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Pressure Drop and Heat Transfer Analysis for Fluid Flow through Micro and Mini Channel

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Abstract: *For the heat exchanging applications, heat transfer enhancement is become major hurdle and it is the need of today's world. As we know day by day miniaturization, energy efficiency and cost effectiveness are becoming essential goals to stand in today's competitive world. Hence, it becomes necessary to remove high heat flux from highly compact systems such as high-performance computer chips, laser diodes and nuclear fusion and fission reactors for ensuring their consistent performance with long life. Micro-channels and mini-channels are naturally well suited for this task, as they provide large heat transfer surface area per unit fluid flow volume. Hence, facilitating very high heat transfer rate. Use of micro-channels can be explored in various applications i.e. turbine blades, rocket engine, hybrid vehicle, hydrogen storage, refrigeration cooling, thermal control in microgravity and capillary pump loops. Heat flux removal requirement varies significantly based on the type of application. Heat dissipation requirement will continue to rise with more advancement in technologies and further reduction in the size of these applications. Considering facts, it can be concluded that microchannel heat sinks seem to be the plausible solution of twenty first century cooling problems. In the recent years' micro channel heat exchangers have been applied in refrigeration and air conditioning because they provide larger heat transfer area per unit volume and they are smaller and lighter than those obtained from conventional heat exchanger. We know that micro channel heat exchanger is more effective for a performance enhancement than cross fin and tube heat exchanger in residential air-conditioner. And micro channel heat exchanger helps to reduce refrigerant quantities in residential air-conditioner systems for the purpose of replacing all aluminum parallel flow heat exchangers as a heat exchanger for all kinds of air conditioner, the improvement of anti-corrosion technology and degree of flexibility for product application should be done. This paper deals with the review of rigorous behavior of micro-channel heat transfer rate, fluid flow visualizations in the micro-channel and their application in industries.*

Keywords: Microchannel Heat Exchanger, Air conditioning, Electronic cooling, cooling Capacity, Coefficient of Performance

I. INTRODUCTION

1.1 General Introduction

Over the past decade and with the rapid growth of the miniaturizations of electronic device, the heat dissipation from these miniaturized electronic devices becomes the major challenge in current scenario. If this heat dissipation is not done effectively, then this will affect the life of device adversely which will result in decrease efficiency. Micro-channel is the one of the best options for removing heat, due to its compact size and higher thermal efficiency. Numerous researchers have been investigated behaviour of micro-channel heat transfer rate, fluid flow visualizations in the micro-channel and their application by theoretically in nature as well as experimentally.

The significant research has been conducted on heat transfer and fluid flow in microchannels. The current understanding and identifies future research priorities across six key areas: single-phase gas flow, single-phase liquid flow enhancement and flow boiling, flow boiling instability, condensation, electronics cooling, and microscale heat exchangers. Electronics cooling remains a major application, driving innovations in thermal transport. Research is

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expected to focus on enhancing performance through novel designs, nanostructures, and practical micro heat exchanger implementations. [1]

Investigation of microscale thermal devices is motivated by the single-phase internal flow correlation for convective heat transfer:

$$h = Nu_c \frac{k}{d}$$

Where-

h is the heat transfer coefficient,

Nu_c is the Nusselt number,

k is the thermal conductivity of the fluid and

d is the hydraulic diameter of the channel or duct.

In internal laminar flows, the Nusselt number becomes a constant. This is a result which can be arrived at analytically: For the case of a constant wall temperature, $Nu_c = 3.657$ and for the case of constant heat flux $Nu_c = 4.364$ for round tubes.[2] As Reynolds number is proportional to hydraulic diameter, fluid flow in channels of small hydraulic diameter will predominantly be laminar in character. This correlation therefore indicates that the heat transfer coefficient increases as channel diameter decreases. Should the hydraulic diameter in forced convection be on the order of tens or hundreds of micrometres, an extremely high heat transfer coefficient should result?

Micro heat exchangers, Micro-scale heat exchangers, or microstructure heat exchangers are heat exchangers in which (at least one) fluid flows in lateral confinements with typical dimensions below 1 mm. The most typical such confinement are microchannels, which are channels with a hydraulic diameter below 1 mm. Microchannel heat exchangers can be used for many applications like high performance aircraft gas turbine engines, heat pumps, microprocessor and microchip cooling, air conditioning.

Kandlikar and Grande (2003)[3] adopted a different classification based on the rarefaction effect of gases in various ranges of channel dimensions, "*D*" being the smallest channel dimension:

1µ*m* <*D* < 10µ*m* : Transitional Microchannels

10µ*m* <*D*< 200 µ*m* : Microchannels

200 µ*m*<*D* <3 *mm* : Minichannels

3 *mm* <*D* : Conventional Passages

The increasing demand for efficient thermal management in modern applications such as high-performance electronics, micro-electromechanical systems (MEMS), and compact heat exchangers has driven significant research into micro and mini channel heat transfer systems. These channels, typically ranging from **10 µm to 3 mm** in hydraulic diameter, offer high surface-area-to-volume ratios, enabling enhanced heat dissipation with minimal space requirements. However, fluid flow and heat transfer behavior in such small-scale passages deviate significantly from conventional macro-scale theories due to dominant surface effects, viscous forces, and entrance region influences.

Significance and Applications

The insights gained from this work will directly benefit:

Electronics Cooling: Optimizing heat sink designs for CPUs, GPUs, and power electronics.

Microfluidics: Enhancing lab-on-a-chip devices for biomedical diagnostics.

Energy Systems: Improving compact heat exchangers in refrigeration and renewable energy applications.

By bridging the gap between **experimental data, simulations, and theoretical models**, this study aims to advance the design and operational efficiency of next-generation microscale thermal systems.

1.2 Application of Computational Fluid Dynamics (CFD)

Numerical methods are extensively used to analyze the performance of the behaviour and also to design the micro channels heat exchanger. Computational Fluid Dynamics (CFD) is a computer-based numerical tool used to study the fluid flow, heat transfer behaviour and also its associated phenomena such as chemical reaction. A set of mathematical model equations are first developed following conservation laws. These equations are then solved using a computer programme in order to obtain the flow variables throughout the computational domain. Examples of CFD applications in the chemical process industry include drying, combustion, separation, heat exchange, mass transfer, pipeline flow, reaction, mixing, multiphase systems and material processing. Validation of CFD models is often required to assess the accuracy of the computational model. This assessment can assist in the development of reliable CFD models. Validation is achieved by comparing CFD results with available experimental, theoretical, or analytical data. Validated models become established as reliable, while those which fail the validation test need to be modified and revalidated.

Further model equations can be simulated by CFD method for designing the micro channels and also to do parameter sensitivity analysis.

1.3 OBJECTIVES OF THE PRESENT WORK

As is evident from the diversity of application areas, the study of flow and heat transfer in microchannels is very important for the technology of today and the near future, as developments are following the trend of miniaturization in all fields. Literature shows that the microchannels and microchannels heat sinks were studied extensively, but there is limited research related to the performance study of microchannel heat exchangers using CFD models. This work studies the CFD simulation of micro channel flow and conjugates heat transfer, which couples' fluid convection in a tubular micro channel and heat conduction in the solids.

The present work is undertaken to study the following aspects of

- Computational Fluid Dynamics modelling and simulation of single-phase micro
- channel heat exchanger to understand its hydrodynamic and thermal behaviour.
- Validation of the CFD models by comparing the present simulated results with the data available in the open literature.
- Parameter sensitivity study of micro channel

II. LITEATURE REVIEW

Micro and mini channels have gained significant attention in recent years due to their applications in microelectronics cooling, biomedical devices, compact heat exchangers, and microfluidic systems. The fluid flow and heat transfer characteristics in these channels differ significantly from conventional macrochannels due to dominant surface effects, increased viscous forces, and possible rarefaction effects. This literature review examines previous studies on pressure drop and heat transfer in micro and mini channels, focusing on experimental, numerical, and theoretical approaches.

In macrochannels, pressure drop is typically predicted using the Hagen-Poiseuille equation for laminar flow and the Darcy-Weisbach equation for turbulent flow. However, in micro and mini channels, deviations from classical theory are observed due to: (Kandlikar et al., 2005)[4]

- Surface roughness effects
- Compressibility and rarefaction effects **in gas flows**
- Viscous dissipation

Following is the Few research papers mentioned with their findings,

2.1 Experimental Studies on Pressure Drop and Heat Transfer

Technological progress demands efficient cooling for compact systems. Microchannels, with their high heat transfer efficiency, are vital in applications like electronics, aerospace, and refrigeration. As cooling needs increase, microchannel heat sinks offer an effective solution, though advancements in durability and adaptability are still required [5].

As electronic devices continue to shrink in size, effective heat dissipation has become a critical challenge. Inadequate cooling can reduce device lifespan and efficiency. Microchannels offer an optimal solution due to their compact design and superior thermal performance. Researchers have extensively studied microchannel heat transfer behavior, fluid flow dynamics, and industrial applications through both theoretical and experimental approaches. This paper reviews key findings on microchannel heat transfer rates, flow visualization, and their practical implementations in various industries [6].

Friction is a critical force influencing numerous interfacial applications. Recent years have seen renewed interest in both fundamental understanding and practical control of friction. This review explores advances in **solid-liquid interfacial friction**, covering theoretical foundationsfrom bulk to molecular interactionsand regulation strategies observed in natural and engineered systems [7]. Key mechanisms include liquid, solid, gas, and hydrodynamic coupling effects. The discussion extends to applications where interfacial friction either hinders or enhances performance. Finally, we outline remaining challenges in understanding and manipulating friction at interfaces.

Sheth et al., has compared the plate and fin liquid/liquid heat exchanger with microchannel heat exchanger. the microchannel heat exchanger met all requirement except pressure drop across the cold side and it shows higher heat transfer rate, effectiveness and UA with lesser weight. the microchannel design shows 26% and 61% in mass and volume respectively [8].

Study on hydraulic and thermal characteristics of Mini-channel is conducted by Md Wasi Uddin [9] with different secondary channels in parallel and counter flow directions. In his work the different geometry channels were tested for range Reynolds number under parallel and counter flow condition. They found that the thermal performance of minichannel heat sink was enhanced by secondary channel (varying flow geometry) flow with insignificant pressure drops.

Chenlei Qu [10] did an optimization of thermal and hydraulic performance of hybrid Fe_3O_4-graphene nanofluids with different concentration in a microchannel. Their results indicate that the Fe_3O_4-graphene nanofluids is an attractive heat transfer medium in the MCHS and with higher concentration heat transfer increases without increasing the loss of pumping power (pressure drop). But the increase in the concentration of nanofluids can constantly decrease the dimensions of the MCHS in the long-term run.

Weilin Qu et al.,[11] presents a combined experimental and numerical investigation of thermal-hydraulic performance in a single-phase microchannel heat sink. The oxygen-free copper heat sink, featuring rectangular microchannels (231 μm width × 713 μm depth) with a polycarbonate cover, was tested using deionized water coolant. Experiments were conducted at two heat flux levels (100 W/cm² and 200 W/cm²) with corresponding Reynolds number ranges of 139-1672 and 385-1289. Numerical simulations employed conjugate heat transfer analysis to resolve three-dimensional temperature distributions in both solid and liquid domains. Results showed excellent agreement between measured pressure drops/temperature profiles and numerical predictions, validating the applicability of conventional Navier-Stokes and energy equations for microchannel heat sink analysis. The work provides comprehensive insights into local and system-level heat transfer characteristics.

III. EXPERIMENT SETUP & VALIDATION

This chapter outlines the experimental framework designed to test the research questions presented in earlier sections. It describes the setup, execution, and validation procedures to ensure reproducibility, accuracy, and reliability of results.

This chapter details the experimental methodology to investigate pressure drop (ΔP) and heat transfer characteristics for fluid flow (single phase) in micro and mini channels. The setup ensures controlled variation of geometric, flow, and thermal parameters while validating results against numerical models.

The sole purpose of experimentation is to validate numerical results and That's why we are performing experimentation for only tube of internal diameter of 4mm (Tube D1). While the objective of this study is investigating pressure and heat transfer characteristics with variable geometry.

3.1. EXPERIMENT DESIGN AND SETUP

The Primary Objectives of experimentation is as mentioned bellow:

Quantify ΔP and heat transfer coefficients (HTC) experimentally.

To validate the numerical simulation result with experiment

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Experimental Variables

Variable Type	Parameters
Independent	- Channel diameter (Dh), length (L) - Flow rate (Q), Re - Heat flux (q″), wall temperature (Tw)
Dependent	- ΔP (measured via pressure sensors) - HTC (derived from Tw, bulk fluid temp Tb)
Control	- Fluid type (e.g., water, refrigerants) - Inlet temperature (Tin) - Surface roughness

Table No. 3.1 Exprimental Variables and Parameters

Temp. Measurement Display

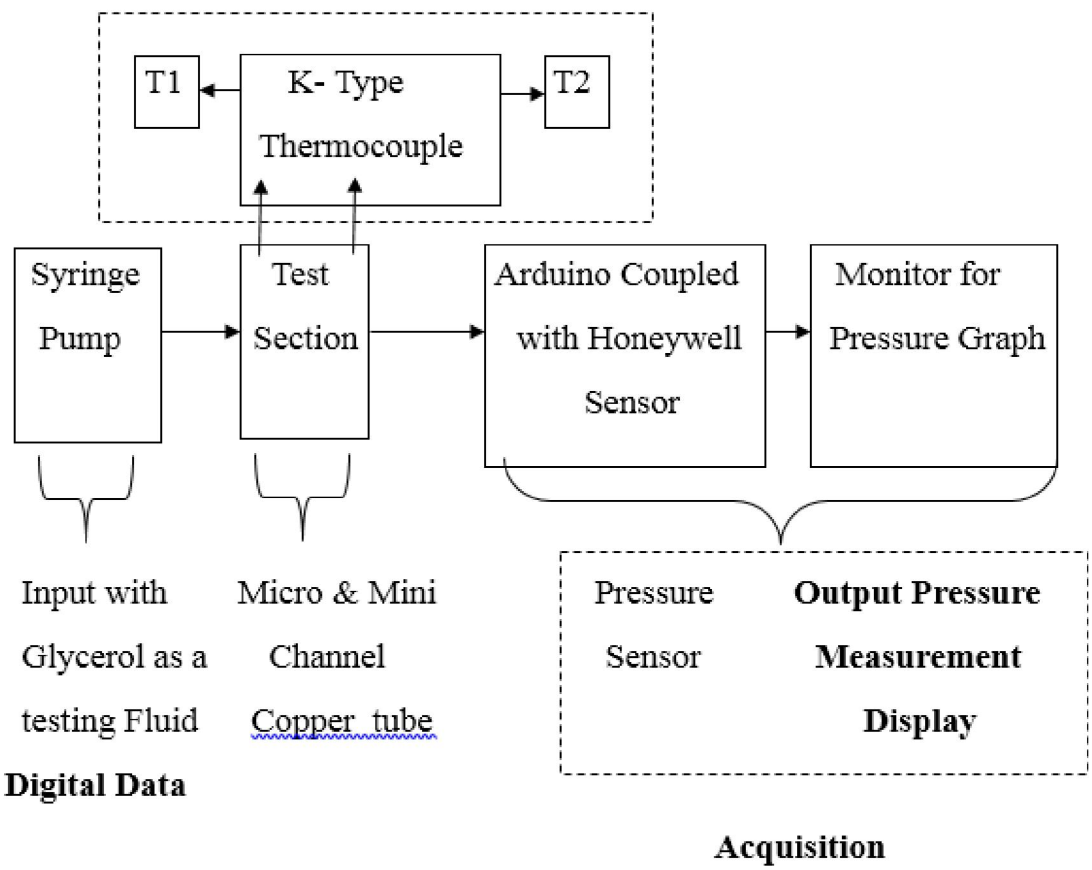
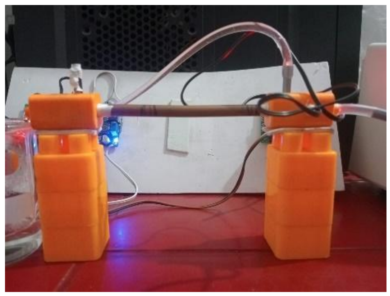


Fig No. 3.1 Block Diagram of Experimental Setup

Experimental Setup
Apparatus & Instrumentation
Test Section:
Micro/Mini channels: Fabricated in copper
Heating: resistive elements heater is use heat glycerol to achieve desired amount of heating.

2.3 Experimental Setup
Apparatus & Instrumentation
Test Section:
Micro/Mini channels: Fabricated in copper
Heating: Uniform heat flux via embedded heaters/resistive elements.



Flow Loop:
Pump: Syringe/gear pump for precise flow control.

Measurement Systems:
Pressure Sensors: Differential transducers (e.g., 0–100 kPa range, ±0.1% FS).

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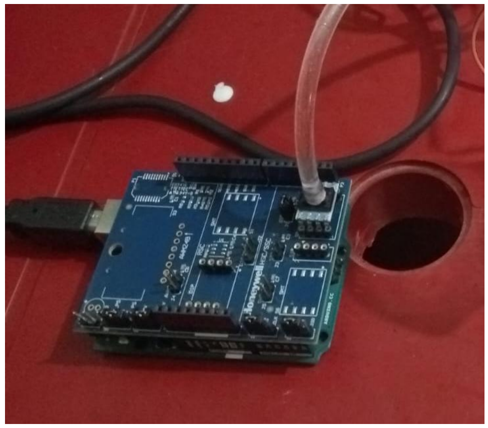
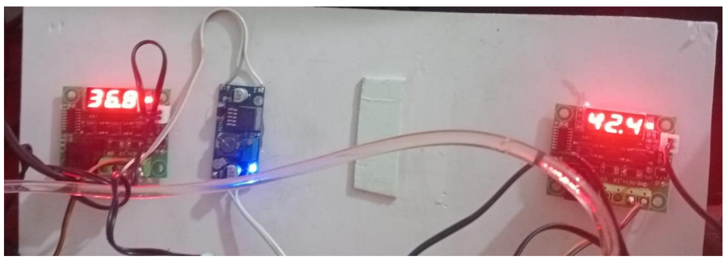


Thermocouples/RTDs: Embedded at inlet/outlet/channel walls (calibrated to ±0.1°C).



3.2. EXPERIMENTATION

Setup, Boundary condition, material properties used for Experimentation and Numerical Simulation (with Ansys)

SN	Particulars	Specification
1	Geometry used	Inner Diameter = 4 mm Outer Diameter = 6 mm Thickness = 2 mm Length of Tube, L= 100 mm
2	Boundary condition	Fluid flow rate = 226 ml/hr (For fluid velocity of 0.005 m/s) Inlet Temperature = 328 K (55 ^{o}C) Outer Surface constant temp at copper tube=307K (34 ^{o}C)
3	Fluid properties (Glycerol)	Molar Mass =92.09 kg/kmol Dynamic Viscosity = 1495 mPa.s Density = 1262 kg/m3 Thermal Conductivity = 0.27 W/m-K Coefficient of Thermal Expansion = 0.00047 1/k Specific Heat (at const pressure) = 2400 J/kg.k
4	Solid Wall Properties (Copper)	Molar Mass =63.55 kg/kmol Density = 8933 kg/m3 Thermal Conductivity = 401 W/m-K Specific Heat (at const pressure) = 385 J/kg.k

Table No. 3.2 Setup, Boundary condition, material properties

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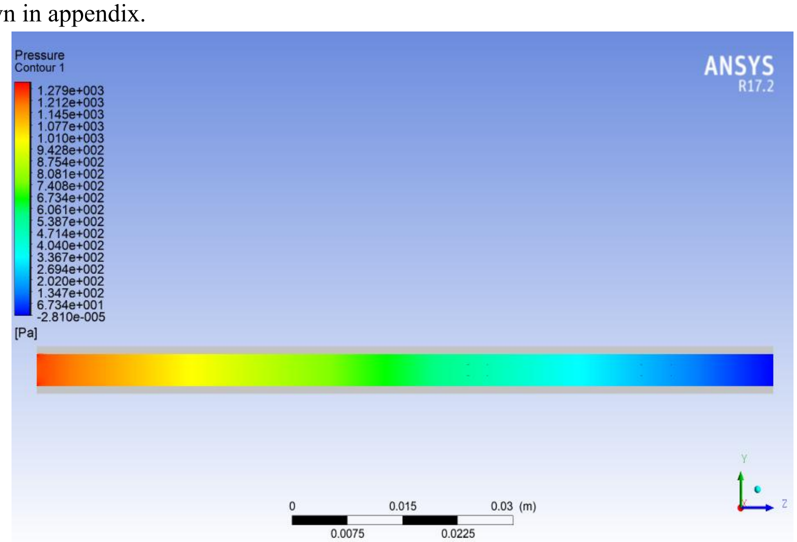
Experimental Reading:

The reading of temperature (at inlet and Outlet) and pressure (at inlet of test section of copper tube) is recorded manually and in computer as follows.

Sr. No.	Time interval (min)	Inlet Temp. T_{in} (^oC)	Outlet Temp. T_{out} (^oC)	Pressure P_{in} (PSI)
1	0 min	59	44	0.18
2	3 min	58	42	0.18
3	6 min	56	42	0.18
4	9 min	55	41	0.18
5	12 min	54	40	0.18
6	15 min	54	39	0.18
7	18 min	53	39	0.18
8	21 min	53	39	0.18

Table No. 3.3 Actual Reading of Temp. and Pressure.

The last two readings show similar values indicating steady state is reached, and that's why this reading are chosen for calculation. Also, the pressure at outlet is an atmospheric pressure and pressure sensor at inlet is indicating the gauge pressure. So, outlet pressure can be approximated to zero-gauge pressure and didn't require to measure. The Result and calculation are shown in appendix.



V. RESULT & DISCUSSION

In this chapter we have discuss the graphical results obtained from numerical simulation (Ansys). The provided figure in this chapter are line graphs showing the variation of temperature and pressure along the length of a tube for four different designs (D1, D2, D3, D4), consistent with the CFD simulation images analysed previously. Also, it include the analysis of the graphs, which show the relationship between tube diameter, pumping power, and heat transfer for the different tube designs (D1, D2, D3, D4).

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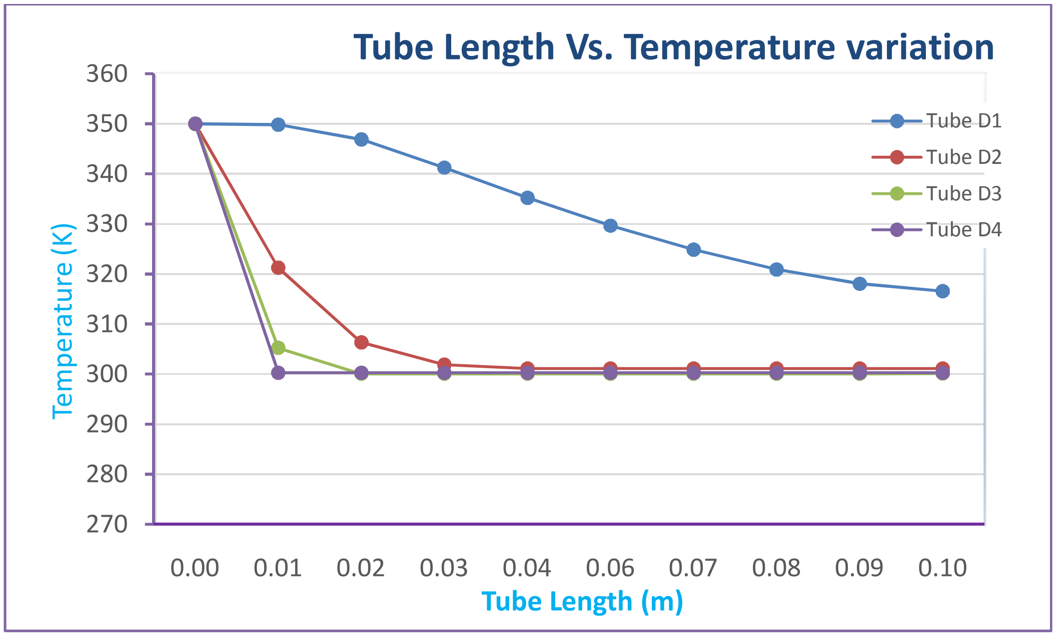

Graph No. 5.1 Graphical Plot of Tube Length Vs. Temperature variation

All four graphs start at approximately the same inlet temperature. D1, D2, D3 and D4. All tubes are introduced with a hot fluid at around 350 K while the outer wall (copper) surface temperature is at 300K. The parameter is set to vary is diameter of tube and with its cross-section area varies and in result mass flow rate is also affects.

Temperature Drop Profile:

Tube D1 (Blue): Shows the slowest temperature drop. From 350 K at the inlet, it gradually decreases to around 317 K at 0.10 m. This indicates the least effective cooling or heat transfer along the tube length among the designs. This aligns with the CFD image of D1, which showed a persistent hot core.

Tube D2 (Orange): Exhibits a much steeper initial temperature drop compared to D1. It drops from ~350 K to around 320 K by 0.01 m, and then further drops to approximately 301 K by 0.02 m. After 0.02 m, the temperature remains relatively constant at around 301-300 K. This indicates better and faster heat transfer than D1. This also aligns with the D2 CFD image showing a more confined hot region that dissipates quicker than D1.

Tube D3 (Grey): Shows an even more rapid initial temperature drop than D2. It falls from ~350 K to about 305 K by 0.01 m, and then quickly stabilizes around 300 K from 0.02 m onwards. This signifies highly effective heat transfer in the initial section of the tube. This matches the D3 CFD image where the hot region quickly diminished.

Tube D4 (Yellow): Displays the most abrupt and immediate temperature drop. It plunges from 350 K at the inlet directly to 300 K by 0.01 m, and then remains constant at 300 K for the rest of the tube length. This is indicative of extremely efficient and rapid heat exchange or mixing right at the inlet. This strongly corroborates the D4 CFD image, which showed virtually no hot fluid propagating downstream.

Conclusion for Temperature Variation:

Based on the temperature profiles, the designs show a clear progression in terms of heat transfer efficiency: **D1 < D2 < D3 < D4**.

D1 is the least efficient in cooling the fluid. **D4** is the most efficient, achieving a significant temperature drop within the first 0.01 m of the tube and then maintaining a stable, lower temperature. This implies that D4 has the best heat dissipation or mixing characteristics, leading to the fastest thermal equilibrium with the cooler surroundings

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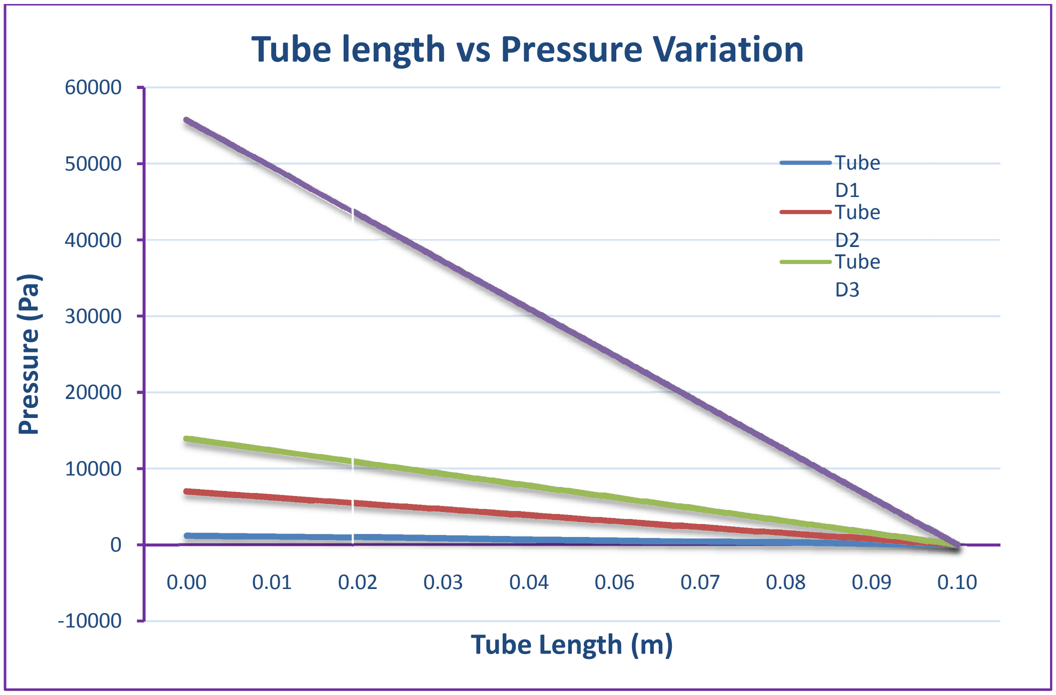

Graph No. 5.2 Graphical Plot of Tube Length Vs. Pressure Variation

Pressure Drop Profile:

Tube D1 (Blue): Shows a very minimal pressure drop, Maximum pressure drop value is close 1233 Pa across the tube length. This indicates very little flow resistance, possibly due to a very wide or straight channel.

Tube D2 (Orange): Shows a relatively small but noticeable linear pressure drop, decreasing from ~6,500 Pa to nearly 0 Pa at 0.10 m.

Tube D3 (Grey): Exhibits a moderate linear pressure drop, starting from ~14,000 Pa and decreasing to nearly 0 Pa at 0.10 m.

Tube D4 (Yellow): Demonstrates the steepest and largest pressure drop. It starts from a very high pressure of ~55,000 Pa and linearly drops to nearly 0 Pa at 0.10 m.

Conclusion for Pressure Variation:

The pressure drop (or pressure loss) along the tube length is directly related to fluid friction and flow resistance. A higher pressure drop implies greater resistance to flow, which can be caused by:

Higher fluid velocity.

Smaller tube cross-section.

Increased surface roughness.

More complex or tortuous flow paths (e.g., sharp bends, sudden contractions/expansions).

From the pressure plots:

D1 has the lowest pressure drop, suggesting the least resistance to flow.

D4 has the highest pressure drop, indicating the greatest resistance to flow.

There's a clear trade-off between efficient heat transfer (temperature drop) and pressure drop (flow resistance).

D1: Least effective heat transfer, but also the lowest pressure drops. This design would be suitable where maintaining flow with minimal energy input is critical, and temperature control is secondary or achieved by other means.

D2 & D3: Offer a good balance. They achieve significant temperature drops within the initial sections while incurring moderate pressure losses. D3 is better for temperature reduction than D2, but also has a higher pressure drop.

D4: Achieves the most rapid and complete temperature reduction, making it the most effective for heat transfer. However, this comes at the cost of the highest pressure drop. This suggests that D4's design likely involves features (like narrow constrictions, high velocities, or specific inlet geometries) that enhance heat exchange but also significantly increase flow resistance.

In practical applications, the choice of design would depend on the specific requirements:

If rapid cooling is paramount, even at the cost of higher pumping power, **D4** would be preferred.

If minimizing pumping power is critical, and a slower temperature reduction is acceptable, **D1** would be chosen.

D2 and **D3** represent intermediate solutions, potentially offering a good compromise between thermal performance and hydraulic efficiency.

Chapter No: 6

VI. CONCLUSIONS AND FUTURE SCOPE

In this chapter the salient accomplishments and major conclusions of this work are summarized and recommendations for the future are made.

6.1 CONCLUSIONS

In this work the hydrodynamics and thermal behaviour of circular microchannel present in a test rig were studied. Glycerol ($C_3H_5(OH)_3$) were used as the working fluid in the channel. A steady state computational fluid dynamics (CFD) models was simulated by ANSYS CFX 17.2 here. Based on the analysis of the circular microchannel behaviour the following conclusions can be drawn

Computed Pressure, temperatures and heat transfer were found in close agreement with the experimental values.

The diameter/ cross sectional area plays very crucial role for heat application. So by using smaller (micro) channel we can achieve the heat transfer which is not achievable by long heat exchangers.

The flow is almost laminar as velocity, density and viscosity are constant while only diameter is the variable. Since Reynolds number is decreases as diameter decrease and flow remains laminar.

Rapid cooling can be prioritized if higher pumping power is acceptable.

Minimizing pumping power becomes essential when a slower temperature reduction is tolerable.

For smaller diameter we can use with still higher velocities, as their full length is not utilized for heat transfer. This would ensure higher heat transfer but also require higher pumping power.

The pumping power not solely depends on pressure drop, but it also depends on volume flow rate (i.e. Cross section tube area and flow velocity).

Heat transfer is found higher value with larger diameter tubes due to higher surface area for heat transfer.

If the objective is to maximize the total heat added to or removed from the system, larger diameters are more effective, making them suitable for heat exchangers handling high thermal loads.

On the other hand, if the aim is to achieve a rapid temperature change within the fluid such as quickly cooling a small stream, while also minimizing absolute pumping power, smaller diameters are more appropriate, even if the total heat transfer is lower.

This approach is particularly beneficial in microfluidic applications or processes requiring swift temperature changes in small fluid volumes.

Future Scope

Modelling and Simulation of two-phase flow in micro channel.

Analysis of the boiling characteristics of nanofluids using CFD models.

The design of a microfluidic system should be application-specific and guided by the operational priorities associated with its intended use.

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