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# Analysis of Heat Exchanger for Single-Phase Cooling Applications using Micro-channels of Copper Material

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## Abstract

*The design of a microchannel heat exchanger can be achieved using various approaches. The design includes various materials, such as ceramics, silicon, metals, and polymers, that are used to make microchannels, depending on their specific requirements. Polymers such as silicon, glass, and other polymeric materials are utilized on metallic substrates. The current study includes microchannels fabricated from metallic copper. Further, the design solutions do not consider the implications of the second law of thermodynamics. Hence, performing an energetic analysis of microchannels is imperative to design and assess thermodynamic systems that use them efficiently. One technique to improve a thermodynamic system's efficiency is using a well-designed microchannel heat exchanger with excellent energetic performance. This can be achieved by creating a thermodynamic system that eliminates energetic losses and limits only unavoidable losses. The use of high-conductivity material like copper also achieves this. To identify possible reasons for exergy loss and perhaps address them, a thorough energetic analysis of an existing heat exchanger is necessary. A microchannel heat exchanger with 19 microchannels in a flat tube is considered for this study. The study finds the energetic losses, which are useful for the thermal design of the heat exchanger.*

**Keywords:** *Copper Microchannel, Exergy, Heat Exchanger, Second-Law Efficiency, Thermal Design*

## 1.0 Introduction

Experiments have been carried out utilizing a readily accessible heat exchanger design and simulation program, as well as Computational Fluid Dynamics (CFD) modelling. Demonstrations are conducted to compare material consumption, refrigerant charge, volume, and heat transfer performance. Research has shown that by utilizing internally improved copper tubes, condenser coils can be engineered to function with a reduced amount of refrigerant and have the possibility of being lighter and more compact compared to commercially available aluminium coil designs that use microchannel tubes[1].

Microchannels utilizing Micro Electromechanical Systems (MEMS) have garnered significant attention in the disciplines of microfluidics and biomedicine during the past four decades, as demonstrated by a recent study. Manufacturers have responded positively to polymers due to their improved properties and mass flexibility. Javaid Afzal *et al.* have demonstrated that there is still a strong need for advanced heat dissipation technologies. As a result, there will be a significant increase in the implementation of tailored microchannels using polymers and composites on a wider scale in the coming decades[2].

The utilization of microchannel heat exchangers in the food processing industry has experienced a recent

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surge. The study conducted by Neha Bisht *et al.* examines the various uses of copper-based engineered materials in medical devices, wound dressings, personal protective equipment, and self-cleaning surfaces. They have stated that the infectivity in the CuO film is significantly diminished. This fact is a compelling incentive for using copper as a microchannel material[3].

The properties of the substrate material and the features of the active side can impact the cycle of bubble formation and release, which in turn affects the pace of heat transmission and the pressure drop in microchannel evaporators. Zaidi *et al.* conducted an empirical investigation on flow boiling patterns, heat transfer rates, and pressure drop in evaporators consisting of several microchannels built of copper and aluminium. The study's findings suggest that aluminium heat sinks can provide thermal performance like copper heat sinks and are suitable for cooling high heat flux systems. Choosing the right heat sink material is crucial when designing micro-evaporators, and copper is one of the options available. The reason for this is that copper possesses exceptional thermal conductivity, as well as being highly malleable, easily machinable, and recyclable[4].

Ignacio Lopez Paniagua *et al.*[5] have identified three main pathways by which exergy loss occurs, resulting in irreversibility. The three primary mechanisms of heat loss are convection between the fluid streams, frictional losses resulting from fluid flow through the tubes, and heat dissipation to the surrounding environment caused by temperature disparities. The third loss is dependent on the ambient temperature. When the temperature decreases, the exchanger releases energy to the surrounding environment. If the surrounding environment's temperature surpasses the exchanger's temperature, the flow direction will invert. It is widely observed that these three losses often occur together[5].

Saberi *et al*. have also experimented with various materials such as copper, aluminium, and their composites. Their investigations in the realm of materials have resulted in the creation of cellular copper-based materials utilized in industrial sectors such as filtration, fuel cell technology, and heat exchange systems. Nevertheless, owing to copper's superior thermal properties, it is seen as a more favourable substitute for microchannels[6].

Kotas *et al.* have found three elements that lead to irreversibility in heat exchangers. The heat transfer in this system is influenced by three factors: the thermal exchange between the hot fluid and cold fluids, the heat transfer between the heat exchanger and its surroundings, and the pressure drop caused by the fluid movement. Among these three losses, the heat transfer between the exchanger and the surroundings is usually ignored because it makes up a small fraction of the total losses[7].

Ozdemir *et al.* have done an energy-economic analysis of microchannels for single-phase flow. Rectangular plain copper microchannels were considered for the analysis. The performance was also based on the relative cost difference and unit cost per unit product. It was concluded that the cost is directly proportional to the aspect ratio for the microchannels for a given test section length[8].

Irreversibility arises when heat is exchanged between two streams, leading to a continuous reduction in temperature. The quantification of this can be achieved either by empirical measurements or by utilizing simulation methodologies[9]. The present study provides data on the temperature fluctuations along the whole extent of the microchannel. The temperature distribution at intermediate places throughout the length of microchannel tubes provides significant data. This data allows for the calculation of exergy losses associated with it. Furthermore, additional factors are necessary, including heat transfer coefficients, exchange surface areas, tube cross sections, fluid velocities, etc[10]. The main causes of irreversibility are the loss of exergy due to a reduction in temperature and the loss of exergy due to head losses. The dissipation of heat to the surroundings does not necessarily lead to the depletion of exergy, especially in this scenario where the surrounding air is used as a cooling agent. The total exergy loss in the heat exchanger is the sum of these three separate exergy losses[11,12].

Research conducted by different scholars in the microchannel sector shows that MCHX is extensively employed for two-phase flows, but there is quite limited documentation for single-phase flows. The present study aims to address this gap in the existing literature, with a specific emphasis on the exergy analysis of MCHX.

## 2.0 Exergy Analysis

To do an exergy analysis of a microchannel heat exchanger, it is necessary to compute each of the four terms individually. The data includes only the input and output conditions of both fluids, along with their corresponding thermodynamic properties. Therefore, it is crucial to devise a method for measuring exergy losses[13]. To implement this method, it is imperative to calculate every term in Equation (1) as given.

$$\dot{L} = T_0\dot{\sigma}_{\nabla T} + T_0\dot{\sigma}_{\nabla \mathrm{P}} + \dot{B}_{\mathrm{Q}} \tag{1}$$

$$\dot{B}=\int d\,\dot{Q}\mathrm{surr}\,(1-\frac{T_0}{T}) \tag{2}$$

$$\dot{\sigma}\Delta\mathrm{T} = \int d\,\dot{Q}\mathrm{exch}\,(\frac{1}{T_c} - \frac{1}{T_h}) \tag{3}$$

$$\dot{\sigma}\Delta\mathrm{P}= -\dot{m}\mathrm{c}\int \frac{v_c dP_c}{T_c}\, -\dot{m}\mathrm{h}\int \frac{v_h dP_h}{T_h} \tag{4}$$

$$\dot{L}=\sum\nolimits_{\forall J} \dot{\mathrm{E}}j \tag{5}$$

The term on the right-hand side of Equation (2) corresponds to the integration throughout the complete outer surface area along the length of the microchannels. An "exchanger" is a term used to describe the process of heat transfer between a system and its surroundings within a defined volume. The variable "T" represents the temperature of the exchanger. The text provides information about the heat absorbed by the cold fluid, specifically the ambient air in this context, as well as the mass flow rate of the cold fluid. The value will be negative because of the transfer of heat from the exchanger to its surroundings.

The exergy of a heat exchanger can be calculated by conducting an exergy balance if the inlet and outlet parameters and mass flow rates are established. To compute the integral terms in Equation (2) and Equation (3), it is important to possess knowledge about the temperatures at intermediate locations along the length of the exchanger, both for the hot and cold fluids. Equation (4) can be solved using Equation (1) later.

The energy transfer in the heat exchanger takes place through two distinct mechanisms: the transfer of heat between the two fluid streams, and the release of heat from the exchanger to the surrounding environment[14]. The two heat flows are denoted as "Q1" and "Q2", and their values are calculated using the heat balancing equations.

$$\dot{Q}\mathrm{c} = \dot{m}\mathrm{c}\,.\,(h_{c,o} - h_{c,i}) \tag{6}$$

$$\dot{Q}\mathrm{h} = \dot{m}\mathrm{h}\,.\,(h_{h,o} - h_{h,i}) \tag{7}$$

It is important to mention that Qc has a positive value whereas Qh has a negative value, as the cold fluid absorbs heat and the hot fluid releases heat. Hence, the dissipation of energy to the surrounding environment $dQ_{surr}$ is

$$\dot{Q}\mathrm{surr} = \dot{Q}\mathrm{c} + \dot{Q}\mathrm{h} \tag{8}$$

The heat exchange between the two streams of fluids is given by Equation (9).

$$\lceil \dot{Q}exch \rceil = \min\,(\lceil \dot{Q}\mathrm{c} \rceil, \lceil \dot{Q}\mathrm{h} \rceil) \tag{9}$$

The total exergy loss $\dot{L}$ Is determined by Equation (1), which is derived by analyzing the exergy at the inlet and outflow of both fluids. Equation (10) expresses the relationship between this and the ambient temperature, specific enthalpy, and entropy.

$$\dot{\mathrm{L}} = \sum\nolimits_{\forall \mathrm{j}} \dot{\mathrm{E}}\mathrm{j} = \dot{m}\mathrm{h}\,.\,(\mathrm{eh,\,i} - \mathrm{eh,o}\,) + \dot{m}\mathrm{c}\,.\,(\mathrm{ec,\,i} - \mathrm{ec,o}\,) =$$
$$\dot{m}\mathrm{h}\,.\,(\mathrm{hh,\,i} - \mathrm{hh,o} - \mathrm{To}\,.\,(\mathrm{sh,\,i} - \mathrm{hh,o}\,)) +$$
$$\dot{m}\mathrm{c}\,.(\mathrm{hc,i} - \mathrm{hc,o} - \mathrm{To}\,.\,(\mathrm{Sc,i} - \mathrm{Sc,o}\,)) \tag{10}$$

The results are derived by referencing the characteristics of water and air from a properties table and utilizing the equations above at various places along the length of the microchannels.

## 3.0 Parameters under Study

The current research focuses on two conflicting objectives: parametric analysis and size estimation. To evaluate the performance of the heat exchanger, it is crucial to consider these parameters across the complete range of possible values, as shown in Table 1.

Augmenting the quantity of channels results in a simultaneous rise in efficiency and pressure drop. Furthermore, circular channels have superior thermal and hydraulic performance compared to other channel designs[9]. The current study is conducted based on the geometric characteristics listed in Table 2.

**Table 1.** The range for operating parameters

| Parameter | Operating Range |
|---|---|
| The inlet temperature of the fluid (Thi) | $80^oC$- $90^oC$ |
| Outlet temperature of fluid (Tho) | $70^oC$ - $80^oC$ |
| The inlet temperature of air (Tci) | $20^oC$ - $40^oC$ |
| The pressure of the system | 1.1 bar -1.5 bar |
| Mass flow rate inside microchannel tubes ($\dot{m}$) | 0.05kg/sec - 0.20kg/sec |
| Velocity fins side | 10 m/s – 35 m/s |

**Table 2.** The range for geometric parameters

| Geometric Parameter | Value/Range |
|---|---|
| Microchannel hydraulic diameter | 0.5 – 1 mm |
| Length of Microchannel | 200 mm |
| Type of fins on Airside | Plain fins |
| Fin spacing | 0.5 mm |

## 4.0 Results and Discussions

The exergy study of a microchannel heat exchanger is presented in a tabular format and thoroughly examined for single-phase flow. The study also examined and addressed the impact of the length of the microchannel that is heated and the surrounding temperature on several factors such as total exergy loss, exergy efficiency, and irreversibility ratio.

**Table 5.** Global analysis of microchannel heat exchanger

| | Watt |
|---|---|

**Table 3.** Estimates at intermediate points along the length of microchannels

| Intermediate points along Microchannel length (mm) | 40 | 80 | 120 | 160 | 200 |
|---|---|---|---|---|---|
| Total exergy loss $L^{\cdot}$ | 940.99 | 1059.53 | 933.43 | 940.99 | 880.46 |
| Exergy loss surr $B^{\cdot}$ | 469.95 | 516.02 | 448.98 | 437.89 | 395.00 |
| Exergy loss temp drop $\dot{\sigma}$ ΔT | 13.98 | 13.43 | 13.09 | 12.92 | 12.74 |
| Exergy loss press drop $\dot{\sigma}$ ΔP | 457.54 | 530.00 | 470.94 | 489.59 | 471.96 |
| % $\dot{\sigma}$ ΔT exergy loss | 1.44 | 1.27 | 1.45 | 1.44 | 1.53 |
| % $\dot{\sigma}$ ΔP exergy loss | 48.62 | 50.02 | 50.45 | 52.03 | 53.60 |
| Irreversibility Ratio Ø | 75 | 49 | 17 | 17 | 20 |

**Table 4.** Effect of the surrounding temperature

| Surrounding Temperature $^0$C | 30 | 33 | 36 | 39 | 42 |
|---|---|---|---|---|---|
| Exergy loss surr B˙ | 1001 | 912 | 831 | 754 | 681 |
| Exergy loss temp drop σ˙ ΔT | 13.98 | 16.11 | 14.68 | 13.32 | 12.032 |
| Exergy loss press drop σ˙ ΔP | 1013 | 1074 | 1137 | 1197 | 1253 |
| % σ˙ ΔT exergy loss | 6.9 | 8.1 | 7.4 | 6.78 | 6.18 |
| % σ˙ ΔP exergy loss | 50 | 53.6 | 57.4 | 61 | 64 |
| Irreversibility Ratio | 72 | 67 | 77 | 90 | 104 |

| | |
|---|---|
| Total exergy loss | 1301.39 |
| Exergy loss surr | 619.06 |
| Exergy loss temp drop σ˙ ΔT | 13.43 |
| Exergy loss press drop σ˙ ΔP | 668.90 |

Figure 1 depicts the temperature distribution along the length of a microchannel. The temperature variation resulting from heat transfer between the hot fluid and the cold fluid is non-linear and follows a logarithmic profile. The ambient air utilized as the cold fluid maintains a consistent temperature at the entrance. As previously stated, the overall exergy loss is the combined amount of exergy loss caused by a decrease in temperature, a decrease in pressure, and heat loss to the surrounding environment[2]. Figure 2 illustrates the changes in exergy losses over the length of the microchannel. The impact on the three components of total exergy loss at intermediate places along the channel length has been elucidated. From the picture, it is evident that the exergy loss to the surroundings decreases as the temperature of the heat exchanger drops throughout its length. On the other hand, the trends indicate that the other two components grow along the length due to the decrease in temperature differential and fluid pressure. The lowering ambient

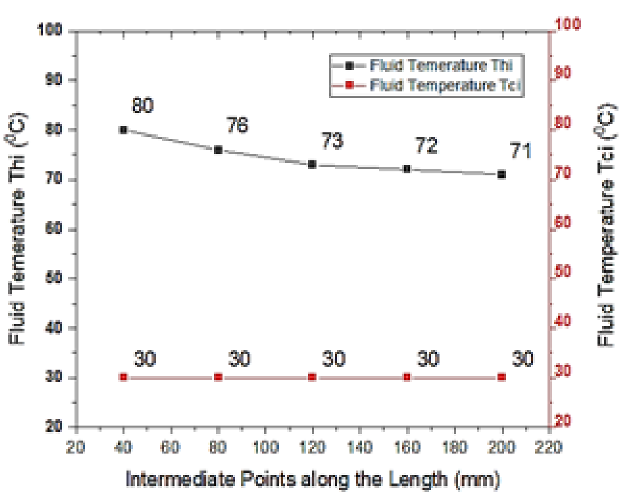


**Figure 1.** Temperature values of hot and cold fluid along the channel length.

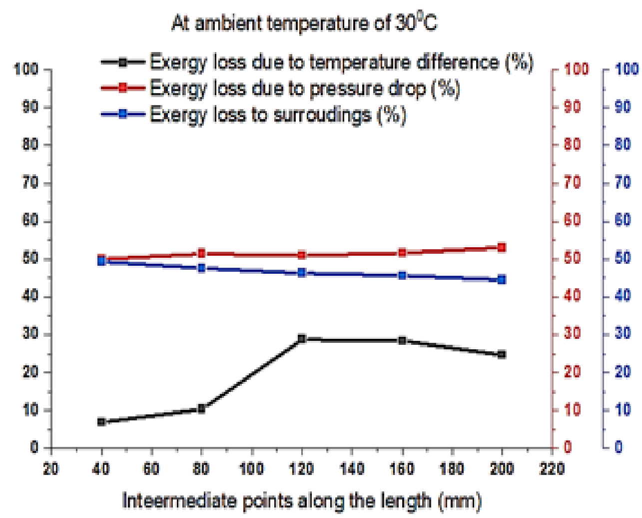


**Figure 2.** Dependence of exergy components on the microchannel temperature.

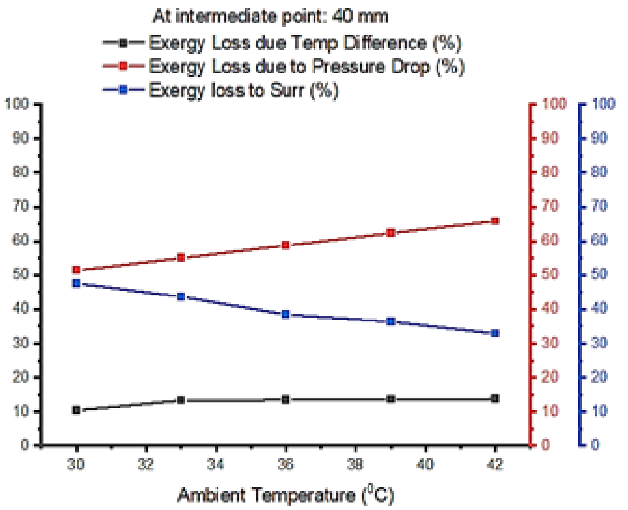


**Figure 3.** Effect of surrounding temperature on exergy loss components.

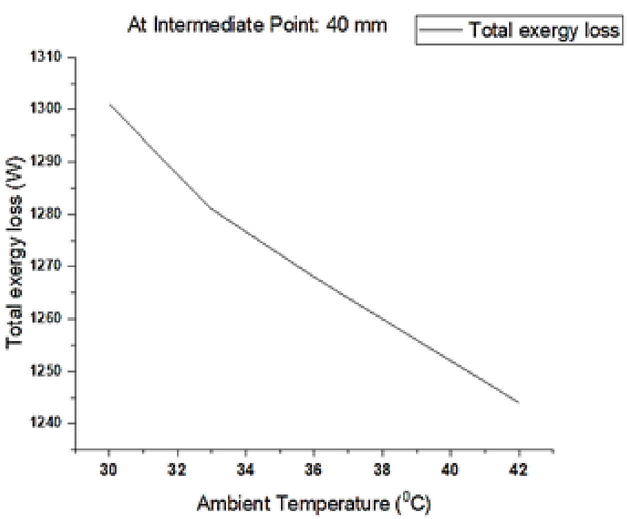


**Figure 4.** Dependence of total exergy loss on ambient temperature.

temperature is responsible for the similar patterns observed in Figure 3. The primary contributors to exergy loss are the temperature difference and pressure drop, which have a greater impact than the exergy loss to the surrounding environment. This is apparent from the patterns depicted in Figure 4. Figure 5 demonstrates the noticeable influence of temperature and pressure decrease on the surrounding environment.

The overall temperature of the heat exchanger exhibits a declining pattern along the length of the microchannels,

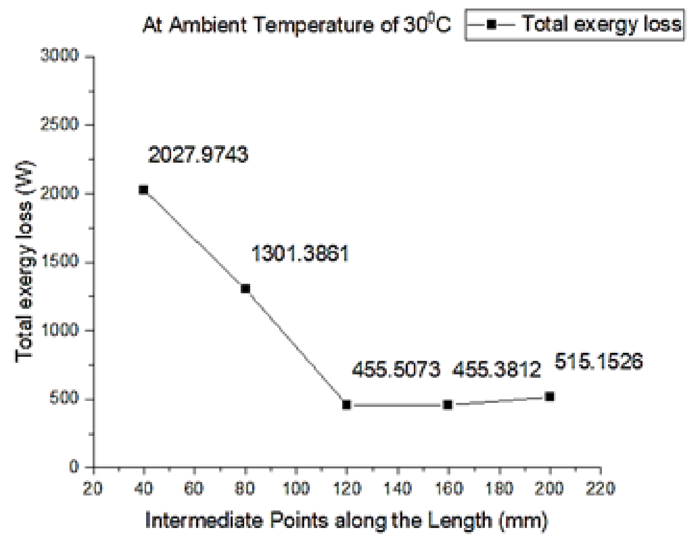


**Figure 5.** Effect of channel heating length on the total exergy loss.

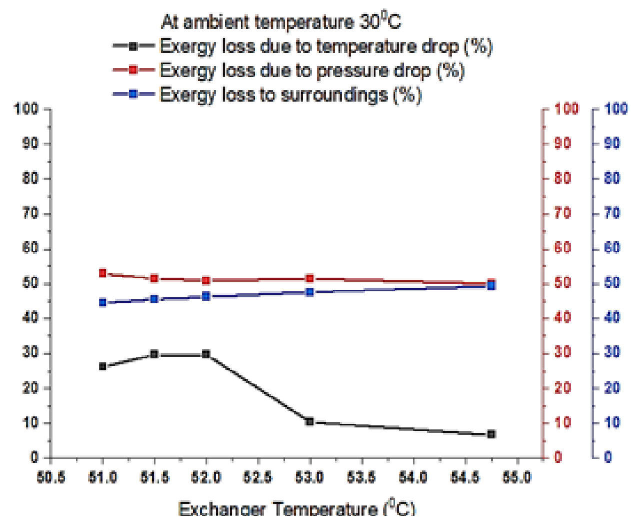


**Figure 6.** Effect of exchanger temperature on exergy loss components.

resulting in a continuous decrease in temperature at intermediate locations along the length. Figure 6 illustrates the exergy loss of several components caused by variations in heat exchanger temperature. It has been noted that the amount of exergy lost to the surroundings reduces as the temperature lowers, while the losses caused by temperature drop and pressure drop show an increasing pattern. Once again, it is proposed that there is a reduction in the overall exergy loss at the intermediate locations along the length, which is mostly owing to

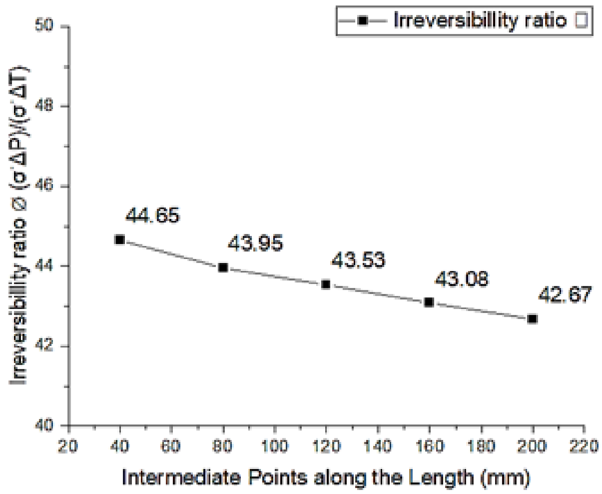


**Figure 7.** Effect of channel heated length on irreversibility ratio.

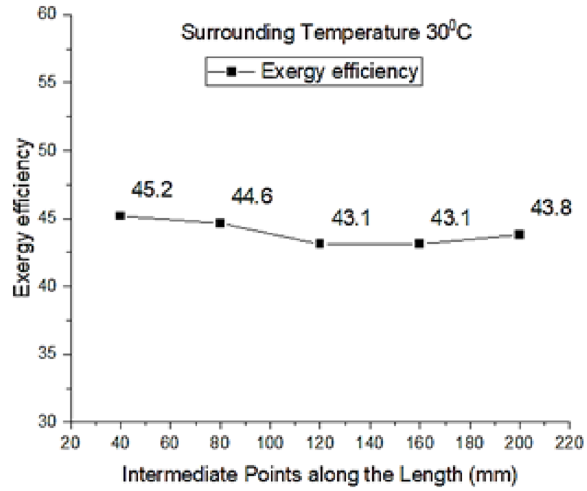


**Figure 9.** The effect of channel heated length on exergy efficiency.

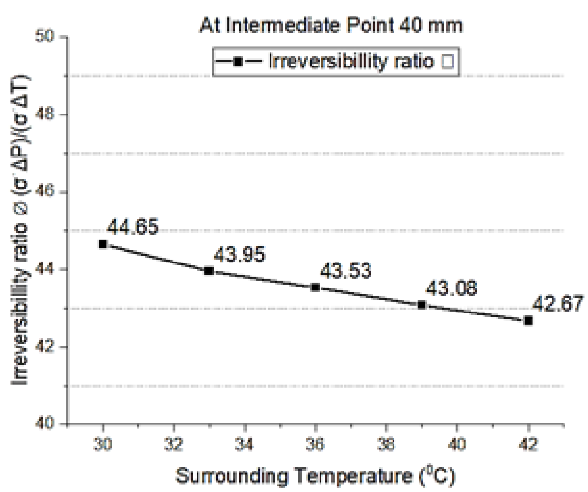


**Figure 8.** Effect of surrounding temperature on irreversibility ratio.

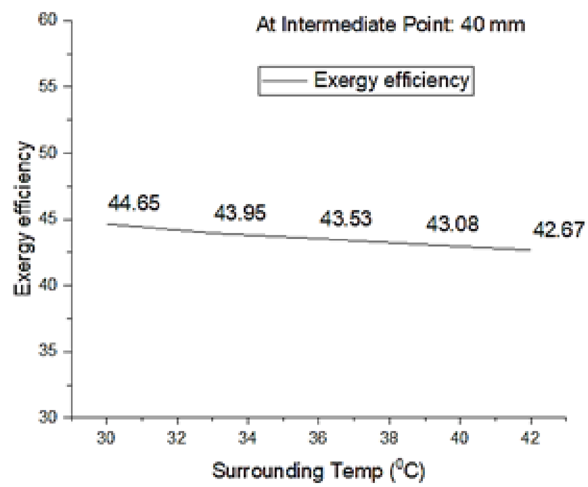


**Figure 10.** Effect of surrounding temperature on exergy efficiency.

the greater influence of exergy loss on the surrounding environment.

It is important to acknowledge that numerous other authors have discovered other methods for determining the overall exergy loss, which in turn represents irreversibility. A novel methodology has been devised in Bejan's work[15,16]. A novel exergetic parameter, known as the irreversibility distribution ratio, has been proposed. It is defined as an . Theoretical analyses of this parameter for various scenarios of microchannel heat exchangers have indicated that the value of this parameter should be minimized for any specific microchannel[17]. Figure 7 illustrates a declining trend in this parameter along the intermediate points of the length, indicating a decrease in the relative dominance of temperature drop. The reason for this is clearly due to the logarithmic decrease in temperature as we move along the intermediate points of the microchannels. Similarly, Figure 8 demonstrates the correlation between rising ambient temperature and the observed phenomenon.

Essentially, the exergetic efficiency of the microchannels may be comprehended by referring to Figure 9 and Figure 10, as they exhibit comparable patterns. It is evident that when the ambient temperature rises, there is a corresponding increase in the temperature of the cold side fluid, while the amount of exergy lost to the surroundings decreases. Therefore, this leads to a decrease in overall exergy losses and, eventually, a reduction in exergetic efficiency. The patterns also indicate that shorter microchannels result in increased irreversibility distribution ratios and efficiency. This is further supported by the fact that to maintain a constant pressure drop for a given mass flow rate, it is necessary to increase the number of channels rather than increasing the length[18]. This ensures that the ratio of length to the fourth power of the diameter remains constant.

## 5.0 Conclusion

The exergetic efficiency of microchannels was evaluated under single-phase conditions, considering a range of ambient temperatures from 30ºC to 42ºC. The assessment was conducted at several positions along the length of the microchannel. The study revealed a negative correlation between exergetic efficiency and ambient temperature, as depicted in Figure 10. This can be attributable to the decreased losses to the surrounding environment. The efficiency is shown to decrease at the intermediate places along the length of the microchannel, as shown in Figure 9. The reduction exhibits a linear and somewhat steady pattern. Nevertheless, shorter heated lengths of microchannels exhibit higher efficiencies, with a decrease in efficiency of 0.7% for every 100 mm.

## 6.0 Authors' Contributions

SB is responsible for conceptualization, data curation, research, methodology, writing the first draft, writing the review, and writing the editing. ML oversaw and handled the article writing tasks. Additionally, ML offered the tools required to finish the paper. The final manuscript was read and approved by all writers.

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## Nomenclature

| | | |
|---|---|---|
| x | [m] | Cartesian axis direction |
| y | [m] | Cartesian axis direction |
| z | [m] | Cartesian axis direction |
| Hx | | Heat Exchanger |
| MCHX | | Microchannel Heat Exchanger |
| LMTD | | Log Mean Temperature Difference |
| k | [W/mK] | Thermal Conductivity |
| h | [W/m2K] | Heat Transfer Coefficient |
| U | [W/m2K] | Overall Heat Transfer Coefficient |
| $\dot{m}$ | [kg/s] | Mass flow rate |
| $D_h$ | [m] | Hydraulic Diameter |
| T | [C] | Temperature |
| Th | [C] | Temperature of hot fluid |
| Tc | [C] | Temperature of cold fluid |
| $\dot{L}$ | | Total Exergy loss |
| $\dot{\sigma}_{\nabla T}$ | | Exergy loss due to temperature drop |
| $\dot{\sigma}_{\nabla P}$ | | Exergy loss due to pressure drop |
| $\dot{B}_Q$ | | Exergy loss to surroundings |
| ΔT | | Temperature drop |
| ΔP | | Pressure drop |
| $A_c$ | [m2] | Area of microchannel |
| $p_t$ | [m] | Tube Pitch |

| | | |
|---|---|---|
| $N_{cf}$ | | Number of microchannel tubes in a single flat tube |
| $N_{ft}$ | | Number of flat tubes |
| $n_{fr}$ | | Number of fins in a row |
| $f_h$ | [m] | Height of a fins |
| $d_o$ | [m] | Outside diameter of Microchannel |
| Special characters | | |
| $\dot{\sigma}$ | | Entropy change |
| $\sum$ | | Summation |
| $f$ | | Fanning Friction Factor |
| Subscripts | | |
| i | | Inlet, Inner |
| o | | Outlet Outer |
| max | | Maximum |
| min | | Minimum |
| h | | hot |
| c | | Cold |
| $surr$ | | Surroundings |