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A Review on Micro-Channel Heat Exchanger and its Optimization

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Abstract - **Micro-channel Heat Exchangers consists of a small-scale finned surface etched in silicon and a manifold system which forces liquid to flow between the fins. A numerical model of multi-dimensional flow and heat transfer was developed to optimize the design parameters. The model shows the effective heat transfer coefficients on the order oof 100 W/cm^{2}K can be achieved with pressure drop of only 1 or 2 bar. The demands of Micro-channel Heat Exchanger (MCHEX) has significantly increased due to its appreciative characteristics high mass and high heat transfer in compact design. The micro channel heat exchanger has higher surface contact area to volume ratio. They are suitable for the automotive air conditioning system due to their compact size. Efficiency of micro-channel heat exchanger increases due to increase in both sensible and latent both cooling-capacity. In this paper attempt have been made to study microchannel heat exchangers in condenser section of package units. The idea is to see how an increase in cross-sectional area through the microchannel increases the area of heat transfer. The effect of grooved cross-section which results in increase of rate of cooling for a fluid flowing through the channel have been studied. R-32 (Freon Refrigerant) is considered as refrigerant along with water for the study using CFD analysis. Two designs were considered for the study considering circular cross section and the grooved cross section considering the channel geometry. From the results of CFD analysis, it can be stated that grooved cross section has performed better in terms of heat transfer and temperature drop as compared to circular cross section. The trend towards miniaturization in various technology sectors necessitates efficient heat dissipation from compact systems like high-performance computer chips and laser diodes. Micro-channels and mini-channels offer a solution by providing large heat transfer surface area per unit fluid flow volume, making them suitable for applications in turbine blades, rocket engines, and refrigeration cooling. As heat dissipation requirements continue to increase with technological advancements, microchannel heat exchangers emerge as a promising solution due to their effectiveness in enhancing performance and reducing refrigerant quantities. However, to fully replace conventional heat exchangers, improvements in anti-corrosion technology and product flexibility are essential. Development of heat exchangers is not east as it seems. Manufacturing microchannel heat exchangers presents notable challenges despite their significant benefits, such as enhanced efficiency. However, issues like poor frost performance persist. To address this, various designs have emerged, incorporating materials like copper and utilizing aluminum flat tubes. While advancements have been made, scientists continue to strive for optimal solutions in overcoming these challenges. Microfluidic systems, developed through micromachining technology, incorporate microchannels which play a crucial role in electronics cooling. These channels are classified based on hydraulic diameter, with microchannels offering high heat transfer rates and attracting significant research interest. Early work by Tuckerman and Pease introduced microchannel heat exchangers for electronic chip cooling, stimulating further research efforts. Studies by various researchers have focused on**

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microchannel heat transfer, with inconclusive findings regarding the effects of miniaturization on heat transfer and pressure drop. Surface patterning or roughness in microchannels can promote nucleate boiling, even during single-phase heating, making them valuable for high heat flux applications.

Keywords —air-conditioning, micro-channel heat exchangers, geometrical analysis, circular section, grooved section, heat transfer behavior, Microchannel, Friction Factor, Pressure drop, manifold, flat tubes, poor frost, aluminum heat exchangers, cost effective.

I. INTRODUCTION

The purpose of a microchannel heat exchanger is to improve the overall heat transfer, which would help to reduce the temperature difference between the air and the Refrigerant. The concept of Micro-channel Heat Exchangers is similar to a human cardiovascular system, with micro-channels acting like capillaries, the single coolant flow like aorta which branches down in distribution like arteries. There are many individual flow each efficiently absorbing a fraction of watt. In heat exchanger, there are usually no heat and work interactions. The temperature drop between channel wall and coolant is only a few degree because of small scale size. The flow in MCHEX is single -phase and lamina0r flow. In laminar flow local heat transfer coefficient is inversely proportional to width of coolant channels. Fins increases effective surface area. There are three essential layers diffused together: the micro channel face sheet, the coolant distribution manifold and coolant supply block.

If the ratio of surface contact area to volume is higher than it is known as compact heat exchangers. Micro channel heat exchangers are compact heat exchangers. In 1980's use of micro-channel heat exchangers increased in high density electronic devices and in MEMS (microelectronic electric system). In households this technology was applied in single-cold air-conditioner condensers but faced big challenges such as complex gas-liquid two-phase uniform streaming.

II. PERFORMANCE OF MICRO-CHANNEL HEAT EXCHANGERS

Conventional heat exchangers were used in air-conditioners before micro-channel heat exchangers but they had some limitations in their performance such as heat transfer coefficient was significantly low as compared to micro-channel heat exchangers, resulting in low refrigeration effect and COP of the system. This drawback of conventional heat exchangers made micro-channel heat exchangers into use for air-conditioners.

Flow characteristics and heat transfer characteristics differentiates in conventional and micro-channel heat exchangers due to their structures and size. Reduced scale results in better fluid compressibility effects, increased roughness leads to increase in drag coefficient, increase in surface area to volume ratio leads to strengthening of surface forces, viscous forces, etc.

Tests were conducted by researchers on prototypes of fin-tube condenser and micro-channel condenser, for determining performance and capacity of the unit under standard climate conditions. They found out that sub-cooling of the liquid side is achieved for micro-channel heat exchangers and leads to increase in refrigeration effect. There was an increase in both latent and sensible heat capacity in (MCHEX). Cost of MCHEX is less as no copper is used. For same cooling capacity the refrigerant charge reduces up to 18%, thus reducing the refrigerant cost.

Study was conducted between micro-channel heat exchangers (MCHEX) and fin-tube heat exchangers (FTHEX) for refrigerant charge. Cooling capacity and COP of the system.

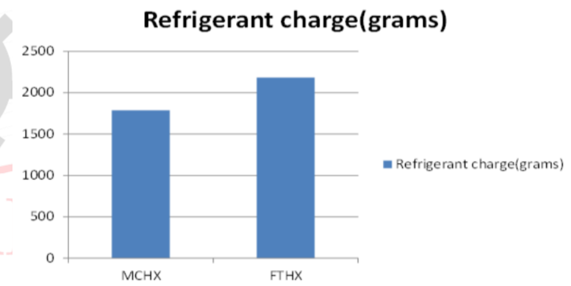

Fig. 1

According to the study it is evident that due to reduction in size of heat exchangers the refrigerant charge has also reduced by 18% in MCHEX as compared to FTHEX. [1]

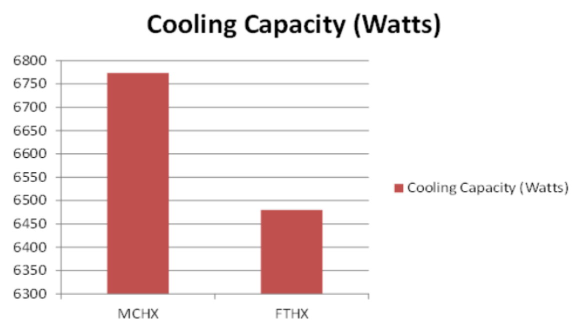

Fig. 2

According to the study it is evident that due to reduction in refrigerant charge in the system the refrigerant effect

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increases by 4.5%. MCHEX has a higher cooling capacity than FTHEX. [1]

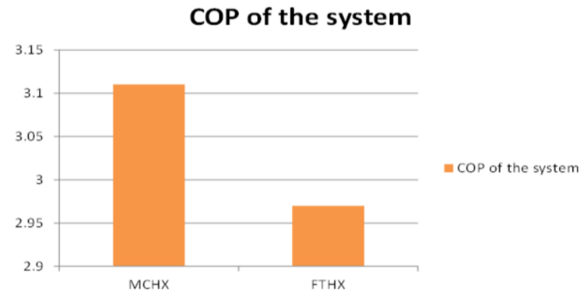

Fig. 3

According to the study it is found that COP of system increases 4.7% after using MCHEX in place of FTHEX. [1]

III. GEOMETRICAL ANALYSIS OF MICRO-CHANNEL HEAT EXCHANGER

The dimensions considered for the microchannel heat exchanger were based on actual dimensions used in industry by scaling down with a scale factor of 4:1. Heat transfer rate (watt) was calculated using the following equation given below. H = m*Cp*DT = m*Cp*(Ti -To) Where Ti and To is the inlet and outlet temperature in degree centigrade, m is the mass flow rate = 0.5 kg/m3 and Cp is the specific heat at constant pressure (for water 4.184 kJ/kg K and for R32 0.84 kJ/kg K). Components considered for analysis are Header, Refrigeration tube and fins. The study includes the design of microchannel heat exchanger and the material have been considered which yields better results for the analysis. It Consists of Inlet Temperature of fluid (TIF), Inlet Temperature of Air (TIA), Inlet Velocity of Fluid (VIF), Inlet Velocity of Air (VIA), Refrigerant (Water or R-32 (is an Freon Refrigerant), Channel Geometry (Circular or Grooved) and Material (Aluminum and Copper). [2]

Analysis was done considering water as refrigerant in micro-channel heat exchangers.

When aluminum circular grooved cross section is considered the maximum temperature of water is 3.690e+002 K and water tube is 3.608e+002 K. The amount of heat transfer taking place in this case is 2.717W. [2]

Second analysis says that when copper circular grooved cross section is considered the maximum temperature of water is 3.69e+002 K and water tube is 3.607e+002 K. [2]

Third analysis says that when aluminum grooved cross section is considered it is observed that the maximum temperature is 3.695e+002 K and 3.657e+002 K for water and reference tube respectively. y. The heat transfer rate taking place in this case is 7.106 W. From this it is observed that the rate of heat transfer taking place in case of grooved (aluminum) cross section is more as compared to circular cross section (aluminum). [2]

Now considering copper grooved cross section e it is observed that the maximum temperature encountered is 3.695 e+002 K. [2]

Another analysis was done considering R32 as the refrigerant.

The temperature gradient for refrigerant R32, for aluminum and grooved cross section, it is observed that the maximum temperature gradient is 3.380e+002 K and 3.158e+002 K for R32 and reference tube. The amount of heat transfer taking place in case of this arrangement is 9.922W. [2]

Now considering aluminum circular grooved cross section, it is observed that the maximum temperature is 3.3802 e+002 K.

The table below summarize all above analysis considering refrigerant as water and R32 for aluminum material. [2]

Table. 1

Geometry	Material	Inlet Temp	OutletTemp	HeatTransfer
Circular (WATER)	Aluminum	369.5 K	368.2 K	2.717 W
Grooved (R32)	Aluminum	338.5 K	327.1 K	4.834 W
Circular (WATER)	Aluminum	369.5 K	366.1 K	7.106 W
Grooved (R32)	Aluminum	338.5 K	315.1 K	9.922 W

From this Table it is observed that comparison is given only for aluminum material as aluminum has performed better as compared to copper material.

IV. APPLICATIONS OF MICRO CHANNEL HEAT EXCHANGER

Micro-channel and mini-channel heat exchangers stand as pivotal components within an array of industries grappling with the challenge of managing high heat flux in increasingly compact systems. This trend towards miniaturization, driven by advancements across technology sectors like computing, electronics, aerospace, and automotive, necessitates innovative solutions to efficiently dissipate heat and ensure sustained performance and longevity of critical components.[3]

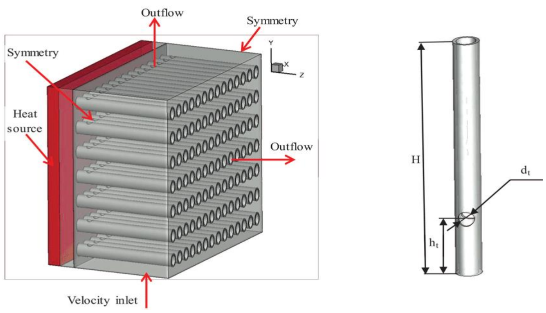

Fig. 3 Micro channel heat exchanger

In a seminal study conducted by Shambhu Prasad Shukla and Dr. D. B. Zodpe, the performance of residential air

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conditioning systems equipped with fin & tube condensers was compared against those featuring microchannel condensers. This investigation, conducted in adherence to ISHRAE standards, underscored the distinct advantages offered by microchannel condensers. Notably, these condensers demonstrated the capability to achieve sub-cooling and reduce refrigerant charge, resulting in an enhancement of overall performance and cost-effectiveness. [4]

Within the realm of electronics cooling, microchannel heat sinks have emerged as indispensable assets, leveraging their compact size and superior heat transfer efficiency to effectively manage heat generated by increasingly powerful electronic components. The efficacy of microchannel heat exchangers hinges upon several factors, including the intricate geometry of inlet and outlet manifolds, channel design, and the selection of an appropriate cooling fluid. By optimizing these parameters, engineers can maximize heat dissipation and ensure the reliability of electronic systems. [5]

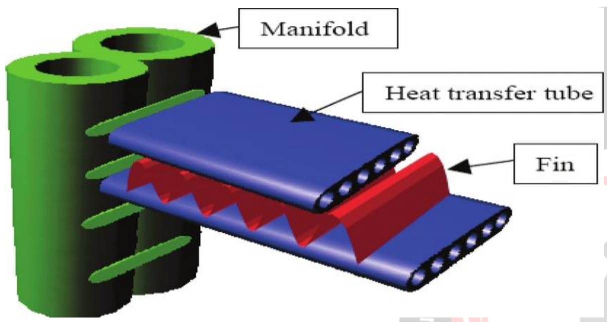

Fig. 4 Manifold, tube & fin of heat exchanger

Despite their undeniable benefits, microchannel heat exchangers present their own set of challenges. Issues such as elevated pressure drop and the potential for corrosion necessitate careful consideration during the design and implementation phases. However, ongoing advancements in manufacturing processes hold promise for mitigating these challenges. Through innovations in material science and fabrication techniques, researchers aim to enhance the durability and performance of microchannel heat exchangers, ensuring their continued viability across diverse applications. [5]

The journey towards unlocking the full potential of microchannel heat exchangers is one characterized by innovation and collaboration across academia and industry. As researchers delve deeper into understanding the intricacies of fluid dynamics and heat transfer phenomena within microchannels, new avenues for optimization and improvement continue to emerge. Ultimately, microchannel heat exchangers are poised to remain at the forefront of cooling technology, offering efficient and reliable solutions to address the evolving thermal management needs of the 21st century. [6]

V. Development Of Micro Channel Heat Exchanger For Residential Air-Conditioners

The transition towards all-aluminum parallel flow type heat exchangers marks a significant shift in the air conditioning industry, prompted by the escalating cost of copper since 2006. Traditional fin & tube heat exchangers, comprising copper tubes and aluminum fins, have been the norm, but the need for cost-effective alternatives has driven innovation in this space. [7]

In the automotive sector, the introduction of the parallel flow type heat exchanger in 1988 revolutionized cooling systems, achieving smaller size and lighter weight while enhancing heat transfer capacity. By incorporating micro-channel flat tubes and leveraging NOCOLOK brazing technology, this innovation not only reduces manufacturing costs but also improves heat transfer efficiency. [7]

Fig. 5 Aluminum fin

In the context of residential air conditioning systems, the adoption of micro-channel flat tubes brings about notable advantages. Our exclusive parallel flow evaporator, meticulously designed to meet regulatory standards, offers enhanced performance while minimizing size and weight. The parallel flow condenser, despite its reduced size compared to conventional counterparts, maintains equal capacity, thanks to optimized design and manufacturing processes borrowed from the automotive industry. [7]

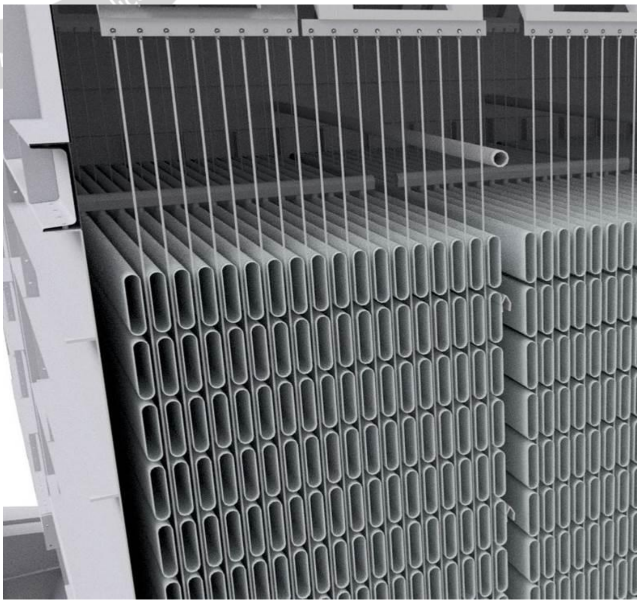

Fig. 6 Flat tubes

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To address the challenge of hetero-metal junctions during assembly, we've developed a novel piping method using specially designed STS parts. This innovation not only enhances corrosion resistance but also streamlines the assembly process, ensuring reliability and durability of the heat exchanger. [7]

Despite these advancements, challenges persist when applying all-aluminum parallel flow heat exchangers to heat pump systems. Poor frost characteristics and limitations in configuration suitability highlight areas for further improvement and research. However, the integration of vertical headers and horizontal micro-channel flat tubes in both indoor and outdoor units represents a step towards overcoming these challenges, offering simplified assembly and enhanced performance. [7]

In the pursuit of excellence, materials improvement remains a focal point. The post-coat technique utilized in aluminum heat exchangers undergoes rigorous optimization to enhance corrosion resistance and streamline manufacturing processes. By minimizing flux application and incorporating organic crosslinking agents and $Cr3+$ inhibitors, we aim to achieve higher efficiency and durability in our heat exchanger designs. [8]

In conclusion, the transition towards all-aluminum parallel flow type heat exchangers signifies a paradigm shift in the air conditioning industry, driven by the need for cost-effective and efficient cooling solutions. Through continuous innovation and improvement in materials and design, we strive to deliver high-performance heat exchangers that meet the evolving needs of residential and automotive air conditioning systems. [8]

VI. EFFECT OF DIFFERENT STRUCTURE OF MICRO-CHANNEL HEAT EXCHANGERS

Researchers tried to modify the structure of heat exchangers to comprehend the thermal properties.

Zhang et al proposed design where upper layer have more number of channels i.e. less width compared to bottom layer of microchannel. They found that due to this unequal structure, flow in lower channel is more than that of upper channel which helps in decreasing thermal resistance. [9]

Similar kind of study was done by Zhai et al, where they proposed complex channel geometry i.e. micro-channel with triangular cavities and ribs in bottom layer and conventional rectangular micro-channel upper layer. After comparing this configuration, it was observed that DL-MCHS with rectangular channel in upper layer has better thermo-hydraulics performance. Reason for this result was rectangular channel quickly takes away hot fluid and also avoid local temperature rise. [10]

Patel and Mehta developed heat exchangers with two different channels i.e. coarser and denser are used in both layers. They found out that when coolant flows through both layers of micro-channel heat exchanger in counter flow directions it has both positive and negative temperature compensation effects. At the outer region of bottom channel, coolant temperature in upper layer is lesser than that of lower layer, so coolant in upper layer takes heat from lower layer and enhances heat transfer. [11]

The use of porous materials got popular in the study of micro-channel heat sinks. Primarily porous materials were used in channels to increase the convective surface area, but this would lead to a drastic increase in pressure drop. Overcoming this situation Chuan et al made the walls of microchannel to be porous instead of solid. Resulting that pressure drop was reduced from 43% to 47% depending on the flow rate. [12]

VII. HEAT TRANSFER BEHAVIOR

The investigation focused on the friction factor, the transition from laminar to turbulent flow, and the Nusselt number in channels with a hydraulic diameter below 1 mm. It analyzed the convective heat transfer and flow friction for water flow in microchannel structures. The findings highlighted the substantial impact of geometric configuration on single-phase convective heat transfer and flow characteristics. Laminar heat transfer was observed to rely on the aspect ratio and the ratio of hydraulic diameter to center-to-center distance of the microchannels. Various micro heat exchangers were developed, such as polymer microchannel heat exchanger with aluminum separation foil, electrically powered lab-scale microchannel evaporator, ceramic counter-flow microstructure heat exchanger, among others. Experiments by Ameel et al. explored the thermal performance of stacked microchannel structures, revealing an overall thermal resistance of less than 0.1 K/W for both counter-flow and parallel-flow configurations. At low volumetric flow rates, the parallel-flow setup exhibited lower overall thermal resistance compared to the counter-flow configuration. However, at high volumetric flow rates, the overall thermal resistances of both configurations became indistinguishable. [13]

The study examined how different channel shapes, such as square, circular, rectangular, iso-triangular, and trapezoidal, affect performance. Circular microchannels performed the best overall, followed by square ones. Increasing the number of channels in a microchannel heat exchanger improves heat transfer but also raises pressure. Through numerical methods, a total heat flux of 13.6 W/cm2 was achieved with this micro heat exchanger. Counter-flow arrangements consistently yielded higher heat flux compared to parallel-flow. Heat transfer rates remained largely consistent despite variations in substrate thickness from 1.2 to 2 mm. The study also explored single-phase heat transfer in a rectangular-shaped microchannel heat exchanger using experimental data and numerical simulations. Microchannels were sealed using two layers of

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PMMA bonded to the substrate using UV light. [14]

A. DESIGN AND FABRICATION

The experimental system consists of three main parts: the test section (microchannel heat exchanger), syringe system, and overall testing loop, as shown in Figure. This heat exchanger, made of aluminum, can be used to cool electronic devices or for other cooling purposes. The aluminum substrate has specific properties: thermal conductivity of 237 W/(mK), density of 2,700 kg/m3, and specific heat at constant pressure of 904 J/(kgK). Its thickness is 1.2 mm**.**

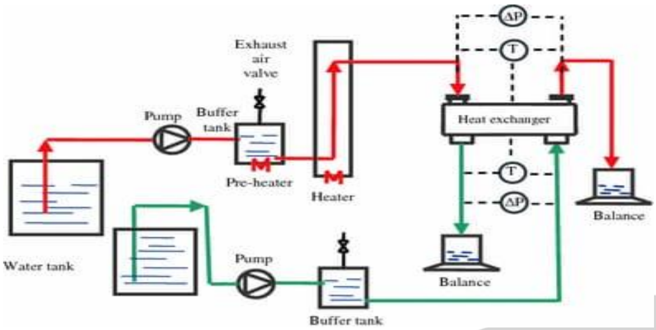

Fig. 7

Each side of the heat exchanger has 10 microchannels, with a length of 32 mm each. These microchannels are rectangular in shape, with a width of 500 μm and a depth of 300 μm, resulting in a hydraulic diameter of 375 μm. The distance between two microchannels is 500 μm. [15]

Table 2

Material	Density kg/m3	Thermal conductivity W/(mK)
PMMA	1420	0.19
Glass wool	154	0.051

B. NUMERICAL METHOD

Numerical study of the behavior of the microchannel heat exchanger with 3D single-phase heat transfer was done by using the COMSOL Multiphysics software. For this study, water was used as the working fluid. No internal heat generation is allowed, resulting in Qi = 0. Modulization of this model was done by using 26,151 mesh elements; the number of degrees of freedom was 76,411; a relative tolerance was 10-6. the inlet temperature and the mass flow rate of the cold side were fixed at 22.5 ºC and 0.2043 g/s, respectively. For the hot side, the mass flow rate was fixed at 0.2321 g/s and the inlet temperatures were varying from 45 to 70 ºC. The convective heat transfer coefficient between the wall and the ambient used for this solver was 10 W/(m2K). [16]

C. EXPERIMENTAL RESULTS

1. Thermocouple wires: Model PT-100, made by Omega
2. Pump for the cold side: Model VSP-1200, made by Tokyo Rikakikai
3. Pump for the hot side: Model PU-2087, made by JASCO
4. Heater: Model AXW-8, made by Medilab
5. Differential pressure transducer: Model PMP4110, made by GE Druck
6. Micro-electronic balance: Model TE-214S, made by Sartorious. [17]

For the counter-flow case, the outlet temperature at the cold side is higher than that obtained at the hot side. However, for the parallel-flow case, the outlet temperature at the cold side is lower than that obtained at the hot side. . The maximum difference of the heat flux is 1.174 W/cm2; it occurs at high inlet temperature of the hot side for the parallel-flow arrangement, and the maximum percentage error is 9.7%. When the inlet temperature of the hot side is increased, the heat transfer rate Q of the heat exchanger increases also. the heat transfer result obtained from the effectiveness (NTU method) increases with rising inlet temperature at the hot side. comparison between numerical and experimental results of the effectiveness (NTU method) for the microchannel heat exchanger with counter-flow. The maximum difference of the effectiveness is 0.009; it occurs at low inlet temperature of the hot side, and the maximum percentage error is 1.6%. [18]

VIII. MICROCHANNELS

A. CLASSIFICATION

The classifications of channels are proposed by Mehendale et al. they distributed the ranges of channel from 1 to 100 μm as microchannels, 100 μm to 1 mm as meso-channels, 1mm to 6 mm as compact passage, and more than 6 mm as conventional passage. Due to high heat transfer rate, microchannel becomes an interested area for researchers in last two decades. Tuckerman and Pease was first announced the conception of microchannel heat exchanger for high heat flux in electronic chip for cooling. the single phase forced convection through microchannels and concluded that the literature is inconclusive with respect to the effect of miniaturization on heat transfer and pressure drop. microchannels with surfaces patterned or rough surfaces through micro pin fins essentially have nucleation sites. [19]

Table 3

Conventional Channel	**Dh > 3 mm**
Minichannels	**3 mm ≥ Dh > 200 μm**
Microchannels	**200 μm ≥ Dh > 10 μm**

B. PRESSURE DROP

The pressure drop is the function of friction factor. The investigators usually dignified the pressure drop at the inlet and outlets of the channel. experimental results for round and square microchannel with 15 – 150 μm hydraulic diameters which is made of fused silica and stainless steel, methanol, isopropanol, distilled water taken as working

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fluid. first found the friction factor in silicon microchannels. Different microchannels were tested, having different hydraulic diameter (55.81, 55.92 and 72.38 μm) in trapezoidal cross-section. Gases (N2, H2, Ar) were used as a working fluid and the dignified values were greater (10 – 30%) than those expected in conventional theory. dignified the friction factor in a trapezoidal silicon microchannel with 45μm hydraulic diameter and for a rectangular microchannel with 67 μm hydraulic diameter. [20]

the friction factor for a fully through silica micro-pipes with nitrogen gas as a test fluid having a different hydraulic diameter (3, 7, 10, 53, 81 μm) with Reynolds numbers going from 30 and 20 000. laminar convective heat transfer in the rectangular cross-section microchannels which is subjected to H1 boundary condition. studied pressure drop in smooth arbitrary cross-sections channels to find relationship for fRe√A using existing logical solutions. They establish that square root of cross-sectional area √A, as the length scale, is larger to the conventional hydraulic diameter. the apparent friction factor is a weak function of the geometrical shape of the channel. [21]

C. NUSSELT NUMBER

Nusselt number represents the enhancement of heat transfer through a fluid layer as a result of convection relative conduction across the same fluid layer. experimental setup of circular micro-ducts with different hydraulic diameters investigated single-phase laminar flow. the heat transfer rate increased due to advanced relative roughness in 620 μm tube because Nusselt number affected by relative roughness. And also showed the good agreement between their experimental results of Nusselt number to the conventional theory. the heat transfer in converging diverging microchannel using de-ionized water as a working fluid to obtain Nusselt number. [22]

They proposed a pragmatic co relation for calculate the Nusselt number in converging diverging microchannel heat exchanger. the laminar forced convection in rectangular etched silicon microchannels using water as tested fluid. in rectangular microchannel of 425 μm hydraulic diameter with R124 as a tested fluid measured the Nusselt number. Also in turbulent regime the Nusselt number improved with the Reynolds number. Nusselt number are varies for different geometrical shapes and sometimes the experimental results are matched with the conventional results. [23]

IX. CONCLUSION

From the microchannel heat exchanger considering channel geometry, it is observed that grooved cross section provides more heat transfer as the surface area is more as compared to circular cross section. The heat transfer rate observed was 7.106W in case of grooved cross section considering water as refrigerant. – The heat transfer rate observed is 9.922W for grooved section considering R32 refrigerant. From this it can be concluded that high heat transfer rate in case of grooved cross section was observed when R32 was used in case of microchannel heat exchangers and the corresponding temperature drop is also more as compared to water when used as refrigerant. From these results, it is evident that R-32 as a refrigerant can provide much better results in comparison with water. Micro-channel heat exchangers offer significant advantages over traditional fin and tube types in HVAC systems, but challenges like anti-corrosion technology, refrigerant distribution, and manufacturing standards persist. Despite these hurdles, ongoing research aims to optimize heat transfer and address manufacturing issues, paving the way for broader adoption in the industry. To replace aluminum parallel flow heat exchangers in air conditioners, improvements in anti-corrosion technology, flexibility for product application, and refrigerant distribution are crucial. Unlike fin and tube heat exchangers, which offer versatility in design, aluminum parallel flow exchangers lack flexibility, necessitating module design and hybrid systems. Additionally, addressing refrigerant flow mal-distribution requires dynamic and static control mechanisms independent of operating conditions. Despite advancements in fin and tube designs, the all-aluminum parallel flow heat exchanger remains a favored alternative, emphasizing the need for further research and development. The analysis suggests that advancements in micro-fabrication techniques have led to improved control over channel cross-sections and reduced surface roughness in microchannels. However, understanding fluid behavior and heat transfer mechanisms in these channels remains a scientific challenge. Experimental and numerical investigations were conducted on a microchannel heat exchanger with rectangular channels, focusing on heat transfer behaviors of single-phase fluid in both counter-flow and parallel-flow configurations. A heat flux of 17.81×10^4 W/m^2 was achieved for water, with counter-flow consistently outperforming parallel-flow configurations. The study recommends employing counter-flow in most cases. Results showed good agreement between numerical simulations and experimental data, with a maximum percentage difference of less than 10%.

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