{avgfluid}$	Average fluid temperature
Nu	Nusselt number
D_h	Hydraulic Diameter
\dot{V}	Volume flow rate
W_{pump}	Pumping power
ΔP	Pressure Drop

CHAPTER-1

INTRODUCTION

An energy conversion device using electrochemistry known as fuel cell (FC) transforms chemical energy of fuel into electrical energy. Numerous researchers are searching for new, effective energy conversion technologies because of the rising demand for energy, the need for clean energy production, and other environmental concerns [1]. Due to their many practical benefits, including their high energy density, low environmental impact, strong dynamic response, and light weight, FC systems may be seen as a feasible alternative in this perspective. Fuel cells are classified as polymer membrane, alkaline, phosphoric acid, molten carbonate, and solid oxide depending on the type of electrolyte material used [2]. The PEM fuel cell has distinctive characteristics that make them the most optimistic system for power generation in the applications such as automotive, distributed power generation, and portable electronic devices [3]. These characteristics include a low operating temperature, high power density, quick start, rapid response, and high modularity.

1.1 Background of Fuel Cell

Sir William Grove revealed the fundamental workings of FCs to the scientific community for the first time in 1839. Grove later created a 50-cell stack in 1842 and gave it the term "gaseous voltaic battery". It took over a century after Grove's development before the FCs were once again made available to scientists. F.T. Bacon started working on practical FC in 1937, and by the end of the 1950s, he had successfully constructed a stack with a 6 kW output. Grubb and Niedrach constructed a fuel cell in the early 1960s employing solid ion-exchange membrane electrolyte. Sulfonated polystyrene-based membranes were initially used as the electrolytes; immediately after, Nafion membranes were substituted for these membranes. The Nafion membrane is the most often used one despite being shown to be more effective and durable. This form of FC is also known as a proton exchange membrane fuel cell (PEMFC). Initially, sulfonated polystyrene-based membranes were used as the electrolytes, and immediately after that, Nafion membranes were used in their place.

PEM fuel cells (PEMFC), which General Electric created based on the work of Grubb and Niedrach, were initially utilised in the Gemini space programme in the early 1960s. The FC was used in the Apollo programme, which came after the Gemini programme, to generate energy for communications and life support. Based on the Bacon's patents, Pratt and Whitney produced these FCs.

FC systems were only used in a few specialised applications and in space applications due to their expensive cost. Ballard Power Systems began working on PEMFC systems in 1990. Ballard's aim was to lower the price of the fuel cell by utilising inexpensive materials and construction techniques, which led to FC becoming a viable choice for many applications. Ballard Power Systems introduced fuel cell-powered buses in 1993.

Energy Partners unveiled the first PEMFC-powered passenger vehicle in 1993. By the turn of the century, nearly all automakers had taken notice of this activity and had developed and produced a fuel cell-powered vehicle.

1.2 Benefits of Fuel Cells Compared to Conventional Engines

The fuel cell turns the chemical energy of the fuel and oxidant straight into electricity. When H_2 is utilised as a fuel, the fuel cell emits no hazardous emissions, in contrast to the combustion engine. In this sense, sometimes fuel cells are referred to as "zero emission engines.". Fuel cells are silent and long-lasting because they don't have any moving parts. Since hydrogen may be created from a variety of fossil and renewable energy sources (hydrogen-rich gases like natural gas, biogas, and producer gas), the fuel adaptable technology is a key component of fuel cells. The three benefits of the fuel cell—high efficiency, little or minimal pollutant emissions, and fuel flexibility—make it a highly desirable power generation technology with significant potential.

1.3 Fuel Cell Concept

The electrochemical process that occurs between oxygen and hydrogen to make water in fuel cells generates energy and heat. Today, combined heat and power (CHP) systems and fuel cell systems are widely used in small and large-scale applications. Mobile power systems include, but are not limited to, portable power systems, portable computers, and military communication devices [4]. It is a substance design technique for supplying energy through electrochemical redox processes that happen at the cathode and anode of

the cell. The power module guarantees a clean, highly effective energy source that may be designed to consume an almost infinite supply of fuel.

Similar to a battery, it generates current from an external source of fuel and oxygen, as shown in Figure 1 [30], and is made to allow for the ongoing replacement of the reactant used. There are two cathodes and an electrolyte in each energy component.

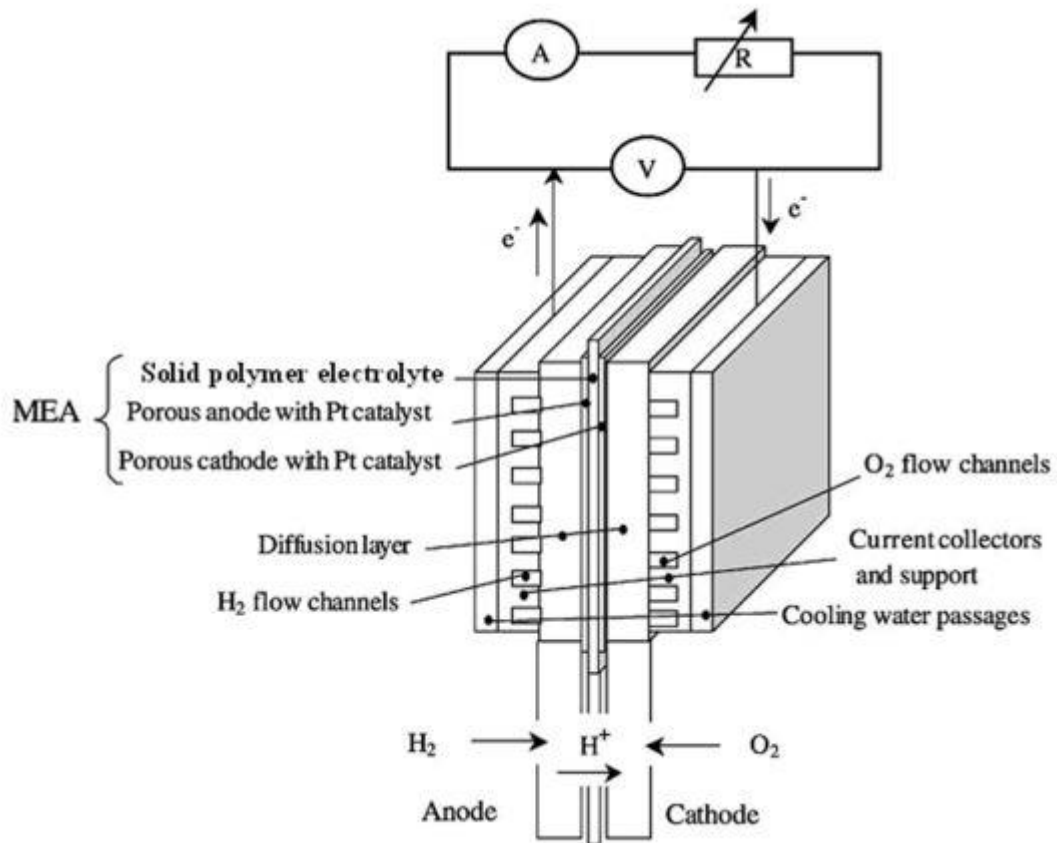


Fig. 1 Basic Fuel Cell Components [30]

The cathode and anode, which are the two terminals, are designated as -ve and +ve, respectively. They permit the responses that, and the electrolyte plays a crucial role in ensuring that only the right particles can flow between the anode and the cathode. The synthetic response and the impetus work, which accelerates the reactions at the cathodes, would be disrupted if free electrons or other substances could pass through the electrolyte [5]. Energy units have emerged as the primary alternative to the gas-powered engine and other devices with lower energy thickness power capacities, such as batteries, due to their amazing attraction for producing power with almost no pollution. The majority of the hydrogen from the fuel and the oxygen used to generate electricity eventually combine

to form a harmless substance, particularly water. The goal of a power device is to provide an electrical flow that can be directed away from the phone to handle tasks like lighting a light or powering an electric engine. An energy unit generates electricity artificially rather than by ignition and is therefore exempt from the four thermodynamic restrictions that govern a typical power plant. In this sense, power modules are better at obtaining energy from a fuel. Additionally, waste heat from certain cells can be restrained, increasing the efficiency of the framework. Because of the way power behaves, the electrical circuit is completed when the current from a power source returns to the cell. Accordingly, the way an energy component works depends on the chemical reactions that collect this electrical current.

1.4 Classification of Fuel Cells

There are many different kinds of fuel cells that have been created. Since the electrolyte restricts the operating temperature and the kind of fuel that can be used, they are typically categorised based on the type of electrolyte that is utilised.

1.4.1 Alkali Fuel Cell

An alternative to polymer electrolyte layer power modules is alkaline fuel cells (AFC). They operate on compressed H_2 and O_2 . Typically, they use water mixed with a KOH solution as their electrolyte. From potassium KOH, the -OH particle (goodness) travels from the cathode to the anode [6].

H_2 gas reacts with the goodness particles at the anode to produce water and deliver electrons.

An outside circuit receives electrical capacity from electrons created at the anode before returning to the cathode. There, the electrons (e^-) react by releasing a large number of -OH particles that diffuse into the electrolyte together with O_2 and water. Its efficiency is roughly 70%, and its operating temperature ranges from 90 to 100 °C. As with other energy components, the AFCs' cell output ranges from 0.3kW to 5kW and produces almost no pollution [7]. They have been a wise choice for rocket because they provide edible water in addition to power. However, the fact that antacid cells require exceptionally pure hydrogen is a big drawback. If an unfavourable material reaction occurs, a strong carbonate is formed, which interferes with the reactions of other

compounds inside the cell. Since most methods for producing H_2 from various sources also produce some CO_2 , the need for pure H_2 has slowed down development of antacid power devices in recent years [7]. Another drawback is the need for enormous quantities of an outrageous platinum impetus to speed up the reaction. Antacid power units were chosen by NASA for the Apollo programme and the Space Transport armada mostly due to their force-creating efficiency, which are close to 70%. The space travellers can also get drinking water from salt cells.

The cells are expensive; the platinum terminal impetus may make this fuel type too expensive for commercial use, and these energy units can spill just like any other container filled with liquid. Nevertheless, several organisations are working to improve the flexibility of the cells and find ways to reduce expenses.

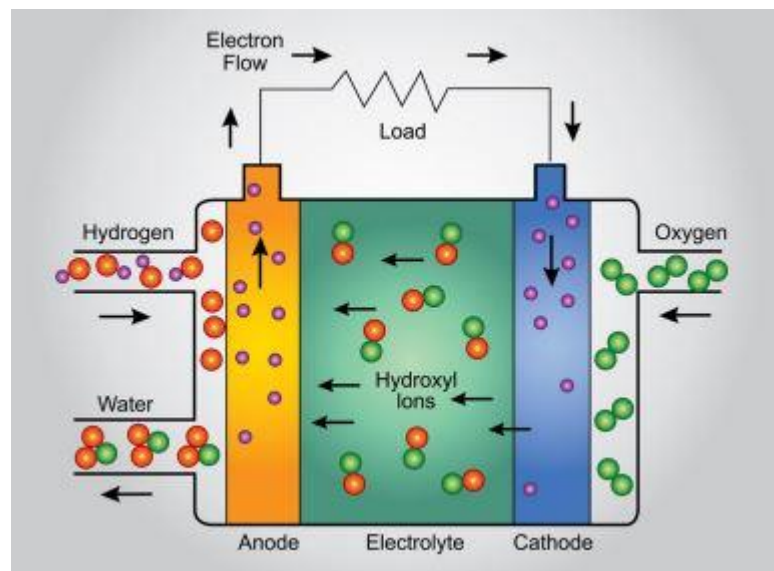


Fig. 2 Alkali fuel cell (AFC) [30]

1.4.2 Molten Carbonate Fuel Cell

A high-temperature salt compound, such as sodium or magnesium carbonates, serves as the electrolyte in a molten carbonate fuel cell (MCFC), as depicted in Fig. 3 [30] (Brouwer et al., 2005; Alkanar and Zhoau, 2006). It has an efficiency range of 56 to 78 percent and an operating temperature of approximately 652 °C. The MCFC power yield is dependent on 2MW. The high operating temperature of the cell prevents the cell from being harmed by CO, and waste intensity can also be recycled to produce additional

power [8]. Their nickel terminal impetuses are less expensive than the platinum used in other cells, but the high operating temperature also restricts the materials and health benefits of MCFCs, making it too hot for use in homes. The complexity of using a fluid electrolyte rather than a strong electrolyte is a significant problem with liquid carbonate innovation. A liquid carbonate cell's substance reaction provides a further one. It is crucial to compensate by injecting carbon dioxide at the cathode because carbonate particles from the electrolyte are expended in the reactions at the anode. When the electrolytes in an MCFC are heated to 652 °C, they dissolve and transfer carbonate particles (CO_3^{2-}) from the cathode to the anode. Hydrogen reacts with the particles at the anode to produce water, carbon dioxide, and electrons [8]. When the electrons return to the cathode, the O_2 from the air and CO_2 recycled from the anode react with the electrons to form CO_3^{2-} , which recharges the electrolyte and transmits current through the power module. The electrons travel through an outer circuit, providing electrical power along the way. Due to its high operating temperature, MCFC is only requested by large stationary power plants. The possibility of using the side-effect waste energy to produce steam for space warming, modern handling, and a steam turbine suited for producing more power is made possible by the high working temperature of the cells.

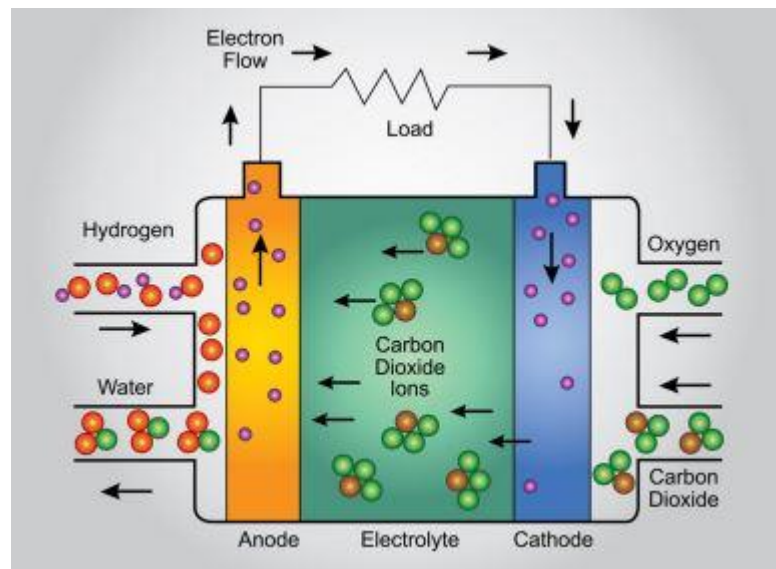


Fig. 3 Molten Carbonate Fuel Cell [30]

1.4.3 Phosphoric Acid Fuel Cell

Energy crises in the 1970s inspired experts at the Los Alamos Public Research Centre to begin focusing on power gadgets. They had the choice to design a golf truck that was propelled by a phosphoric corrosive fuel cell because their objective was to develop electric cars. The current availability of phosphoric acid fuel cells (PAFCs) requires preparation time, which has limited their use in private vehicles. The efficiency rate of phosphoric acid fuel cells (PAFCs) ranges from 40% to 50%, but if waste volume is treated again in a cogeneration system, productivity can increase to 80% [9]. Existing PAFCs with 200 kW limit caps are operational, while units with 11 MW cap caps have been tried. Phosphoric corrosive is used as the electrolyte in phosphoric acid fuel cells (PAFCs), which operate between 149.9°C and 200°C. Platinum impetus at the anodes accelerates response times [4]. Hydrogen atoms that are strongly charged travel from the anode to the cathode through the electrolyte. The anode produces electrons, which travel through an external circuit, supplying electricity along the way before returning to the cathode. Hydrogen and oxygen atoms combine to form water at the cathode. The range of energies that PAFCs can use is expanded by the 1.50 percent carbon monoxide centralization they experience. If petrol is being used, the sulphur needs to be removed. Platinum anode impetuses are necessary, and interior components should be able to withstand the corrosive's damaging effects.

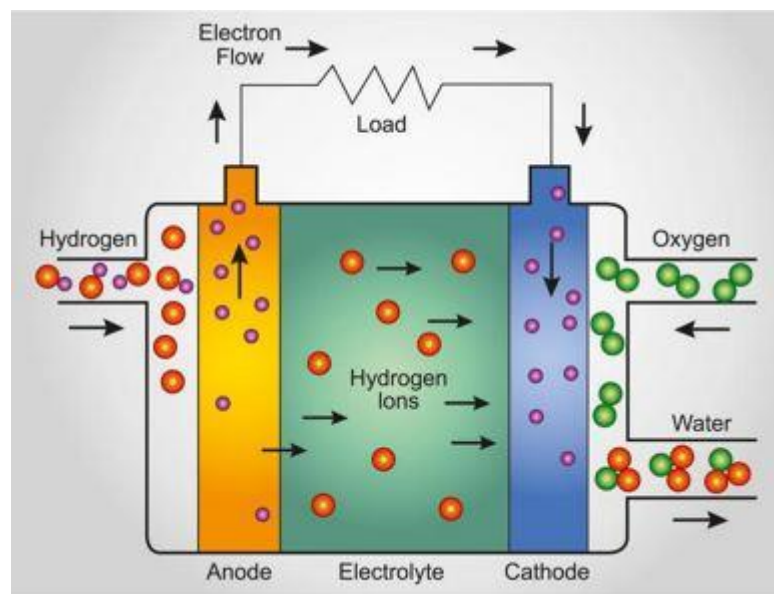


Fig. 4 Phosphoric Acid Fuel Cell [30]

1.4.4 Solid Oxide Fuel Cell

Solid oxide fuel cells (SOFCs) are the best choice for large-scale stationary power generators that can provide communities and processing facilities with electricity. Although other oxide mixtures have also been used as electrolytes, the SOFCs use a hard ceramic metal compound, like CaO, as the electrolyte. Particular permeable anode materials are placed on either side of the strong electrolyte to cover it. The cell efficiency is roughly 60%, and the working temperatures are around 1000°C. The SOFCs' high operating temperatures enable them to simultaneously produce waste heat and steam for space warming, contemporary handling, or to generate more power in a steam turbine [10]. At very high temperatures, oxygen atoms (which have a negative charge) flow through the gem's cross section. In order to oxidise the fuel, a series of negatively charged oxygen particles flow through the electrolyte whenever a fuel gas containing hydrogen is ignored by the anode. At the cathode, oxygen is normally supplied by air.

During their journey from the anode to the cathode, the electrons they produce complete the circuit and supply electricity. Due to the high operating temperatures, a reformer isn't anticipated to separate hydrogen from the fuel in SOFCs, and waste energy can be recycled to produce further power. The output of SOFCs ultimately depends on 100 kW.

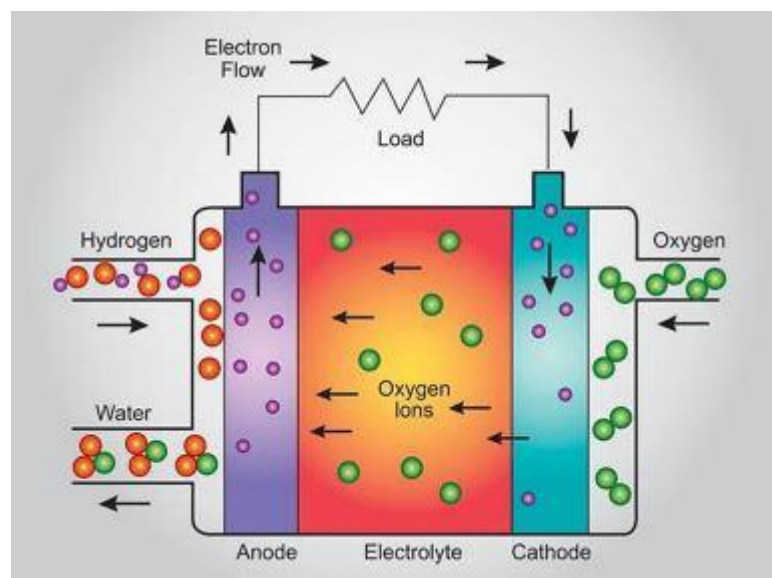


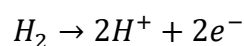
Fig. 5 Solid Oxide Fuel Cell [30]

1.4.5 Proton Exchange Membrane Fuel Cell

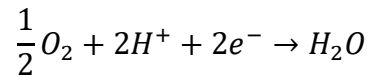
One of the energy unit types which is most promising for widespread application is PEMFC. They are extremely adaptable to various loads and very simple to construct. The PEM energy unit transfers protons from the anode to the cathode using a thin penetrable sheet made of a high level plastic electrolyte [11]. In comparison to a fluid partner, the PEMFC's strong electrolyte is much easier to handle and use, and its low operating temperature enables a quick start-up. A platinum impulse is applied to the layer's two sides to hasten the response. The working temperature for PEMFCs is about 80°C, and their productivity ranges between 40 and 50 percent [12]. The majority of cell yields fall between 50 and 250 kW. The robust, flexible electrolyte won't crack or hole, and these cells operate at a low enough temperature to be practical for use in homes and automobiles. When hydrogen atoms from fuel sources lose all of their electrons in PEMFCs, the highly charged protons move away from the anode and through one side of the permeable layer towards the cathode. The electrons carry electric power as they move from the anode to the cathode through an additional external circuit. At the cathode, air molecules of oxygen, hydrogen protons, and electrons combine to form water. In order for this energy component to function, the proton exchange layer electrolyte must allow hydrogen protons to pass through while preventing the passage of electrons and heavier gases.

Both hydrogen fuel cells and direct methanol fuel cells (DMFC) use proton exchange layers (PEMs) to transfer protons, making them two different types of proton trade layer energy components. Hydrogen Fuel is a good choice because of its powerful energy component and superior performance. Similarly, hydrogen-powered devices are the most environmentally friendly energy sources because they produce water as a by-product. However, the lack of capacity and delivery infrastructure makes it difficult to use hydrogen; as a result, regulation and dispersion concerns must be resolved before hydrogen fuel can be used widely for commercial reasons.

The main advantage of hydrogen is that it may be catalysed efficiently even in mild conditions; at the anode, hydrogen is oxidised to liberate two electrons and two protons.



The electrons move through the electronic circuits as the protons are directed from the impetus layer through the proton trading layer. There is less oxygen at the cathode.



Platinum or ruthenium can be used to catalyse reactions on carbon dark support, which expands the surface area of the heterogeneous impetus region to increase utilisation and reduce carbon monoxide harm at the cathode.

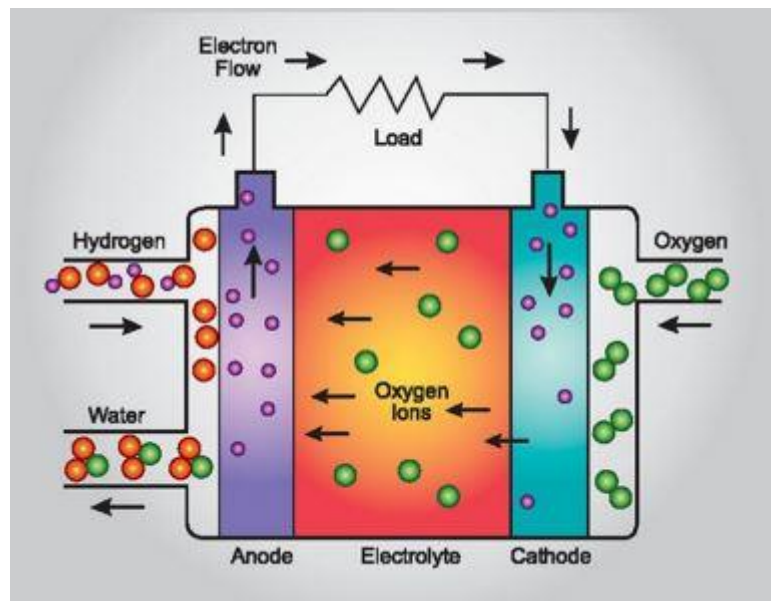


Fig. 6 Proton Exchange Membrane Fuel Cell [30]

1.5 Components of PEM Fuel Cells

PEM fuel cells are made up of a number of components composed of various materials. The membrane electrode assembly (MEA), which is the core of a PEM fuel cell and is made up of membrane and catalyst layers, gas diffusion layers, bipolar plates, current collectors, and end plates, is the major component of a PEM fuel cell.

1.5.1 Polymer Electrolyte Membrane (PEM)

The polymer electrolyte membrane, also known as a proton exchange membrane, is typically made of poly [perfluorosulfonic] acid with a polytetrafluorethylene (PTFE)

support structure. This membrane conducts only positively charged ions while blocking electrons. The PEM is the most crucial part of the fuel cell since it generates the potential difference between the anode and the cathode, which acts as the catalyst for the electron to move from the anode to the cathode externally.

1.5.2 Catalyst Layers

The anode layer and the cathode layer are inserted as catalyst layers on either side of the membrane. These catalytic layers contain high-surface-area carbon with platinum nanoparticles distributed in them. This ionomer-mixed platinum catalyst on carbon support is placed between the membrane and the GDLs. Hydrogen molecules divide into protons and electrons on the anode side in the presence of the platinum catalyst. Water is created on the cathode side when oxygen is reduced on the platinum surface through a reaction with protons and electrons. The paths for the proton to pass through the catalyst layers and arrive at the catalyst sites are created by the ionomer incorporated in these layers.

1.5.3 Gas Diffusion Layers

Transport of reactants into the catalyst layer as well as removal of generated water from the CLs to the channels of the flow field are made easier by the GDLs that are situated between the catalyst layers and the bipolar plates on each side. GDLs are formed of polytetrafluoroethylene (PTFE)-coated carbon fibres in the form of carbon paper or fabric. Gases quickly diffuse via the GDL's pores. The amount of reactants diffused to the catalytic layer may be lessened as a result of the water buildup in the GDL. The GDLs' high electrical conductivity, which is a result of their composition of carbon elements, enables the generated electrons to pass through them.

1.5.4 Bipolar Plates

In most cases, bipolar plates are constructed of graphite, which has strong electrical conductivity for electrons and also gives the cell good physical robustness. Since flow channels are often designed with grooves on their surface, they also serve as flow field

plates. The reactants are more evenly distributed over the entire cell active area thanks to these channel configurations.

1.5.5 Gaskets

Gaskets must be put around the MEA's edges when it is sandwiched between two bipolar plates in a fuel cell to stop reactant gas leakage. The majority of these gaskets are constructed from a rubbery polymer.

1.5.6 Current Collectors

Copper is a primary component of current collectors due to its high electron conductivity. To get to the current collectors, the electrons that are produced on the anode side pass through the catalyst layer, GDL, and bipolar plates. On the cathode side, however, bipolar plates and the GDL allow electrons to travel from the current collectors to the catalyst layer. These externally linked current collectors on the anode and cathode sides assist the passage of produced electrons from the anode to the cathode by closing the circuit.

1.5.7 End Plates

All the fuel cell parts are maintained in place by end plates that are positioned at the rear of the anode and cathode sides. Due to its excellent thermal conductivity, aluminium is used as the primary material in these plates. These plates assist in dissipating the waste heat produced during fuel cell operation to the surroundings.

1.6 Thermal Management of Fuel Cell

Cooling can be accomplished in a number of ways. On the other hand, cooling fins and heat sinks can be used to passively cool the fuel cell. Turbine reheaters, metal hydride containers, and other subsystems that absorb heat can also be connected to the fuel cell. In PEMFCs, some heat is absorbed at the cathode by the evaporation of some product

water, and radiators can be heated actively using air or liquid coolants. The majority of fuel cell stacks need a cooling system to keep the stack's temperature uniform. Despite environmental variations in temperature, humidity, vibration, and impact, portable fuel cells must retain the proper temperature.

There are straightforward fuel cell system designs with cooling channels cut into the bipolar plates or cooling plates put into the stack. A coolant pump circulates the coolant through the system after it has been cooled by a heat exchanger. Thermocouples or temperature sensors are frequently found in the stack, and they provide feedback to a flow controller, which modifies the flow based on the amount of coolant needed. Every sort of fuel cell system can be cooled using a variety of techniques and configurations. The following are some of the stack cooling options:

1.6.1 Cooling Through Free Convection

Free convection is one of the most straightforward ways to cool a fuel cell stack. This technique can be used for tiny or low-power fuel cell stacks because it doesn't call for intricate designs or coolant. Fins can be produced for heat dissipation, or an open cathode flow field design can be used. Because the cooling is heavily dependent on the ambient temperature and humidity, this cooling technology does not provide effective temperature control. It is equally challenging to use free convection to recover waste heat for power.

1.6.2 Cooling Using a Condenser

The stack can run at higher temperatures thanks to condenser cooling than with other forms of cooling. Water from the exhaust can condense and then be reintroduced into the stack in PEM fuel cells. In order to prevent the system as a whole from either gaining or losing water, the condenser must be kept at the water balance temperature. As in stack cooling plate systems, this system needs precise temperature control.

1.6.3 Cooling Using Heat Spreaders

Adding heat spreaders to a stack is an additional cooling method. Outside the stack, heat transfer is evidently more effective. Through conduction, heat spreaders can assist in transferring heat to the exterior of the stack, where it can subsequently be released into the environment by natural or forced convection. High-performance heat spreaders must be utilised if this method is used.

1.6.4 Cooling Using Cooling Plates

Cooling plates are widely used for fuel cell stack cooling. Thin cooling plates can be created and placed inside the fuel cell, or additional channels can be cut into the bipolar plates to let air, water, or coolant flow through the channels to remove heat from the stack. One coolant recirculation path can suffice as the sole component of the total system design. To reliably keep the temperature within a predetermined range, precise temperature control is required. To prevent dehydration of the membrane and flooding within the stack, a simultaneous water and heat balancing must be performed when cooling plates are used in a PEM fuel cell system.

Different types of cooling plate flow channel are shown in fig. 7 [31]

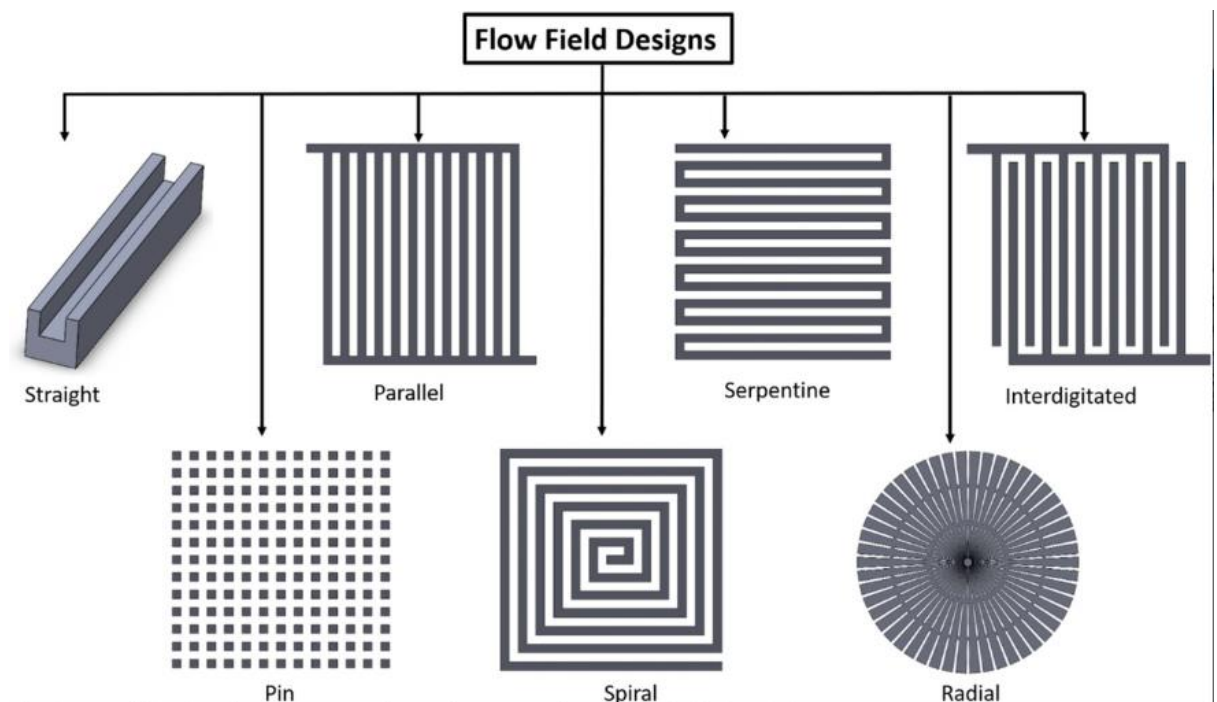


Fig. 7 Different types of flow field designs [31]

1.7 Study of Nanofluids

Nanofluid, an innovative fluid made possible by the advancement of nanotechnology, can be utilised to enhance the functionality of thermal devices. A fluid with better transfer properties than the base fluids is created by combining the base fluid's low thermal conductivity with solid nanoparticles' high thermal conductivity. A fluid in which nanoparticles are floating and forming a colloidal solution is referred to as a "nanofluid". Basic fluids including water, ethylene glycol, and oil are frequently utilised in nanofluids. They frequently contain metals, oxides, carbides, or carbon nanotubes as the nanoparticles. Nanofluids have distinct properties that make them potentially useful in a variety of heat transfer applications, including grinding, machining, decreasing boiler flue gas temperature, microelectronics, fuel cells, pharmaceutical procedures, and heat exchangers.

1.7.1 Thermophysical Properties of Nanofluids

The thermophysical properties of base fluids, such as density, viscosity, specific heat, and thermal conductivity, are present in base fluids, whereas nanofluids have novel properties.

The addition of the nanoparticles changes the thermophysical properties of the base fluid. Nanofluids' most significant thermophysical properties include viscosity, thermal conductivity, convective heat transfer, and specific heat.

1.7.2 Advantages of Nanofluids

- By altering the nanoparticles' size, shape, composition, and volume fraction, solar energy absorption will be maximised.
- Because of their extremely small particle sizes, suspended nanoparticles increase the fluid's surface area and heat capacity.
- The dispersed nanoparticles improve thermal conductivity, which boosts heat transfer systems' efficiency.

- Heat is transferred to a small region of fluid by heating within the fluid volume, which enables the peak temperature to be situated away from surfaces that are losing heat to the outside.
- The fluid's mixing fluctuation and turbulence are heightened.
- Fluid characteristics can be altered by altering the concentration of nanoparticles to suit various purposes.

CHAPTER-2

LITERATURE REVIEW

Internal combustion engines (ICEs) are being phased out of the car industry in an increasingly common trend nowadays. Compared to other fuel cell types, PEM fuel cells have a number of benefits. It is primarily extremely adaptable to offer quick answers to variations in demand for power and capacity in the variety of KW power applications [13]. Additionally, it boasts low operating temperatures, quick starting, extended service life, minimal self-discharges, and high power density [14]. Heat is produced in a PEM fuel cell stack by electrochemical reactions that are irreversible, entropic at the cathode, and ohmic resistances to electron flow. In a PEM fuel cell stack, these elements, respectively, are responsible for 55%, 35%, and 10% of the total heat release [15].

The effects of heat on a fuel cell's performance are complicated because heat is required for the catalyst layers' optimal reaction kinetics, but too much heat would result in an increase in energy transport losses. A specific current density is produced when excessive heat inside the cells evaporates the moisture in the membrane, increasing electrical resistances [16] that can be physically felt as larger voltage drops. In relation to this, a PEM stack's temperature distribution analysis is crucial to preventing the spread of huge temperature gradients. In contrast to cells with significant temperature gradients, in principle, cells with temperature homogeneity would result in the best power outputs [17].

Distilled water is the typical cooling fluid for stacks with closed-cathode construction in PEM fuel cell thermal management. A coolant with a high thermal conductivity would enable both a higher rate of thermal diffusivity within the fluid and an increase in the convection heat transfer coefficient. In contrast, fuel cell cooling fluids need to have a low electrical conductivity value to prevent coolant electrolysis and shunt current, which degrade conversion efficiency [18]. As the working fluid is exposed to an effective electrical environment and ions are continuously generated and moved throughout the system, this is a special circumstance that only occurs in the design of cooling systems for fuel cells [19].

Nanotechnology advancements have given rise to a new class of substances known as nanofluids, in which nano-particles of particular substance are disseminated in

predetermined quantities within a base fluid to enhance its particular features. Nanofluids are actively being investigated because they improve a base fluid's thermal conductivity by distributing metal-based nanoparticles [20,21].

In an experiment, Sozen et al. [22] demonstrated that a parallel flow and counter flow concentric tube heat exchanger's heat exchange efficiency is increased by using nanofluids comprised of fly ash or alumina by 2.8%-31.2%. Due to the difficulty in generating nanofluids with high thermal conductivity combined with a controlled value of electrical conductivity, the use of nanofluids as the cooling fluid is still being studied for PEM fuel cells. The question of system size and efficient operation becomes more important in light of the impending possibility that fuel cells may serve as the power source for automobiles in the future.

A recent field in PEM fuel cell thermal management research is cooling by nanofluids, which has the potential to improve stack architecture for smaller designs and a reduction in system size. Reducing the number of cooling plates inside the fuel cell stack is crucial for cutting the size of the stack. This is possible by using coolants that have higher thermal efficiency than regular distilled water. Nanofluids may hold the key to the problem, as their increased thermal conductivity will result in a faster rate of thermal diffusivity inside the fluid. However, a thorough investigation of the fundamental operating features for conceivable individual nanofluids and their interaction with distinct cooling plate designs must be made.

Between the bipolar plates are the cooling plates of PEM fuel cell stacks. Conduction would transfer heat produced by the irreversibility of the electrochemical reaction, mostly at the cathode side of the bipolar plate, to the cooling plate. As a result, in simulation studies, an external heat flux at the bottom of the cooling plate can represent the heat load [23]. In order to provide a large convection surface area on the cooling plate, small channels (channels having measurements in the order of millimetres) are created. The small channels used in commercial stacks can be different designs, like serpentine flow channels or parallel flow channels. Although they require more pumping power, serpentine channels provide the benefit of higher heat transmission rates and temperature homogeneity.

For PEM fuel cells, a number of nanofluids have been identified as potential substitute coolants. According to a study by Saidur et al. [24], Al_2O_3 has a thermal conductivity ratio of 40 over water as compared to TiO_2 's 8.58 and SiO_2 's 1.29. CuO has the biggest increase in thermal conductivity (76.5), but it also has the best electrical conductivity. This situation is not practical in an electrically active heat transfer application like PEM fuel cells. Regarding this, Zakaria et al. [25] first described the investigation in order to achieve the required thermal and electrical conductivities of Al_2O_3 nano-fluids with distilled water as the primary fluid for fuel cell cooling. To prevent the increase in electrical conductivity, ethylene glycol was added as a primary fluid and mixed with water. To assess the acceptable nanofluids for PEM fuel cell use, a thermo-electrical conductivity measure was devised. It was found that the optimum limit for fuel cell cooling was 0.5% Al_2O_3 volume content. After that, Talib et al. [26] created a characterization research for SiO_2 nanofluids and also restricted its viability for cooling fuel cell up to 0.5% SiO_2 volume concentration.

Using numerical and experimental methods, studies were also conducted at the cooling plate level, where the analysis was focused on comprehending the behaviour of the thermofluids and obtaining the convection heat transfer coefficient, among other heat transfer parameters. Zakaria et al. [27,28] reported computational numerical analysis for Al_2O_3 nanofluids in parallel flow and serpentine flow cooling plates. In a parallel flow cooling plate with large flow distributors, Zakaria et al. [29] have published experimental nanofluids analyses for 0.1% and 0.5% volume concentrations of Al_2O_3 dispersed in 60:40 and 50:50 water and ethylene glycol mixtures. A 23% improvement in heat transfer was also recorded, along with a 20% increase in pump power needed.

2.1 Research Gap

Based on the available literature on nanofluid coolants for PEM fuel cells, it can be concluded that there is a great need for research on the thermal properties of viable nanofluid coolants at both the heat sink and stack operating levels. Current practical research is limited to Al_2O_3 and SiO_2 nanofluids, and a simple flow geometry is used for coolant flow.

2.2 Research Objective

The research objective for this study is to investigate the most effective thermal management approach for cooling fuel cells. Various thermal management approaches have been tested for cooling the fuel cells such as using different types of cooling channels and different types of nano fluids.

CHAPTER-3

METHADODOLOGY

3.1 Measurement of the thermophysical properties of nanofluids

Thermal conductivity, density and specific heat of the nanofluids employed in this study were calculated at a temperature of 27 °C [32].

The equation was used to determine the effective density of the nanofluid,

$$\rho_{nf} = (1 - \varphi)\rho_{bf} + \varphi\rho_{np}$$

The equation was used to determine the effective specific heat of nanofluid,

$$C_{p_{nf}} = \frac{(1 - \varphi) \cdot (\rho C_p)_{bf} + \varphi \cdot (\rho C_p)_{np}}{\varphi \cdot \rho_{np} + (1 - \varphi) \cdot \rho_{bf}}$$

The equation was used to determine the effective thermal conductivity of nanofluid,

$$K_{nf} = K_{bf} \cdot \frac{K_{np} + 2 \cdot K_{bf} + 2 \cdot (K_{np} - K_{bf}) \cdot \varphi}{K_{np} + 2 \cdot K_{bf} - (K_{np} - K_{bf}) \cdot \varphi}$$

Table 1- Thermophysical Properties of nanoparticle [33]

Fluid Name	Thermal Conductivity	Specific Heat	Density	Viscosity
Water	0.615	4180	999	0.000854
<i>SiO₂</i>	1.38	740	2220	-
<i>Al₂O₃</i>	36	765	4000	-
<i>Zno</i>	110	502	5600	-

3.2 Mathematical Model of Uniformly Distributed Parallel Channel Cooling Plate

Based on the dimensions of the cooling plate, a 3D computational fluid dynamic (CFD) model was created. Cooling plate consist of 19 channels. The geometry was formed using

design modular in Ansys. Model consist 2 bodies which are cooling plate and heating pad. Using Boolean operator in design modeller, the cooling plate, heater pad, and coolant body were put together. The cooling plate was placed on top of the heater pad. Figure 8, 9 and 10 displays the distributor plates' overall dimensions [33]. Fig 11 shows the detailed dimension of mini channel of cooling plate.

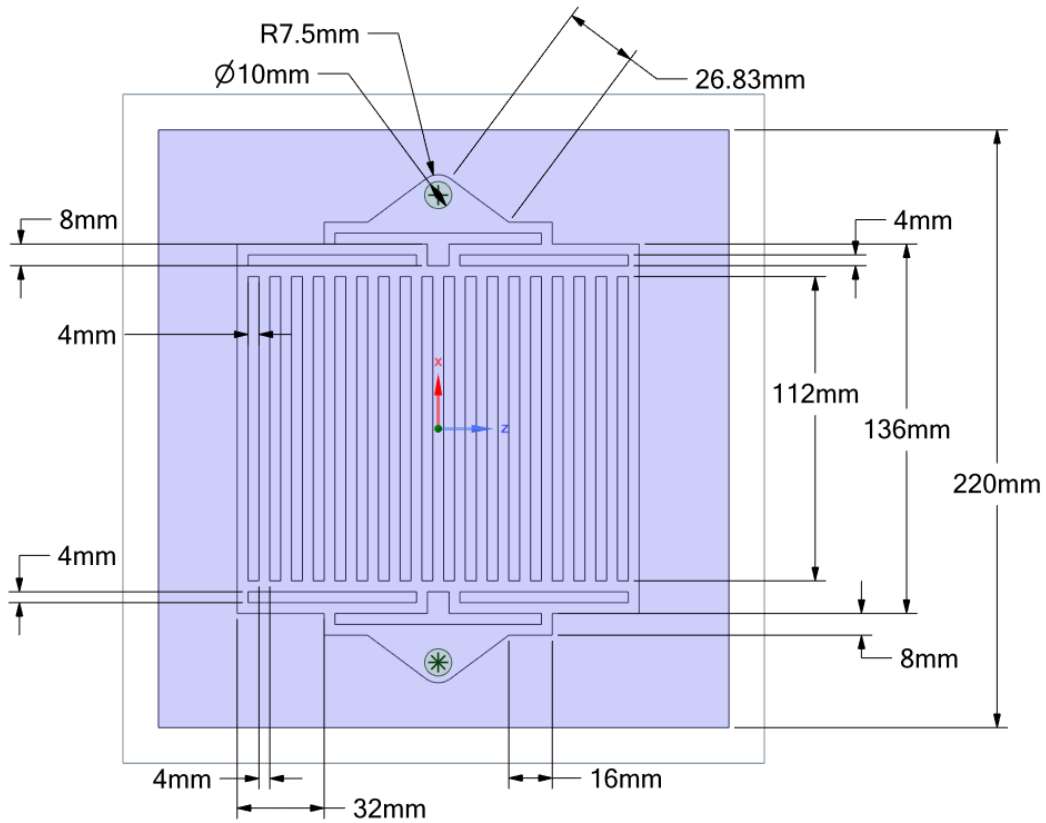


Fig. 8 Top View of Cooling Plate [33]

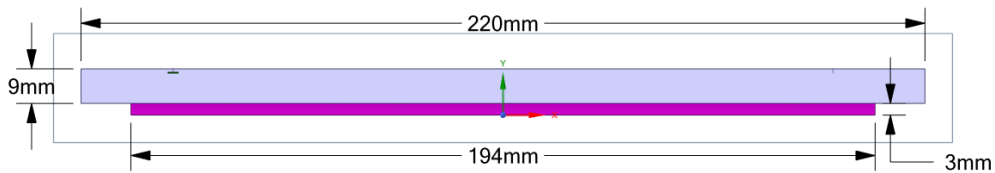


Fig. 9 Side View of Cooling Plate [33]

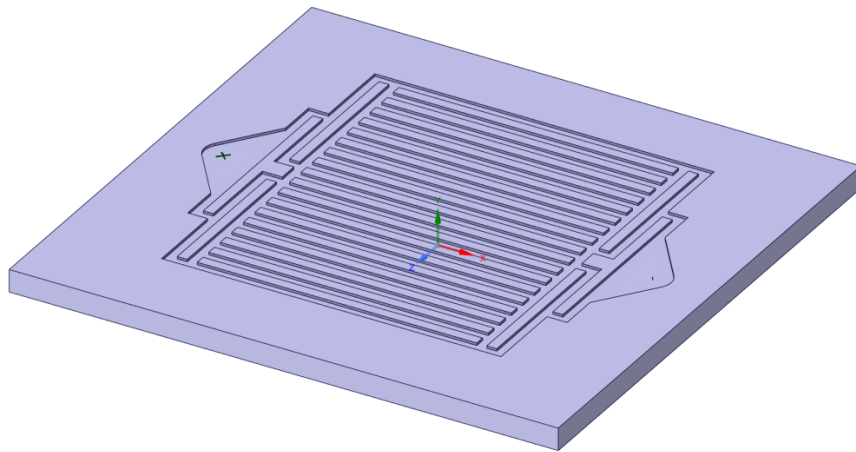


Fig. 10 Isometric view of cooling plate

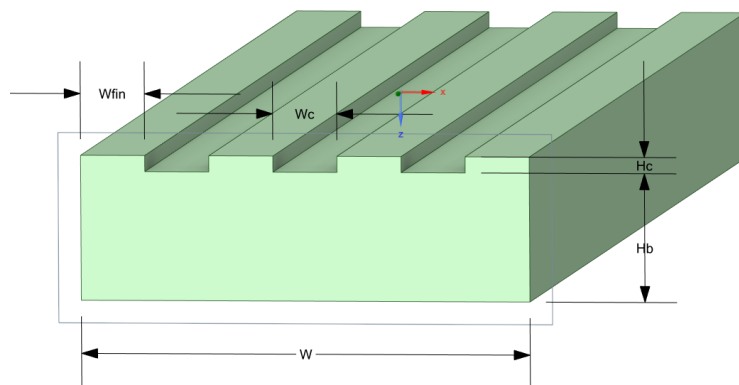


Fig. 11 Detailed dimension of mini channel of Cooling Plate [33]

Table 2- Detailed dimension of mini channel [33]

Parameter	Dimension (mm)
W_{fin}	4
W_c	4
H_c	1
H_b	8
W	28
L	112

3.3 Material properties of each component

The cooling plate was made of carbon graphite material and heating pad was made of silicon rubber.

Table 2- Material properties of Main Components [34]

Component	Material	Density (kg/m^3)	Thermal Conductivity (w/mK)	Specific Heat (J/kgK)
Cooling Plate	Carbon Graphite	2050	61.35	734
Heating Pad	Silicon Rubber	1799	1.375	1175

3.4 Meshing and Grid Independence Test

Meshing is done using Ansys 2022 R2. Polyhedral mesh is used to get best results. Meshing of cooling plate is shown in fig. 12. The results of the grid independence test are shown in Figure 13. Since the plate temperature remained consistent after that, the outcome suggests that 41,87,106 elements were required for cooling the distributor plate.

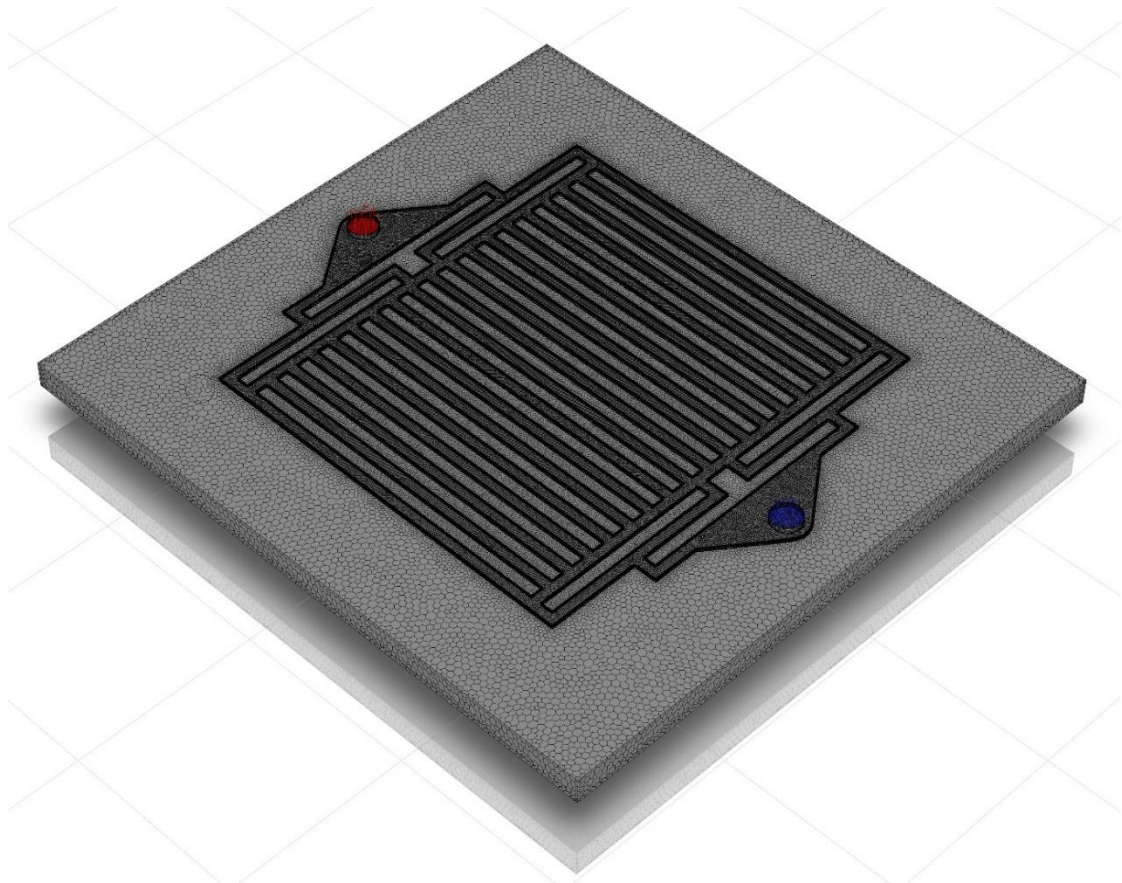


Fig. 12 Meshing of cooling plate

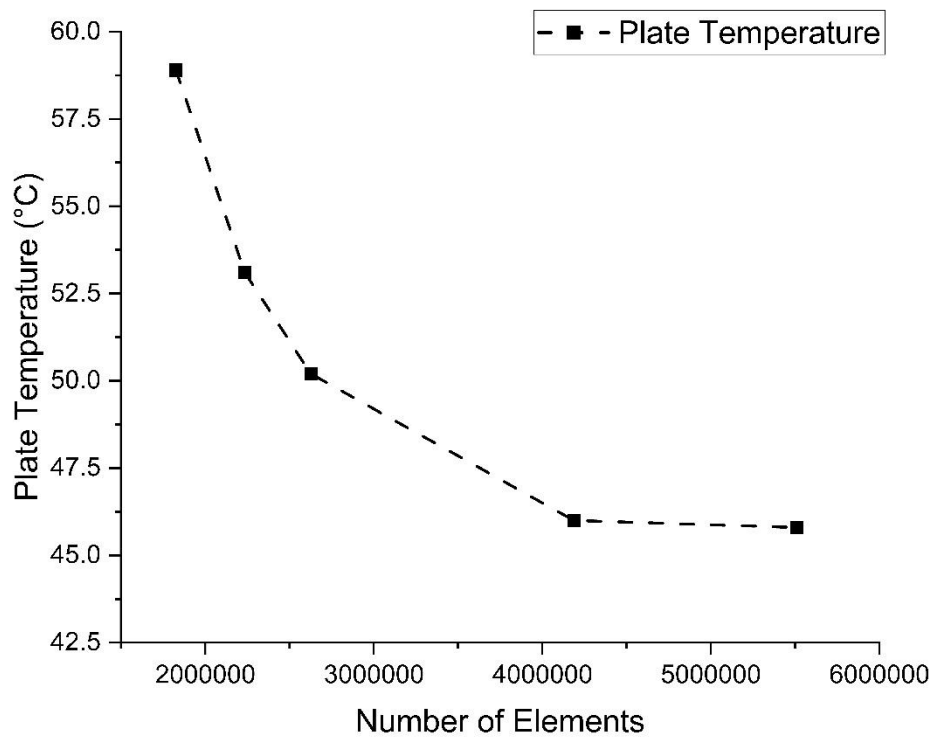


Fig. 13 Grid Independence Test

3.5 Geometrical Modification

By introducing successive wave sinusoidal fluid flow at the bottom of the channel, we altered the structure of the cooling plate channel. Due to these geometrical modifications surface area and turbulence increases which results in better heat transfer. Fig. 14 shows the dimension of sinusoidal wave [35] and Fig. 15-16 shows the isometric view of channel and cooling plate.

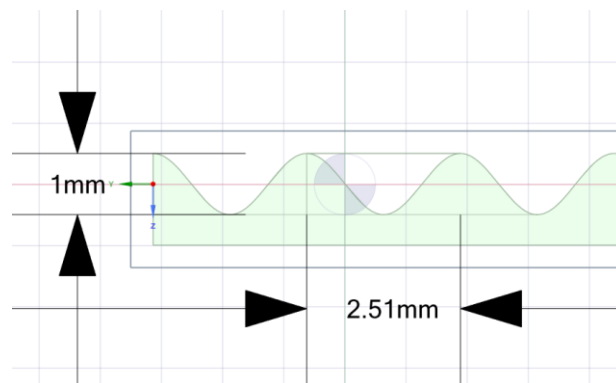


Fig. 14 Dimension of Sinusoidal Wave [35]

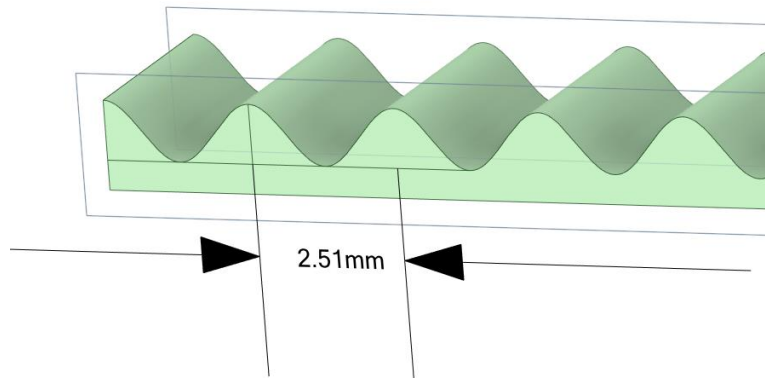


Fig. 15 Isometric View of Channel

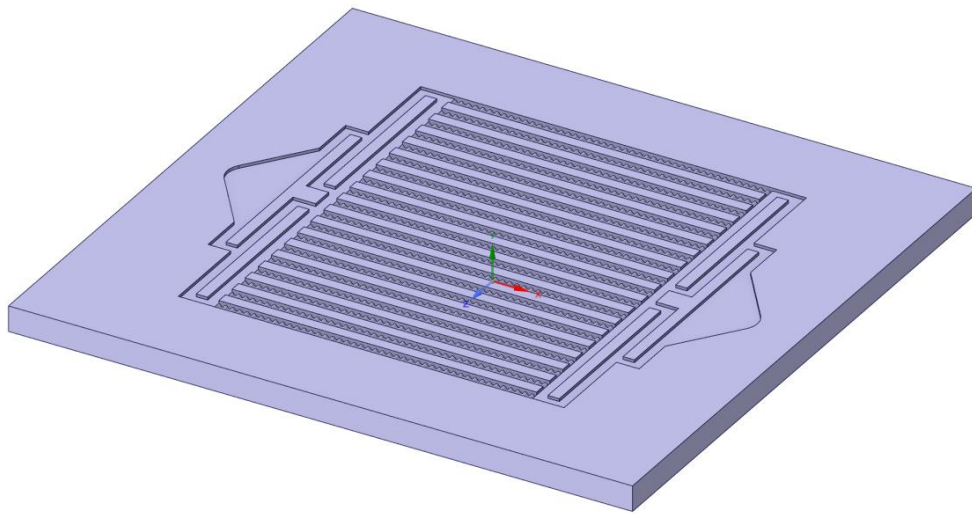


Fig. 16 Isometric View of Modified Cooling Plate

3.6 Governing equations

Several assumptions have been made for simplicity:

- The fluid has constant and viscous characteristics.
- The flow is laminar and is in steady state.
- With zero relative velocities, the fluid phase and nanoparticles are in thermal equilibrium, and the resulting mixture can be regarded as a single phase.
- Every channel in the cooling plate has the same heat transfer and fluid flow.

By resolving the steady-state Navier-Stokes equations, the flow field is derived.

The continuity equation is presented as follows:

$$\nabla \cdot (\rho \cdot u) = 0$$

The momentum equation is expressed as:

$$(u \cdot \nabla) \rho \cdot u = -\nabla p + \mu \cdot \nabla^2 u$$

The energy equation is given by:

$$u \cdot \nabla T = \frac{k}{\rho C_p} \nabla^2 T$$

whereas the solid region's energy equation is provided by

$$k_s \nabla^2 T = 0$$

3.7 Boundary Conditions

At the channel's input, temperature and flow rate were considered to be uniform, while a uniform pressure was assumed at the outflow. The coolant's (water) entrance temperature is taken into account, and a thermally isolated boundary condition was given to the upper surface. It was supposed that heat was convectively transferring from the plate's side edges to the surroundings. The heating pad was chosen as a source term, which has the value $1298701 \text{ W}/m^3$ and is taken as constant. Regarding the boundary conditions, the outlet was subjected to zero pressure while the inlet velocity was adjusted throughout a Reynold Number range of 400 to 2000. The simple method was used for simulation [33].

No slip boundary at the wall:

$$\vec{V} = 0 (@Walls)$$

Boundary conditions at the inlet were taken to be:

$$\vec{V} = V_m(@inlet)$$

$$P = \text{atmospheric pressure} (@outlet)$$

Through forced convection of fluid flowing through the distributor cooling plate, the heat is transferred through the solid and dispersed away. Heat flux is continuous, uniformly heating the bottom surface.

$$-K_{nf} \cdot \nabla T = q'' (@bottom\ of\ distributor\ cooling\ plate)$$

$$-K_{nf} \cdot \nabla T = 0 (@top\ of\ distributor\ cooling\ plate)$$

3.8 Data Acquisition

The heat transfer coefficient and Nu number were used to analyse the heat transfer.

$$h = \frac{\dot{q}}{(T_{avgplate} - T_{avgfluid})}$$

$$Nu = \frac{hD_h}{k_{nf}}$$

Based on the pressure drop between IN flow and OUT flow, fluid flow was examined. The additional pumping power needed to circulate nanofluids through cooling plates was then represented by the pressure decrease.

The necessary pumping power is determined by

$$W_{pump} = \dot{V} \times \Delta P$$

3.9 Model Validation

The simulation was initially tested against published data [33] to guarantee its accuracy. The graph demonstrates that the simulation that was run differed from the published study as shown in Figure 17 by 0.9% to 9%. The slight variance demonstrates the simulation's dependability and allows for additional study.

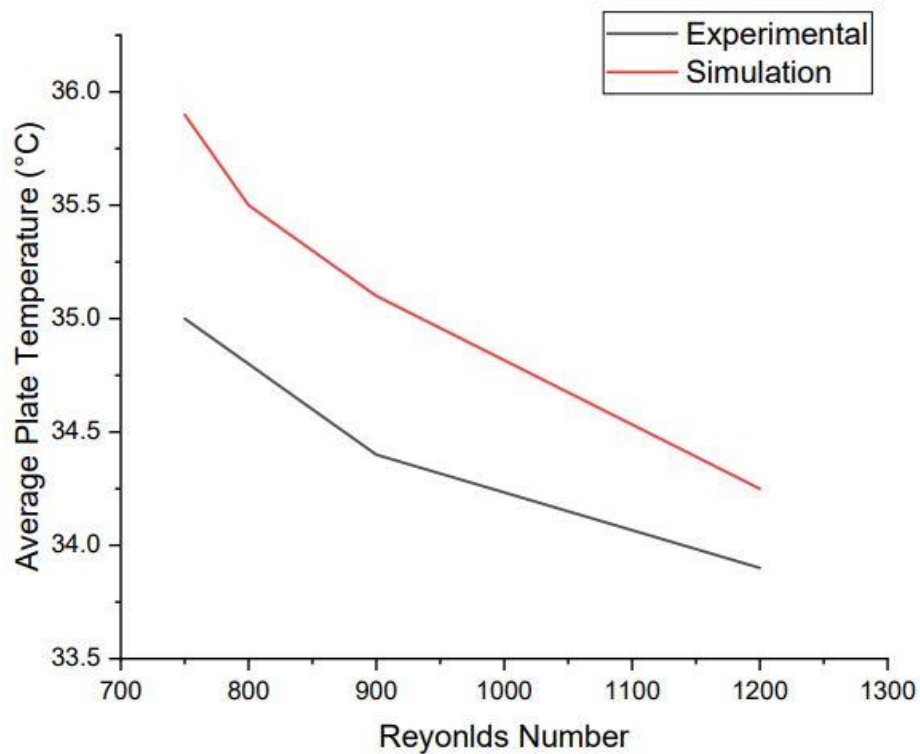


Fig. 17 Verification of this numerical research with Experimental Data

CHAPTER-4

RESULTS AND DISCUSSION

4.1 Average Plate Temperature

The impact of several types of coolant on average plate temperature was noted. As we can see from temperature contour (fig. 18-22), the study is carried out on water with different reynolds number and it was observed that plate temperature is minimum at $Re=2000$ so further study is carried out only on $Re=2000$.

Further study is done using different nanofluids as coolant. From fig. 23-25 shows the temperature contour for different nanofluids and it was observed that ZnO as nanofluid is more effective as coolant. After that geometric modification is also done and ZnO nanofluid as coolant is studied on modified geometry. Fig. 26 shows the temperature contour of modified geometry.

Modified geometry using ZnO as the working fluid shows 1.8% reduction from base fluid water at Re of 2000 demonstrated the lowest plate temperature. ZnO, which reduced by 1.30% as compared to base fluid, came next. Both the Al_2O_3 and SiO_2 nanofluids were lowered by 1.14% and 0.81% from water plate temperature, respectively. The better thermal conductivity of nanofluids over base fluid was the cause of this increase. The plate temperature was reduced more effectively with the improved geometry. Fig. 27 shows the variation of average plate temperature of different working fluids.

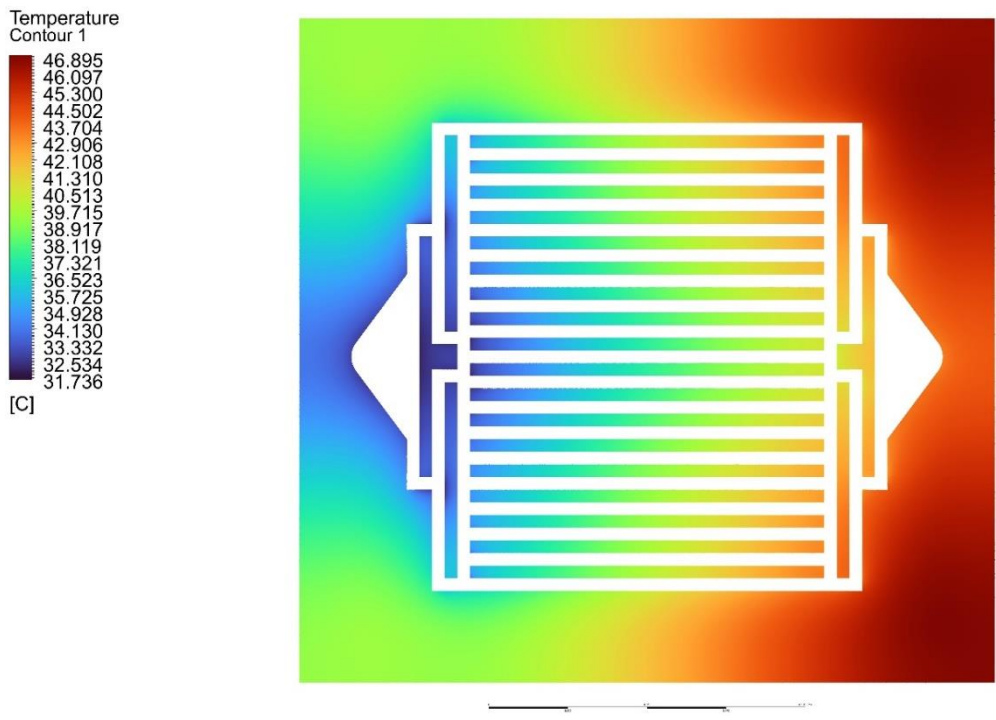


Fig. 18 Temperature Contour of base fluid at Re=400

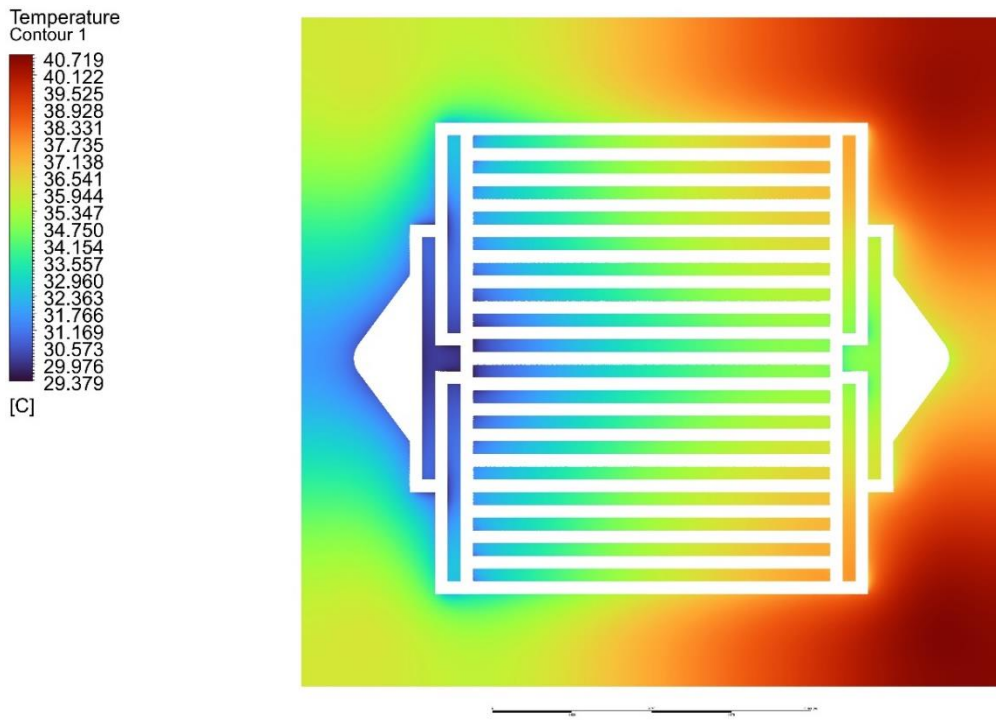


Fig. 19 Temperature Contour of base fluid at Re=800

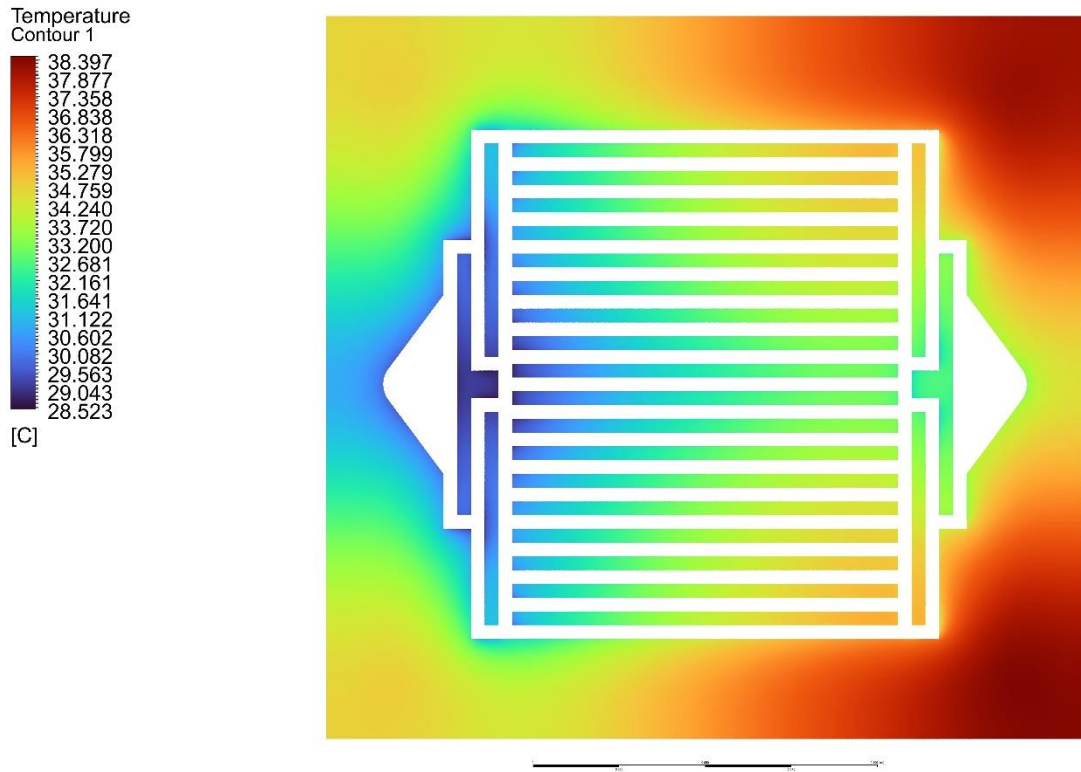


Fig. 20 Temperature Contour of base fluid at Re=1200

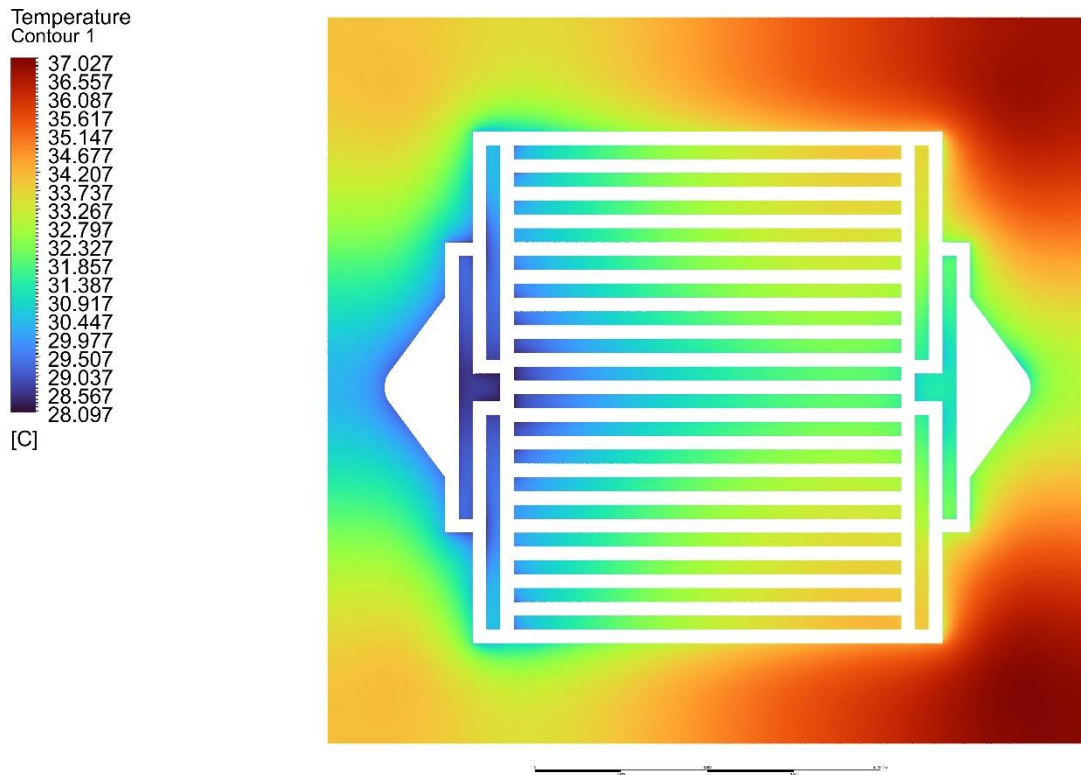


Fig. 21 Temperature Contour of base fluid at Re=1600

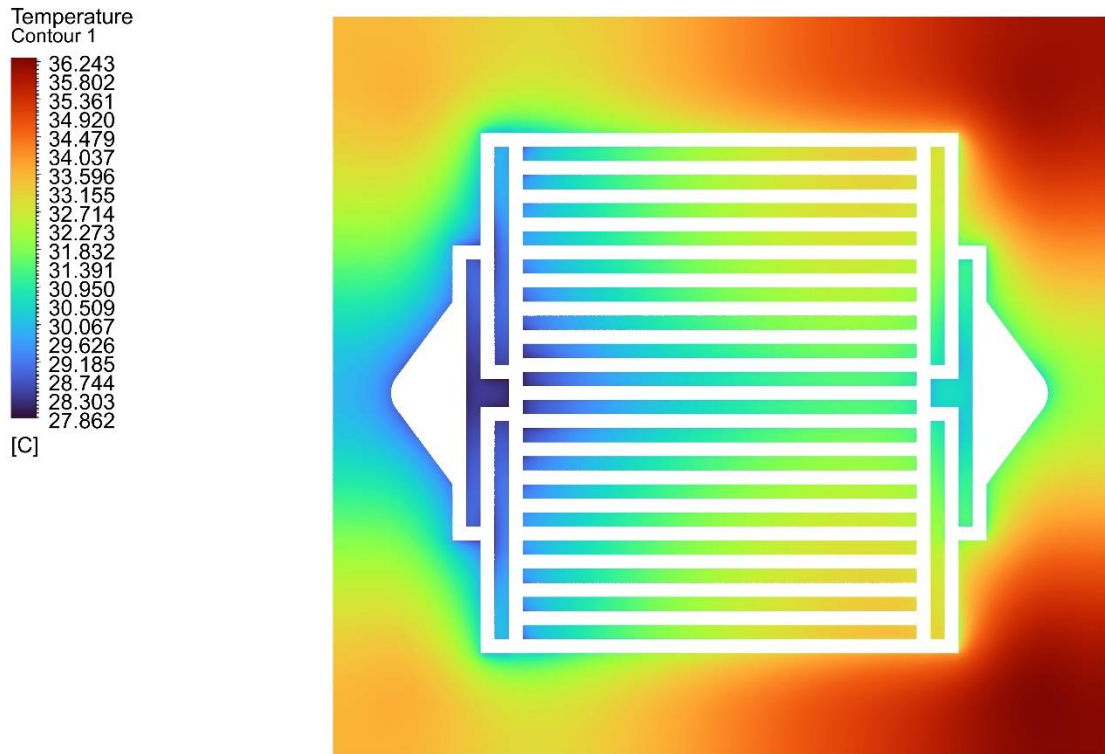


Fig. 22 Temperature Contour of base fluid at Re=2000

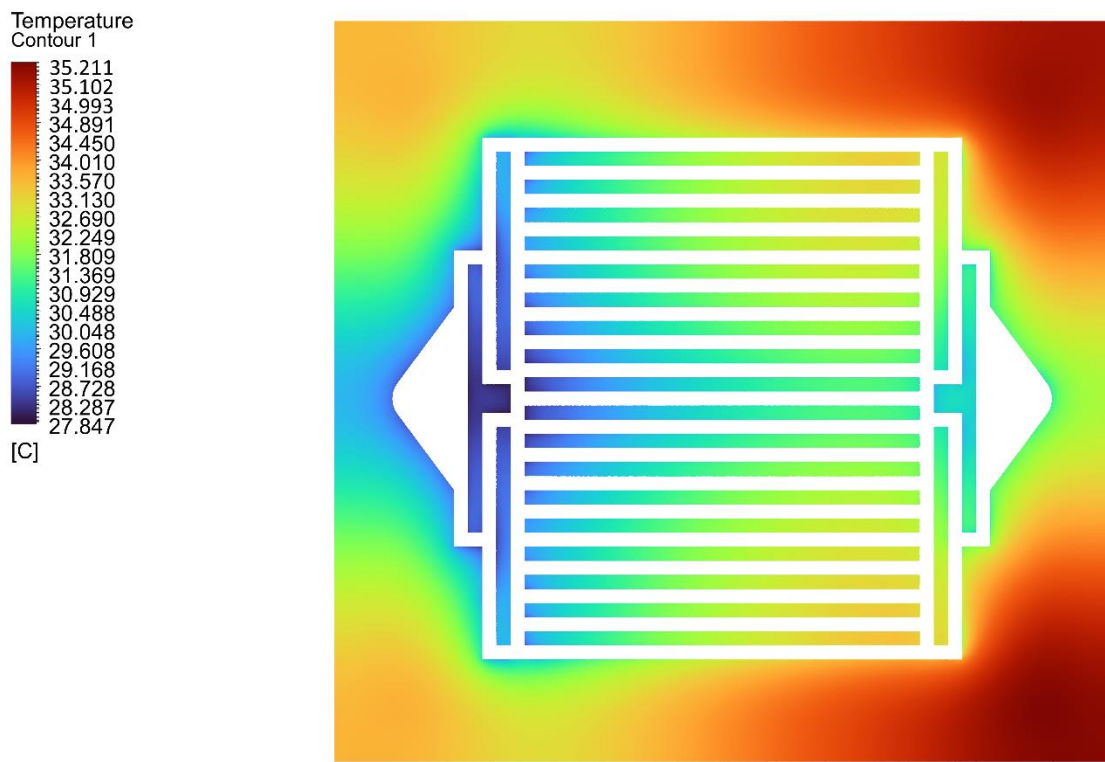


Fig. 23 Temperature Contour of SiO_2 at Re=2000

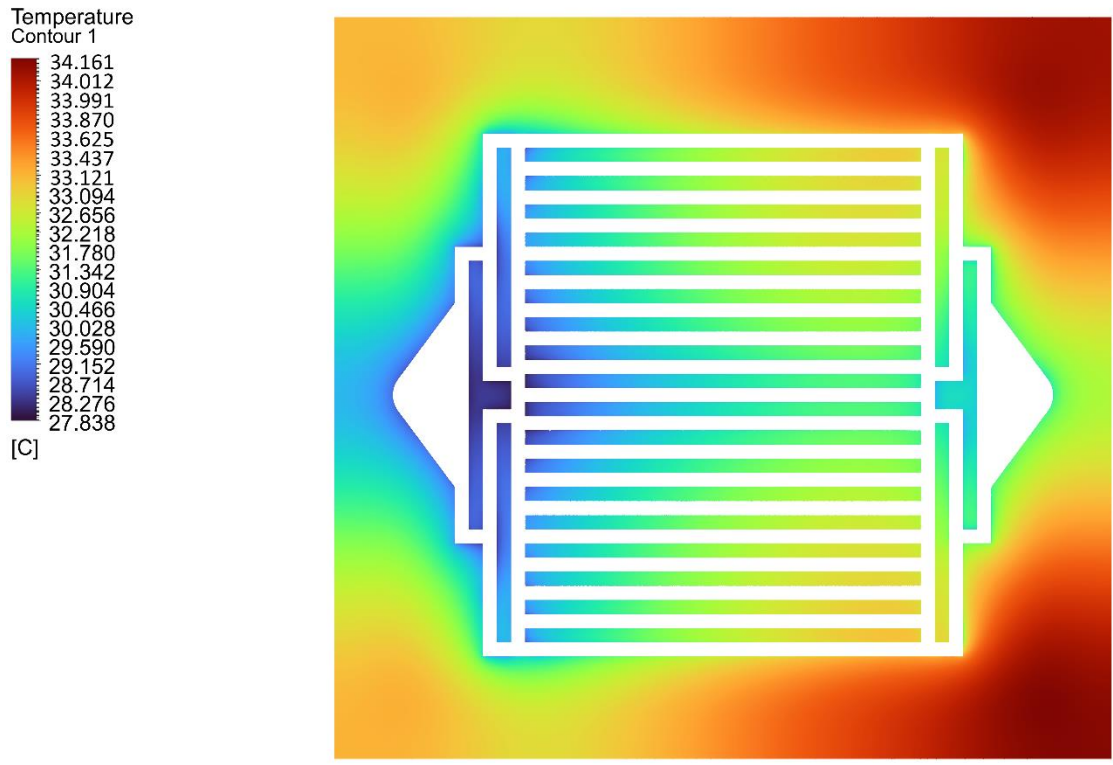


Fig. 24 Temperature Contour of Al_2O_3 at $Re=2000$

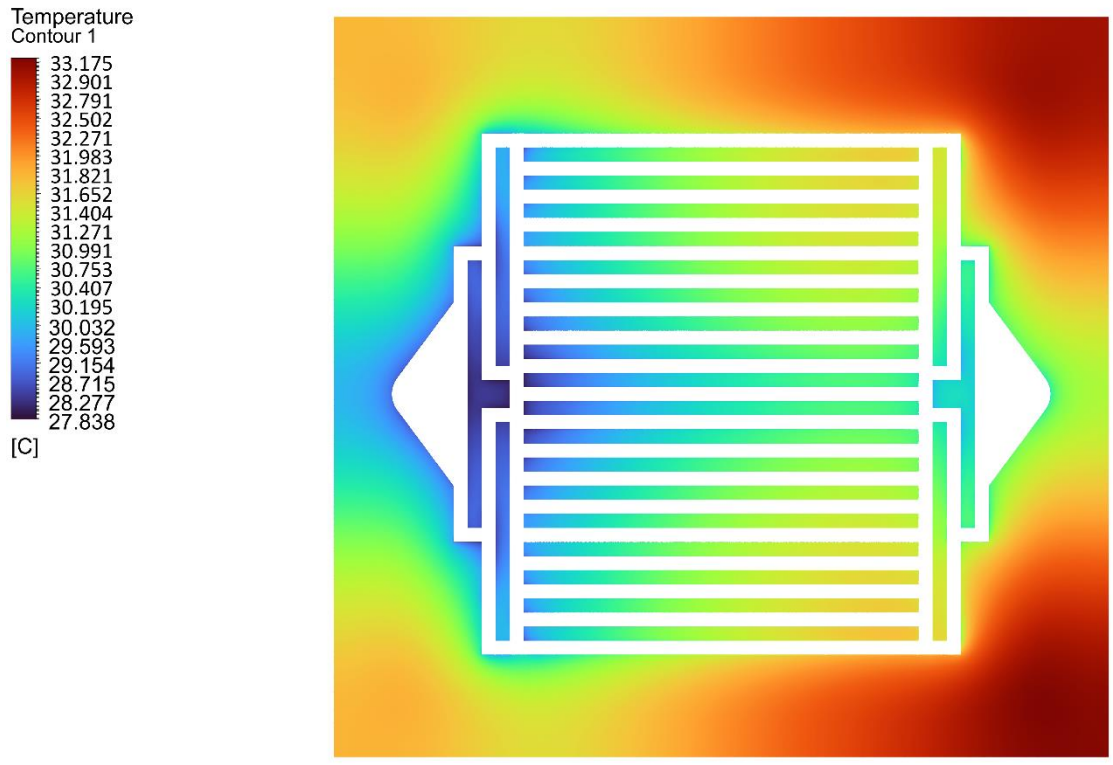


Fig. 25 Temperature Contour of ZnO at $Re=2000$

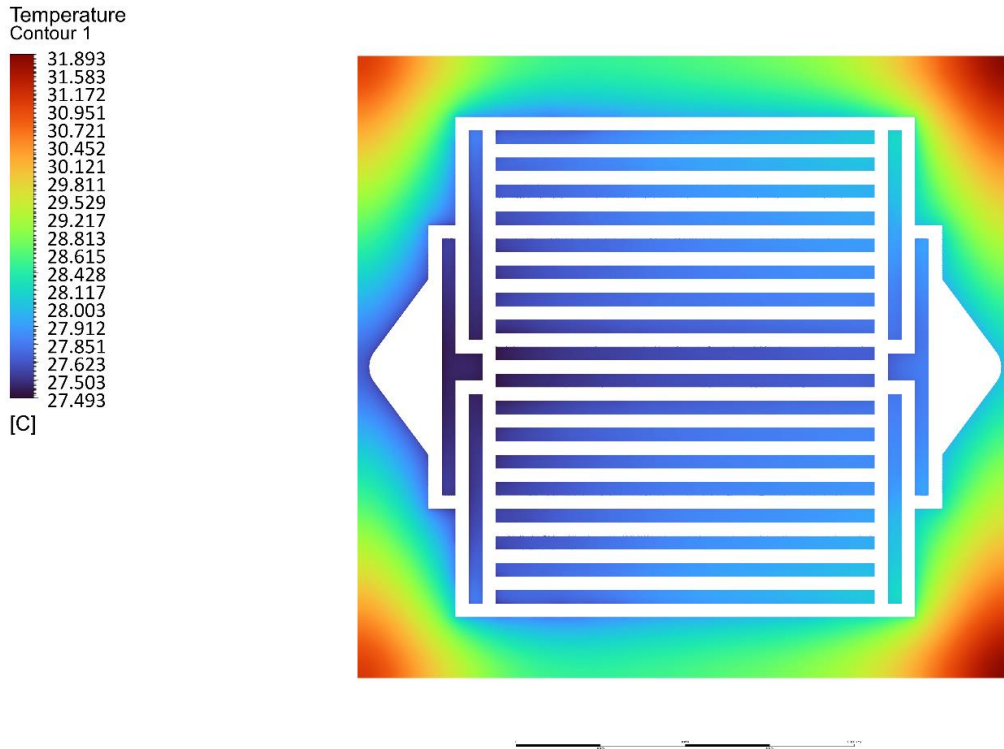


Fig. 26 Temperature Contour of Mod. Geom. ZnO at Re=2000

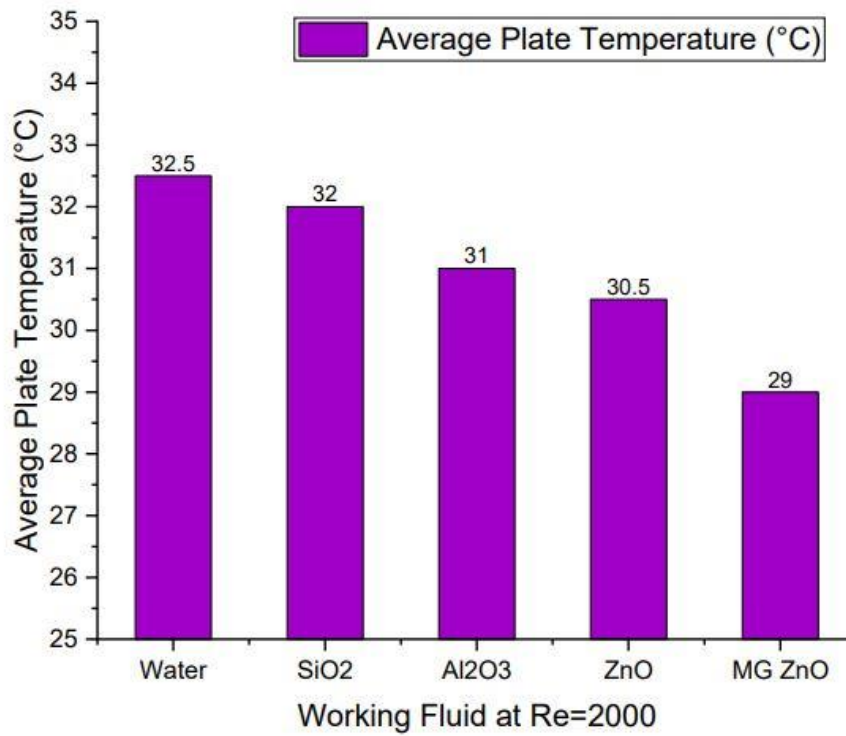


Fig. 27 Plate temperature difference between different nanofluids

4.2 Heat Transfer Enhancement

The temperature of the cooling plate had a significant impact on the improvement of heat transfer. The enhancement of convective heat transfer is proportional to the temperature of the plate. Figure 28 displays the heat transfer coefficients for different working fluid. The modified geometry using ZnO as a nanofluid produced the largest enhancement, with 4.87% more than the base fluid, and ZnO, with 3.6% more. Al_2O_3 nanofluid and SiO_2 nanofluid, meanwhile, demonstrated improvements of 2.63 percent and 1.85 percent, respectively, above base fluid at Re 2000. This shown that altered geometry significantly increased the cooling fluid's heat transfer coefficient.

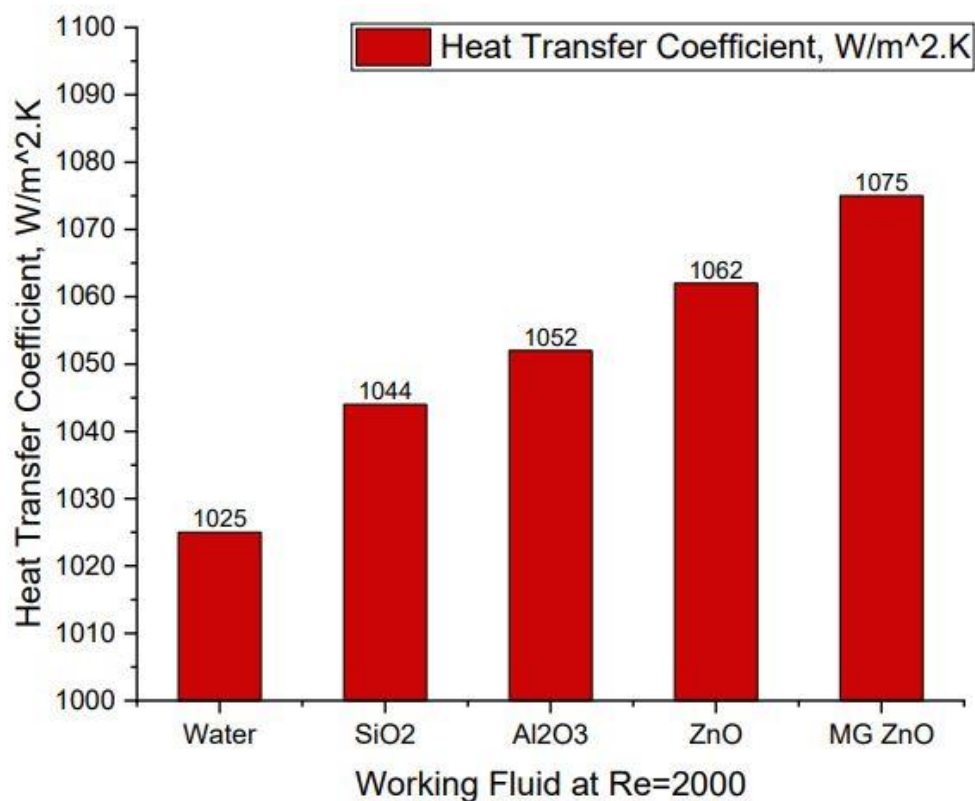


Fig. 28 Heat Transfer Coefficient of Different Working Fluids

4.3 Nusselt Number Comparison

The enhanced non-dimensional heat transfer is therefore represented by the Nusselt number (Nu). The study of the Nusselt number was displayed in Figure 29. The maximum Nusselt number was demonstrated by changed geometry employing ZnO as a nanofluid, similar to the heat transfer coefficient. Al_2O_3 and SiO_2 nanofluids both fell into the lower range of the Nusselt number, with water being the lowest of all base fluids. According to the definition of the Nusselt number, modified geometries using ZnO as a nanofluid exhibit conductive heat transfer across the boundary layer that is less efficient than convective heat transfer.

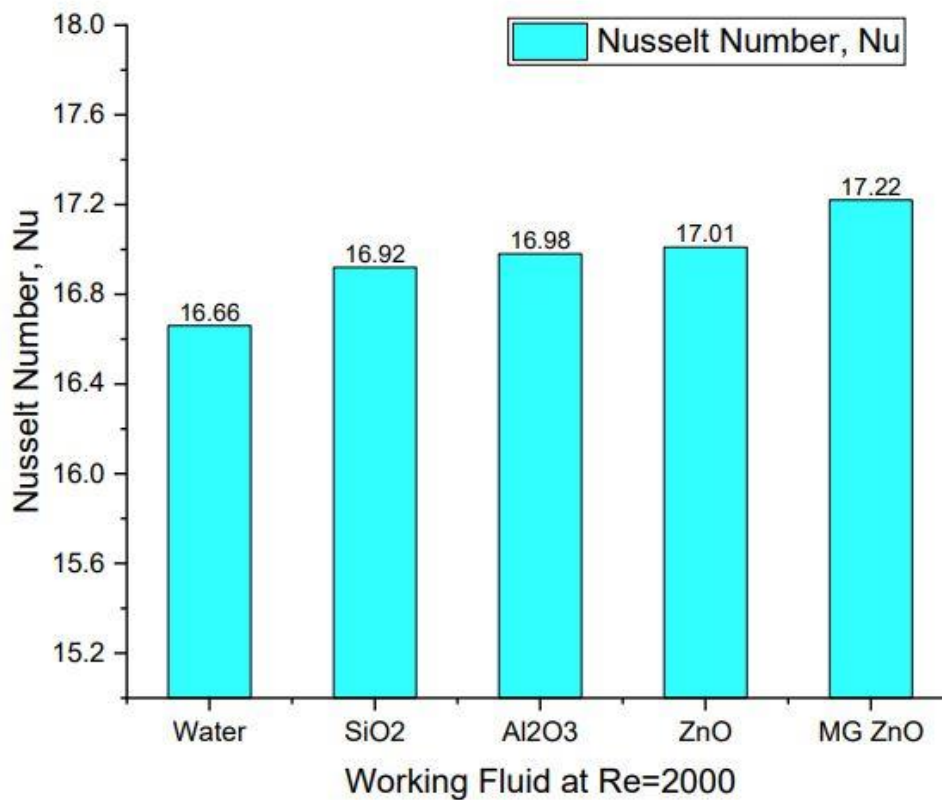


Fig. 29 Nusselt Number Comparison between different Nanofluids

4.4 Pressure Drop Analysis

The pressure drop at the entrance and outlet was monitored to determine the ability of nanofluids to move fluid. Figure 30 details the pressure drop information for coolant flowing through the distributor plate between the intake and output. A high-pressure drop was anticipated as the coolant was compelled to squeeze through the cooling plate's constrained channels.

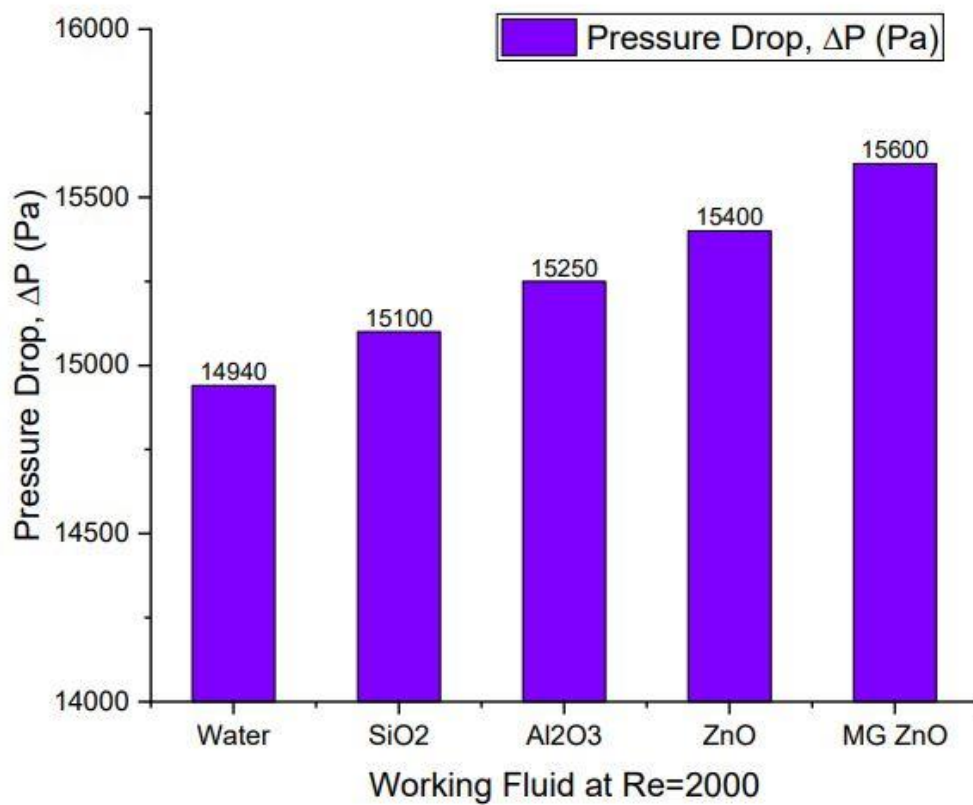


Fig. 30 Pressure drop of different working fluids

4.5 Pumping Power

In order to determine how much more pumping power would be needed if nanofluids were used in the PEMFC cooling system, the pressure drop information was converted to pumping power requirements. Fig. 31 showed the required pumping power. The increased density and viscosity of nanofluids when compared to the base fluid has led to a larger pressure drop. Additional pumping power is needed to compensate for these losses. The modified shape employing ZnO as a nanofluid in the distributor cooling plate needed the maximum pumping power (0.207 W), compared to water (0.197 W). ZnO nanofluid, Al_2O_3 nanofluid, and SiO_2 nanofluid came next with respective power outputs of 0.203 W, 0.201 W, and 0.199 W.

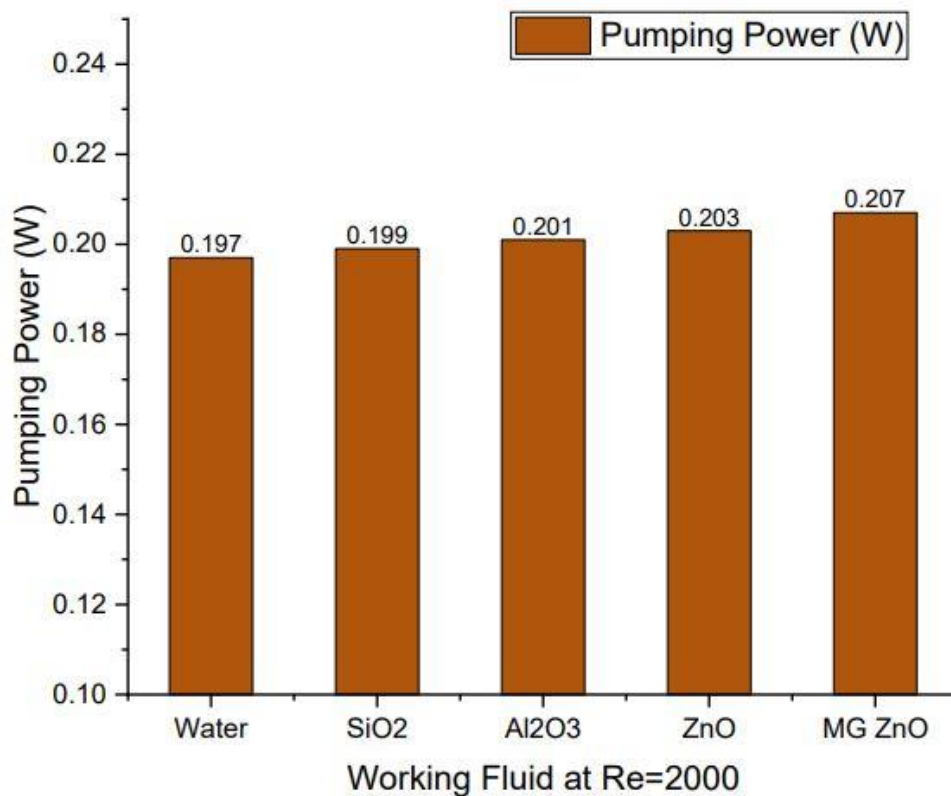


Fig. 31 Pumping Power Required for different Nanofluids

CHAPTER-5

CONCLUSION AND FUTURE SCOPE

This numerical analysis showed the improved heat transfer of several nanofluids over base fluid on the PEMFC distributor cooling plate. ZnO, Al_2O_3 , SiO_2 and water as the base fluid were all examined for improvements in the convective heat transfer coefficient and Nusselt number. It was demonstrated that modified geometry using ZnO as a nanofluid improved heat transfer better than simple geometry using ZnO, Al_2O_3 , SiO_2 , as nanofluids and base fluid. For several nanofluids, the pressure drop analysis was also carried out. The effectiveness of adopting modified geometry with nanofluids as a coolant was demonstrated by balancing pressure drop penalties with parameters that improve heat transfer.

Future Scope

From the above study and conclusion, we draw the following future scope of this study. More analysis can be done on different nanofluids like CNT (Carbon nanotubes), CuO etc and also on different modified geometries.

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