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EXERGY ANALYSIS OF MICROCHANNEL HEAT EXCHANGER FOR SINGLE-PHASE APPLICATIONS

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ABSTRACT

Design of microchannel heat exchanger can be accomplished by various methods available. Most of these methods do not take into consideration the second law of thermodynamics. In view of this, study of microchannel from perspective of exergetic analysis is important for the design and evaluation of thermodynamic system in which it is being employed. The global efficiency of a thermodynamic system can be improved by a good exergetic design of microchannel heat exchanger. This can be achieved by defining a thermodynamic system in which the exergetic losses would be eliminated and limited only to unavoidable losses. Identifying probable sources of exergy loss and possibly reducing them needs a full exergetic analysis of an existing heat exchanger. This study takes into consideration the exergetic losses which would be helpful in thermal design of the heat exchanger.

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

1. Introduction

Ignacio L´opez Paniagua et al. [1] have identified three main sources of exergy loss which cause irreversibility. These three sources are heat transfer between the streams of fluid, pressure losses due to fluid flow through the tubes, and loss of heat to surroundings environment because of the temperature difference. The third loss depends on the ambient temperature. If it is less, then exchanger temperature energy is lost to surrounding. The flow direction reverses if surrounding temperature is more than exchanger temperature. It is generally observed that these three losses occur simultaneously [1].

Kotas, T.J [2] has mentioned three reasons which cause irreversibility in any heat exchanger. These three reasons are heat transfer between the hot fluid and cold fluids, heat transfer between the heat exchanger and its surroundings, and pressure drop because of flow of the fluids. Amongst these three losses, the heat transfer between the exchanger and the surroundings is generally neglected because it’s a small percentage of the total losses [2].

There is an associated temperature drop always, during the heat exchange between two streams, which causes irreversibility. This can be measured during the experimentation or by using some simulation techniques [2]. In the present study, the temperature along the length of microchannel are known. The temperature distribution at intermediate point along the length of microchannel tubes, adds to the constructive data. This data facilitates calculations of exergy losses associated with it. Apart from this, few other parameters are also needed like heat transfer coefficients, area of exchange surfaces, tube cross sections, fluid velocities, etc [3].

Exergy loss due to temperature drop $I_{\nabla T}$ and exergy loss due to head losses $I_{\nabla \mathrm{P}}$ are the two major causes of irreversibility. The heat transferred to the surroundings does not actually mean that exergy $\dot{B}_{\mathrm{Q}}$ is destroyed, especially in the current case when ambient air is being used as a cooling fluid. These three different exergy losses, when summed up, cause the total exergy loss $\dot{L}$ in the heat exchanger [1].

All the four terms have to be calculated independently in order to complete exergy analysis of microchannel heat exchanger. In the current case, since the heat exchanger is in the design stage, the actual data is not available. The only data available is input and output conditions of both fluids and their thermodynamic properties. Therefore, establishing a method to calculate the exergy losses becomes the necessity. In order accomplish this method, each term in Equation (1) below needs to be calculated.

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

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

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

$$\sigma^{\cdot}_{\Delta P}= -\dot{m}c\int\frac{v_c dP_c}{T_c} -\dot{m}_h\int\frac{v_h dP_h}{T_h} \tag{4}$$

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

The term on the RHS of Equation (2) is integral over the entire outer surface area along the length of microchannels. The dQ_{surr} indicates heat exchange between the exchanger and surroundings through control volume and T is the exchanger temperature. dQ_{exch} Indicated the heat absorbed by the cold fluid i.e. ambient air in the current case and, $\dot{m}$ indicated for mass flow rate of the cold fluid. The value of dQ_{surr} will be negative because the heat is transferred from the exchanger to its surroundings [1].

It is observed that $\dot{L}$ can be obtained from an exergy balance of the heat exchanger directly, after the inlet and outlet parameter and mass flow rates are known. The integral terms in Equation (2) and Equation (3) can be calculated if the hot and cold temperature are known at intermediate points along the length of the exchanger. Then, Equation (4) can be solved using Equation (1).

As mentioned, energy flow in the heat exchanger is by means of two different ways: the heat flow between the two streams of fluids, and heat flow from the exchanger itself to the surroundings. These two heat flows are denoted as dQ_{exch} and dQ_{surr} and this is obtained using the heat balance equations

$$\dot{Q}_c = \dot{m}_c \cdot (h_{c,o} - h_{c,i}) \qquad (6)$$

$$\dot{Q}_h = \dot{m}_h \cdot (h_{h,o} - h_{h,i}) \qquad (7)$$

It is worth noting that Q_c is positive whereas Q_h is negative, because the cold fluid receives heat and the hot fluid gives out heat. Therefore, the energetic losses to the surroundings, dQ_{surr}, are

$$\dot{Q}_{surr} = \dot{Q}_c + \dot{Q}_h \qquad (8)$$

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

$$\left[\dot{Q}exch\right] = \min\left(\left[\dot{Q}c\right], \left[\dot{Q}\mathrm{h}\right]\right) \qquad (9)$$

The total exergy loss $\dot{L}$ is given by Equation (1), which can be obtained by considering the specific exergy at the inlet and outlet of both the fluids. This, in turn, can be expressed as a function of the ambient temperature, specific enthalpy and entropy as expressed in Equation (10):

$$\dot{\mathrm{L}} = \sum_{\forall j} \dot{\mathrm{E}}j = \dot{m}_h \cdot (e_{h,i} - e_{h,o}) + \dot{m}_c \,.\, (e_{c,i} - e_{c,o}) =$$
$$\dot{m}_h \,.\, (h_{h,i} - h_{h,o} - T_o \,.\, (s_{h,i} - h_{h,o})) + \dot{m}_c \,.\, (h_{c,i} - h_{c,o} - To \,.\, (S_{c,i} - S_{c,o})) \qquad (10)$$

The results are obtained by consulting the properties of water and air from properties table and applying above equations at the intermediate points along the length of microchannels.

2. Parameters under Study

The present research work is associated with two competing objectives namely the parametric analysis and estimation of size. It is essential to consider these parameters over the entire possible range of values to evaluate the performance of the heat exchanger as depicted in Table-1.

Table 1. Range for operating parameters

Parameter	Operating Range
Inlet temperature of fluid (Thi)	80ºC- 90ºC
Outlet temperature of fluid (Tho)	70ºC - 80ºC
Inlet temperature of air (Tci)	20ºC - 40ºC
Pressure of the system	1.1 bar -1.5 bar
Mass flow rate inside micrchannel tubes (ṁ)	0.05kg/sec - 0.20kg/sec
Velocity fins side	10 m/s – 35 m/s

Increasing the number of channels lead to an increase in both effectiveness and pressure drop. Moreover, circular channels give the best thermal and hydraulic performance among various channel shapes [10]. Given this, the present research is carried out for the following geometric parameters shown in Table 2.

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

3. Results and discussions

The exergy analysis of microchannel heat exchanger is tabulated and also discussed for single-phase flow. The effect of microchannel heated length and ambient temperature on total exergy loss, exergy efficiency and irreversibility ratio etc have also been investigated and discussed.

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 $\dot{L}$	940.99	1059.53	933.43	940.99	880.46
Exergy loss surr $\dot{B}$	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 $\dot{\sigma}\ \Delta P$	457.54	530.00	470.94	489.59	471.96
% $\dot{\sigma}\Delta T$ exergy loss	1.44	1.27	1.45	1.44	1.53
% $\dot{\sigma}\Delta P$ exergy loss	48.62	50.02	50.45	52.03	53.60
Irreversibility Ratio ∅	75	49	17	17	20

Table 4. Estimates at Different Surrounding Temperature

Surrounding Temperature ^{0}C	30	33	36	39	42
Exergy loss surr $\dot{B}$	1001	912	831	754	681
Exergy loss temp drop $\sigma^{\cdot}\Delta T$	13.98	16.11	14.68	13.32	12.032
Exergy loss press drop $\sigma^{\cdot}\Delta P$	1013	1074	1137	1197	1253
% $\sigma^{\cdot}\Delta T$ exergy loss	6.9	8.1	7.4	6.78	6.18
% $\sigma^{\cdot}\Delta P$ exergy loss	50	53.6	57.4	61	64
Irreversibility Ratio ∅	72	67	77	90	104

Table 5. Global exergetic analysis of microchannel heat exchanger

	Watt
Total exergy loss $\dot{L}$	1301.39
Exergy loss surr $\dot{B}$	619.06
Exergy loss temp drop $\sigma^{\cdot}\Delta T$	13.43
Exergy loss press drop $\sigma^{\cdot}\Delta P$	668.90

Figure 1 shows the variation of temperature along the length of microchannel. The variation of temperature as a result of heat transfer from the hot fluid to the cold fluid is not linear whereas it found to follow a logarithmic profile. Whereas the ambient air which is being used as cold fluid remains at a constant surrounding temperature at the inlet. As explained earlier the total exergy loss is the sum of exergy loss due to temperature drop, pressure drop and heat loss to surroundings [2]. The Figure 2 explains the variation of these exergy losses along the length of microchannel. The relative effect on the three components of total exergy loss at intermediate points along the channel length have been explained. As seen from the figure, exergy loss to surroundings goes on decreasing as the heat exchanger temperature decreases along the length, whereas the trends show that the other two components increase along the length because temperature difference decreases as also the fluid pressure. Similar trends are seen in the Figure 3 because of the decreasing ambient temperature.

Exergy loss due to temperature difference and pressure drop are found to be predominant over the exergy loss to surrounding. This is evident from the trends shown in Figure 4. Similarly, the predominance of temperature and pressure drop over the surroundings can be observed in the trends shown by Figure 5.

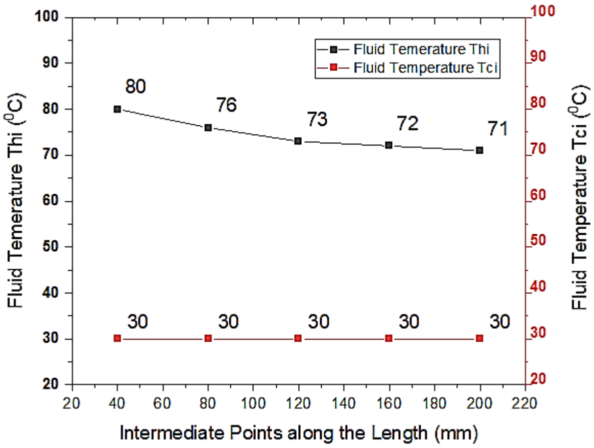

Figure 1. Temperature values of hot and cold fluid along the channel length

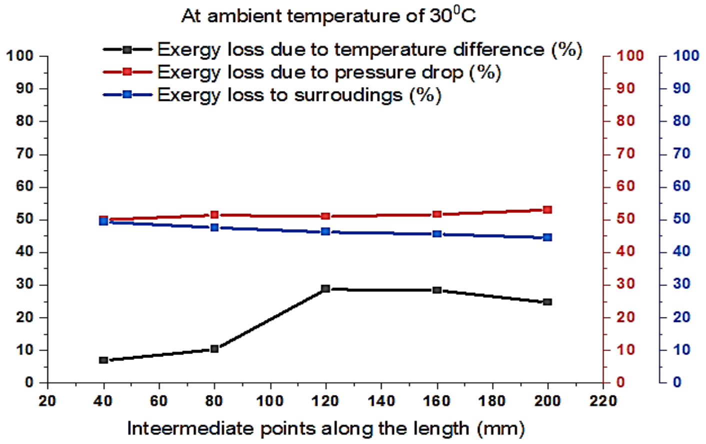

Figure 2. Dependence of exergy components on the microchannel temperature

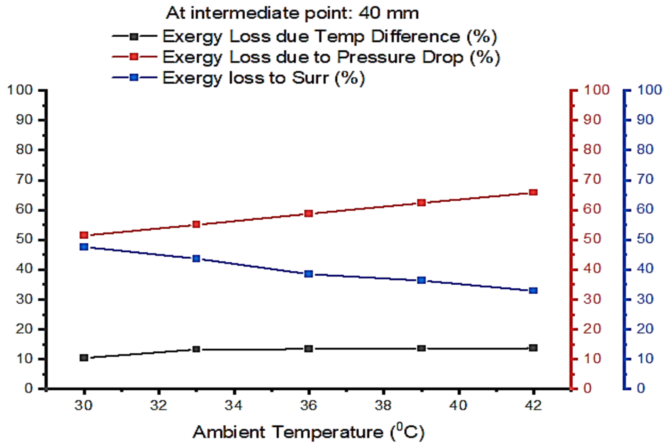

Figure 3. Effect of ambient temperature on exergy loss components

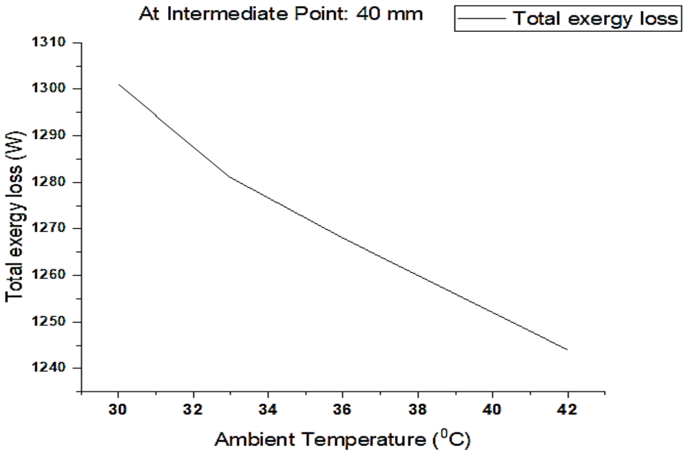

Figure 4. Dependence of total exergy loss on ambient temperature

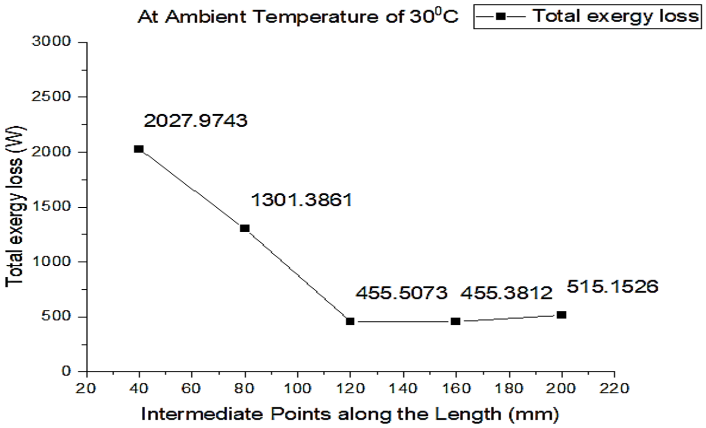

Figure 5. Effect of channel heated length on the total exergy loss

The overall heat exchanger temperature shows a decreasing trend along the length of microchannels, therefore the temperature goes on decreasing at intermediate points along the length. Figure 6 shows the loss exergy of different components due to heat exchanger temperature. It is observed that the exergy loss to surroundings decreases with decreasing temperature whereas loss due to temperature drop and pressure drop show an increasing trend. Again suggesting the total exergy loss decrease along the intermediate points along the length due to relative predominance of exergy loss to surroundings.

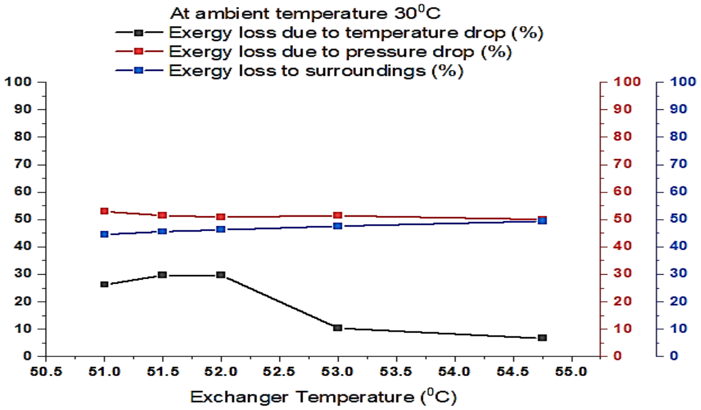

Figure 6. Effect of exchanger temperature on exergy loss components

It must be noted that many other authors have found different approaches for calculating the total exergy loss in turn the irreversibility. An interesting approach has been developed in Bejan [6]. A new exergetic parameter called as irreversibility distribution ratio has been suggested and it is defined as $\emptyset = \frac{\sigma\dot{\Delta}P}{\sigma\Delta T}$.

Theoretical studies of this parameter for different cases of microchannel heat exchanger have suggested that the value of this parameter should as low as possible for any given microchannel. Figure 7 shows the this parameter shows a decreasing trend along the intermediate points along the length indicating that the relative dominance of temperature drop decreases along the length. This is obviously because of the logarithmic temperature drop along the intermediate points along the length of microchannels. Same is the case with increasing surrounding temperature as shown by Figure 8.

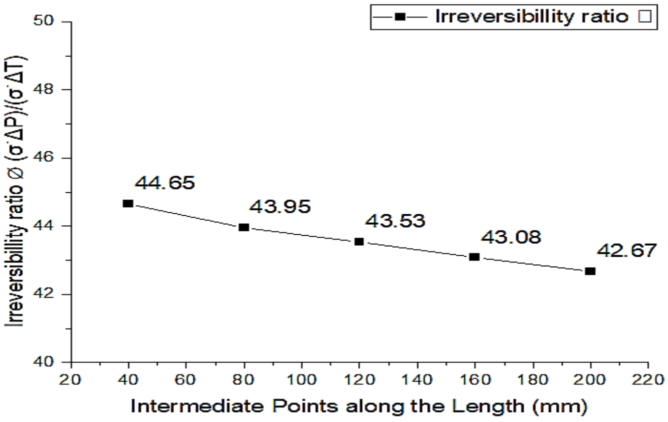

Figure 7. Effect of channel heated length on irreversibility ratio

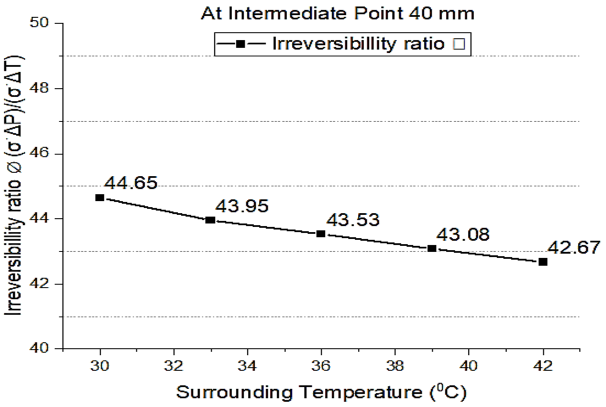

Figure 8. Effect of surrounding temperature on irreversibility ratio

In nutshell, the exergetic efficiency of the microchannels can be understood from Figure 9 and Figure 10, which show a similar trends. It is obvious that as the surrounding temperature increases there is increase in cold side fluid temperature and also exergy loss to surrounding decreases. This results in decreasing total exergy losses and ultimately reduced exergetic efficiency. The trends also show that at short heated length of microchannels the irreversibility distribution ratio as well as efficiencies are higher. This is also being validated by the fact that to keep the pressure drop constant, for the given mass flow rate, number of channels should be increased rather that increasing the length so that the ratio of length to fourth power of diameter remains constant [4].

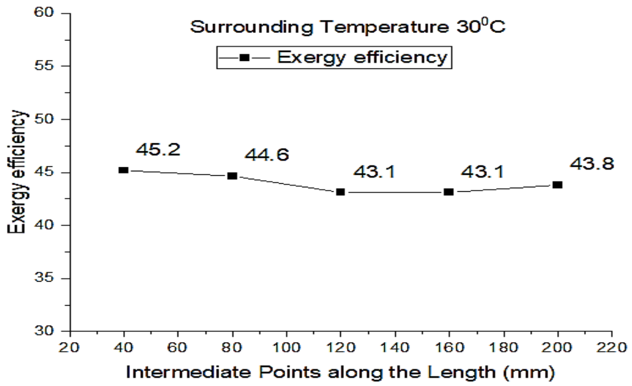

Figure 9. Effect of channel heated length on exergy efficiency

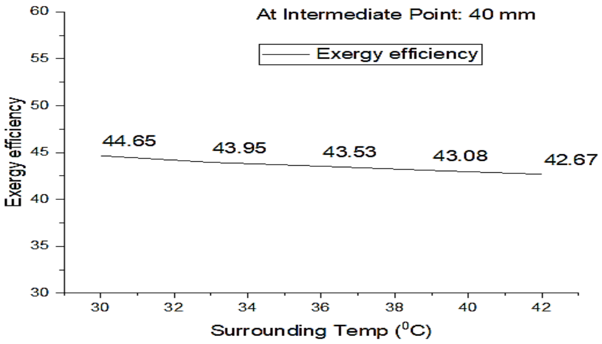

Figure 10. Effect of surrounding temperature on exergy efficiency

4. Conclusion

The exergetic efficiency of microchannels under single phase conditions was assessed at varying ambient temperature values from 30^0C to 42^0C and at intermediate points along the length of microchannel. It was found that the exergetic efficiency is decreasing with increasing ambient temperature as in Figure 10. This is attributed to the reduced losses to the surroundings. The efficiency is also found to be decreasing at the intermediate points along microchannel length as in Figure 9. The decrease is nearly linear and almost constant. However higher efficiencies are observed at shorter heated length of microchannels, the reduction in efficiency is 0.7% for every 100 mm.

References

[1] Ignacio L´opez Paniagua et.al., A New Simple Method for Estimating Exergy Destruction in Heat Exchangers, entropy 2013,PP 473-489

[2] Kotas, T.J. The Exergy Method of Thermal Plant Analysis; 1995 Ed.; Krieger Publishing Company: London, UK, 1985.

[3] Pandey, S.D. Nema, V., An experimental investigation of exergy loss reduction in corrugated plate heat exchanger. Energy 2011, 36, 2997–3001.

[4] Bjorn Palms, Heat transfer in microchannels, 2001, Microscale Thermophysical Engineering, 5:3, 155-175

[5] Mehmed Ozdemir, Exergy analysis of microchannel heat exchanger, Int. J. Exergy, Vol 32, No.03, 2020

[6] Bejan, A. Advanced Engineering Thermodynamics; JohnWiley & Sons: Hoboken, NJ, USA, 1988.

[7] Incropera, F.P.; DeWitt, D.P.; Bergman, T.L.; Lavine, A.S. Fundamentals of Heat and Mass Transfer, 6th Ed.; John Wiley & Sons: Hoboken, NJ, USA, 2006

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		
$\sigma^{\cdot}$		*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*