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Study of Heat Transfer Enhancement and Pressure Drop in Cylindrical Extrusion Type Plate Heat Exchanger

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Abstract:
The study explores the heat transfer rate and pressure drop in a plate heat exchanger using water and MWCNT nanofluid as the working fluids. Flow simulations are performed for a flat plate for reference and plates with cylindrical extrusions of height ranging from 0.5 mm to 3 mm. The working conditions and the boundary conditions like material, ambient pressure & temperature, flow rate, port size, number of flow chambers and channel spacing are kept constant for each configuration. The heat transfer and pressure drop results of the cylindrical extrusion plates are compared to conventionally used chevron type plate as well as flat plate as a reference, which showed improvement in heat transfer rate compared to flat plate and significantly lower pressure drop compared to chevron plate. The effect of the change in extrusion height is verified by using anova test and the heat exchanger is optimized considering equal trade-off between heat transfer rate and pressure drop which comes out to be at almost 0.7 mm extrusion height.
***Key Word**: Plate heat exchanger, heat transfer rate, pressure drop, cylindrical extrusion plate, flat plate, chevron plate*

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I. Introduction

Plate heat exchanger is a device in which heat is transferred between two fluids at different temperatures flowing inside the spacing between two parallel plates. Plates are arranged parallel to each other with gaskets, generally made of insulating material, sandwiched between the plates. The gaskets maintain a space between the plates making chambers through which the fluids flow. The plates are made of material whose thermal conductivity is high so that the resistance to conductive heat transfer is minimum. The whole assembly is held together with the help of nut and bolt joint. This makes the assembly easier to assemble and disassemble for proper cleaning and also to adjust the size and capacity of the heat exchanger.

The hot and cold fluid flows through alternative chambers and the heat is transferred from the hot fluid to the plate and then to the cold fluid. The plate design is altered to induce turbulence in the flow to increase the convective heat transfer rate. The most commonly used plate design is chevron design. While the increase in heat transfer rate is achieved, there is also considerable increase in pressure drop value associated with this type of plate design

II. Literature review

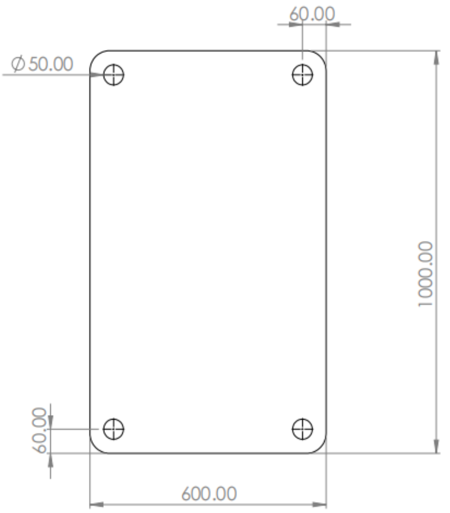
Various studies have been conducted on plate heat exchangers mainly having chevron plate design. The effect of various parameters like Reynolds Number, plate geometry, type of working fluid on the heat transfer rate and pressure drop have been explored previously. Also nanofluid is found to have superior thermal properties compared to base fluid but increased viscosity possesses a problem of increased pressure drop and requirement of more pumping power in case of nanofluid.

Al Zahrani et al. [1] investigated the improvement in the Nusselt number and effectiveness in a plate heat exchanger with new modification to basic chevron plate design. An increase of up to 75% and 42% is obtained for Nusselt number and effectiveness respectively and both showed direct proportional relationship with Reynold's number. Muley and Manglik [2] found the Nusselt number to increase up to 2 to 5 times and pressure drop to be 13 to 44 times higher with the increase in chevron angle and in comparison to flat plate. Focke et al. [3] used an improved flow visualization technique and found that the maximum transfer rate occurs at an angle of 80^o. Talik et al. [4] found the heat transfer rate between 110 to 650 kW for Reynold's number 80 to 720 in a 30^o chevron plate heat exchanger with 31 plates. Albadr et al. [5] found that the heat transfer coefficient of nanofluid is slightly more than that of base fluid at same mass flow rate and inlet pressure and increases with the increase in the mass flow rate and volume concentration of the Al_2O_3 nanofluid in a shell and tube heat exchanger. But with increase in volume concentration the viscosity of the nanofluid also increases leading to increased friction factor. Pak and Cho [6] concluded that for γ-Al_2O_3 and TiO_2 nanofluid at 10% concentration the viscosity is significantly larger. Pumping power requirement is additional 30% at a volume concentration of 3%. Pantzali et al. [8] found that using CuOnanofluid significantly enhanced the heat transfer rates compared to water. It was also found that contribution of nanoparticles to heat transfer is more at lower temperatures. Experiments with different nanofluids like CuO [8], γ-Al_2O_3 , TiO_2 [6], MWCNT [7,9], SiO_2 [10] all showed the heat transfer rate to increase significantly. Javadi et al. [10] found that SiO_2 showed minimum pressure drop and Al_2O_3 to have highest heat transfer rate. Gupta et al. [9] concluded that MWCNT nanofluid showed highest heat transfer rate and significantly less pressure drop. Walvekar et al [11] found an increase of 67%-250% in thermal conductivity and 7%-202% in convective heat transfer in case of CNT compared to water.

III. Methodology

Design and Assembly

Primarily three different types of plates are designed: Flat plate, chevron plate and a new design of cylindrical extrusion plate. The material for all the plates is Copper. The flat plate serves as a baseline against which the results of cylindrical extrusion plates are compared. The flat plate is a plate with smooth surface as shown in figure 1.



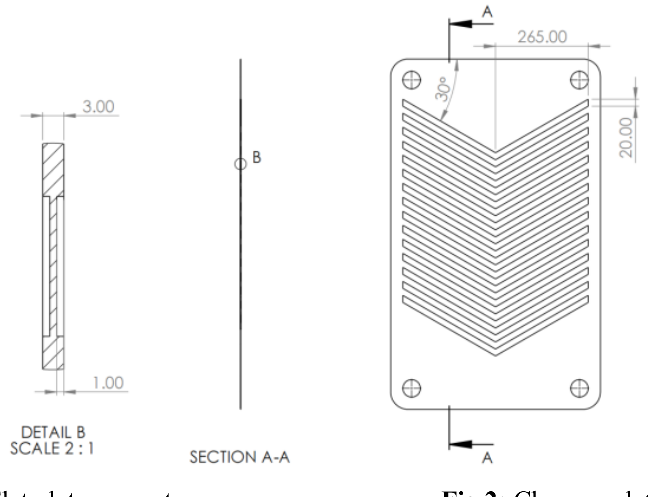


Fig.1: Flat plate geometry **Fig.2:** Chevron plate geometry

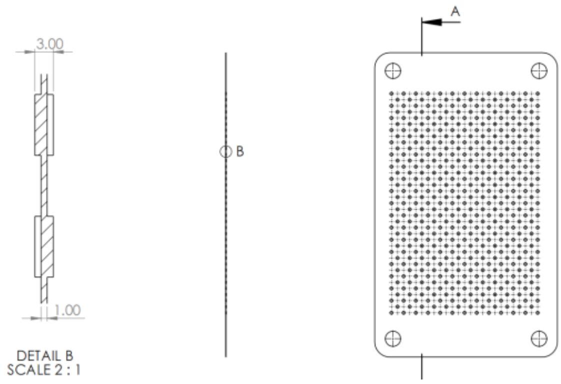


Fig.3: Cylindrical extrusion plate geometry

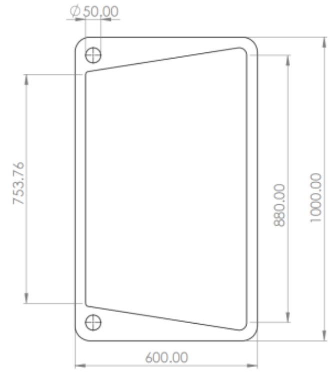


Fig. 4. Gasket geometry

Cylindrical extrusion plate, as shown in figure 3 are plates with multiple small cylinders extruded to a certain height on both sides of the plate. Seven different such plates are designed with different extrusion height: 0.5 mm, 1 mm, 2 mm, 2.25 mm, 2.5 mm, 2.75 mm and 3 mm.

The assembly of the model consists of 9 plates and 20 gaskets. The gaskets are made of Teflon. There are 10 chambers each for cold fluid and hot fluid. The width of each chamber is 3 mm which is equal to the thickness of the gasket. The specification of the plates are mentioned in table 1 and 2

Table 1: Specifications of the plates

Parameter	Values	Description
$\beta(^o)$	30	Chevron angle
D_p(mm)	50	Port diameter
L_h(mm)	480	Horizontal distance between center of ports
L_v (mm)	880	Vertical distance between center of ports
L_w(mm)	530	Width of plate inside gasket
t (mm)	1	Thickness of plate
b (mm)	1	Corrugation depth

Table 2: Specification for cylindrical extrusion plate

Parameter	Values	Description
h_{ex} (mm)	0.5 to 3	Height of the extrusion
D_{ex}(mm)	10	Diameter of the extrusion
S_h(mm)	20	Horizontal spacing between the extrusion
S_v(mm)	20	Vertical spacing between the extrusion

Properties of the nanofluid

The four properties of the MWCNT nanofluid are evaluated at 20°C and 1% concentration with water as base fluid. The properties are density, specific heat, dynamic viscosity and thermal conductivity.The dynamic viscosity and thermal conductivity are extrapolated from the data presented in [12]. The density and specific heat value is calculated using relations (1) and (2) mentioned in [6,13], which depends upon the density and specific heat of the nanoparticles and the base fluid, that is MWCNT and water respectively, and also the concentration of the nanoparticles in the base fluid.

The density of the nanofluid is calculated from,

$$\rho_{nf} = \phi\rho_p + (1-\phi)\,\rho_b \tag{1}$$

The specific heat of the nanofluid is calculated from the relation,

$$\rho_{nf}C_{pnf} = (1-\phi)\,\rho_b C_{pb} + \phi\rho_p C_{p_p} \tag{2}$$

The values of all the four properties are listed in table 3, which are used to define the nanofluid in solidworks to perform the flow simulation.

Table 3: Properties of the MWCNT nanofluid at 20°C and 1% concentration

Property	Values	Description
ρ_{nf} (kg/m^3)	1009.218	Density
C_{Pnf} (J/kgK)	4109.34	Specific heat
μ_{nf} (mPas)	2.69	Dynamic viscosity
k_{nf}(W/mK)	0.669	Thermal conductivity

Flow simulation

The simulation of the heat exchanger is performed in solid works flow simulation. Water is used as hot fluid and MWCNT as cold fluid. The simulation is performed to determine the outlet temperature and inlet pressure of both the fluids for a constant flow rate. The outlet temperature is required to calculate the heat transfer rate and the inlet pressure to determine the pressure drop in the heat exchanger. The various boundary conditions, parameters and values are listed in table 4.

Table 4: Simulation parameters

Parameter	Values	Description
P_{amb} (kPa)	101.325	Ambient pressure
T_{amb} (ºC)	20	Ambient temperature
T_{Ci} (ºC)	20	Inlet temperature of cold fluid
T_{Hi} (ºC)	80	Inlet temperature of hot fluid
v (m^3/s)	0.01	Volume flow rate
I_t (%)	2	Turbulence intensity
L_t (mm)	0.81	Turbulence length

Analysis of the heat exchanger

The following equations are used for calculation and evaluation of the heat transfer rate and pressure drop in the heat exchanger.

For mass flow rate of cold fluid,

$$m_{cf} = \rho_{nf} v \tag{3}$$

For mass flow rate of hot fluid,

$$m_{hf} = \rho_{nf} v \tag{4}$$

For heat transfer rate,

$$Q = m_{cf} C_{pnf} \left(T_{co} - T_{ci} \right) = m_{hf} C_{pb} \left(T_{Hi} - T_{Ho} \right) \tag{5}$$

For pressure drop,

$$\Delta P = P_{amb} - P_i \tag{6}$$

IV. Result

Comparison of the different plate designs

Initially simulation is done for the flat plate, chevron plate and cylindrical extrusion plate of 0.5 mm, 1 mm, 2 mm & 3 mm. The initial results show a drop in heat transfer rate at 3 mm height. Hence three more points between 2 mm and 3 mm extrusion height are studied to determine the maximum heat transfer rate point. These new points are 2.25 mm, 2.5 mm and 2.75 mm extrusion height. Also for the previous plates simulation is repeated five times to obtain a sample on which anova test is done to verify the effect of extrusion height on heat transfer rate as well as pressure drop in the cylindrical extrusion plates. The averaged values are shown in table 5.

Table 5: Heat transfer rate and pressure drop results for all the plates

Plate type		T_{Co}(ºC)	P_{Ci}(kPa)	Q (kW)	ΔP (kPa)
Flat plate		28.48	155.982	351.899	54.657
Chevron plate		39.90	259.231	825.465	157.096
Cylindrical extrusion plate	(0.5 mm)	31.97	159.187	496.038	57.862
	(1 mm)	32.99	162.249	538.906	60.924
	(2 mm)	33.88	169.704	575.792	68.379
	(2.25 mm)	34.03	171.702	581.895	70.377
	(2.5 mm)	34.47	173.609	600.309	72.284
	(2.75 mm)	34.84	175.157	615.555	73.832
	(3 mm)	33.96	177.001	578.916	75.682

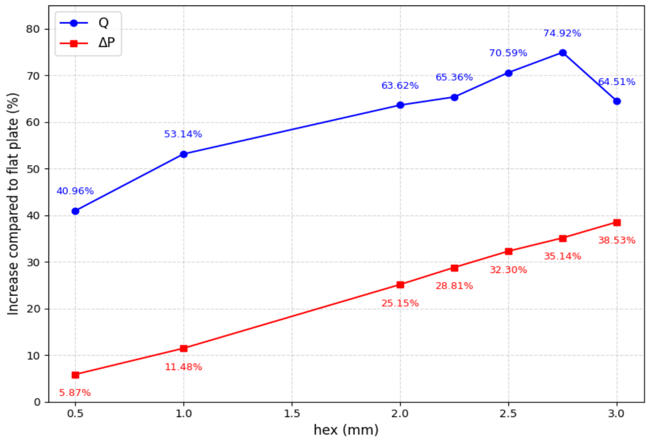


Fig.5: Increase in heat transfer rate and pressure drop in cylindrical extrusion plate compared to flat plate

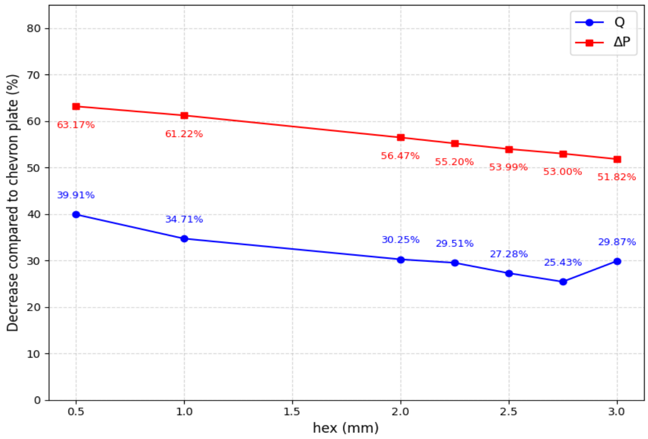


Fig.6: Decrease in heat transfer rate and pressure drop in cylindrical extrusion plate compared to chevron plate

In the range 0.5 mm to 3 mm of extrusion height of the cylindrical extrusion plate, the heat transfer rate shows an increase of 40% to 75% and the pressure drop shows an increase of almost 6% to 39%. The increase in heat transfer and pressure drop for the cylindrical extrusion plate compared to flat plate is shown in figure 5.

Comparing the chevron plate to flat plate, the increase in heat transfer rate is found to be 135% and the increase in pressure drop is 187%. The decrease in heat transfer rate as well as pressure drop in cylindrical extrusion plate compared to chevron plate is shown in figure 6. The decrease in heat transfer rate is between 30% to 40% and the decrease in pressure drop is between 52% to 63%.

Table 6: Anderson-Darling test for heat transfer rate data

Group	Extrusion height (mm)	AD Statistic	h
A	0	1.171	0
B	0.5	1.2034	0
C	1	1.204	0
D	2	1.2039	0
E	2.25	1.1791	0
F	2.5	0.79955	0
G	2.75	0.31633	1
H	3	1.177	0

Table 6 shows the result of AD test for heat transfer rate. The null hypothesis is rejected for all groups except group G. Hence except group G, all other groups cannot be assumed to be normally distributed.The AD test result for pressure drop data is listed in table 7. The null hypothesis is rejected for group E and F. So all groups expect E and F cannot be assumed to be normally distributed

Table 7: Anderson-Darling test for pressure drop data

Group	Extrusion height (mm)	AD Statistic	h
A	0	1.2047	0
B	0.5	1.2047	0
C	1	1.2047	0
D	2	1.1945	0
E	2.25	0.68927	1
F	2.5	0.60279	1
G	2.75	0.79955	0
H	3	1.2024	0

.**Table 8:** Kruskal-Wallis anova table for heat transfer rate data

Source	SS	df	MS	Chi-sq	Prob
Groups	5090	7	727.143	37.28	4.1486×10^{-6}
Error	234.5	32	7.328		
Total	5324.5	39			

Table 9: Kruskal-Wallis anova table for pressure drop data

Source	SS	df	MS	Chi-sq	Prob
Groups	5250	7	750	38.58	2.35273×10^{-6}
Error	57.5	32	1.7969		
Total	5307.5	39			

Since the data for most groups cannot be considered to be normally distributed, therefore non parametric anova test is used. Hence Kruskal-Wallis analysis of variance by ranks test is done on the heat transfer and pressure drop data. The null hypothesis being the medians of all the groups is the same. The Kruskal-Wallis anova table for heat transfer rate and pressure drop data are shown in table 8 and 9 respectively.

The anova test results for both the data shows that the null hypothesis is rejected and the median between the groups varies significantly. Hence it is concluded that the heat transfer and pressure drop in the cylindrical extrusion plate varies significantly with the extrusion height

Optimization of the cylindrical extrusion plate heat exchanger

The variation of heat transfer rate and pressure drop with extrusion height are shown in figure 7 and 8 respectively (0 mm corresponding to the flat plate). The heat transfer rate is varies between 500 to 615 kW and the pressure drop between 58 to 75 kPa. The pressure drop curve shows an almost linear behaviour unlike the heat transfer rate curve. The maximum heat transfer is found to be at 2.75 mm extrusion height. For obtaining the equations for pressure drop and heat transfer rate as a function of extrusion height, the heat transfer rate curve is fitted to a power of 5 and the pressure drop curve to a power of 1. The fit plots are shown in figure 9 and 10 and their respective goodness of fit in table 10 and 11

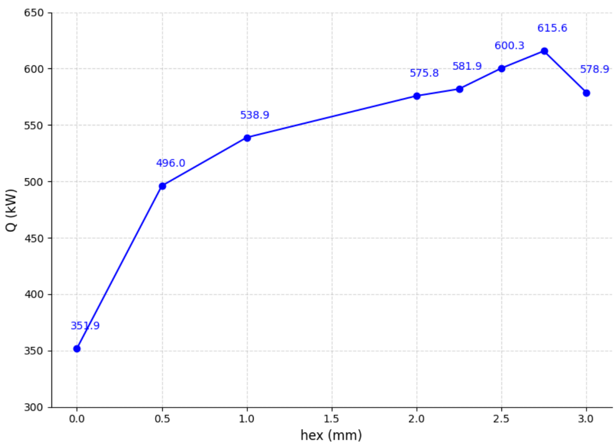


Fig.7: Heat transfer rate vs. extrusion height

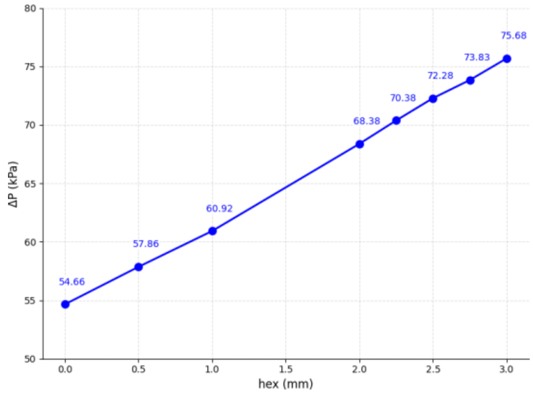


Fig.8: Pressure drop vs. extrusion height

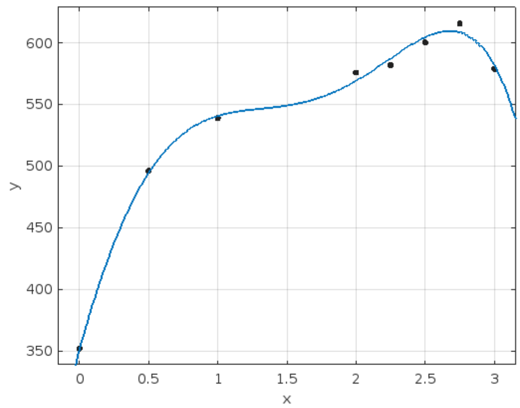


Fig.9: Fitted plot for heat transfer rate

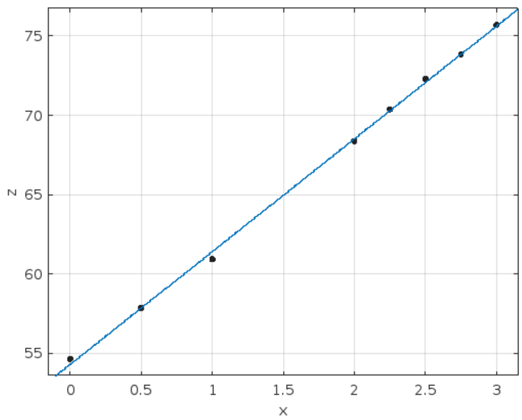


Fig.10: Fitted plot for pressure drop

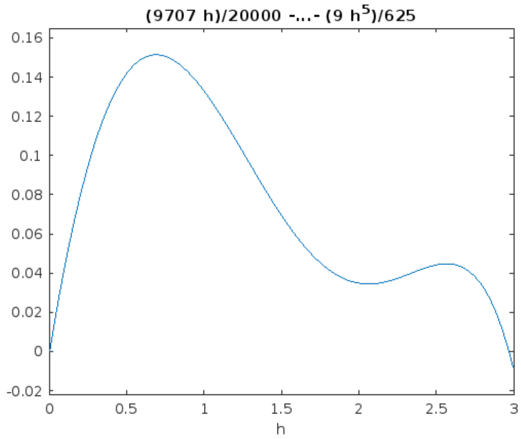


Fig.11: Plot of the objective function

Table 10: Goodness of fit for heat transfer rate curve

	Value
SSE	146.3283
R-square	0.9971
DFE	2.0000
Adj R-sq	0.9900
RMSE	8.5536

Table 11: Goodness of fit for pressure drop curve

	Value
SSE	0.4359
R-square	0.9990
DFE	6.0000
Adj R-sq	0.9988
RMSE	0.2695

Table 12: Optimized heat transfer and pressure drop

Parameter	Values
h_{ex} (mm)	0.7
Q (kW)	521.95
ΔP (kPa)	59.29

The equation for heat transfer rate is,

$$Q = -9.126\, h_{ex}^5 + 39.6952\, h_{ex}^4 + 19.8835\, h_{ex}^3 - 273.7687\, h_{ex}^2 + 413.0578\, h_{ex} + 352.1391$$

And, the equation for pressure drop is,

$$\Delta P = 7.1029 h_{ex} + 54.3194$$

Using multi-objective optimization using normalization, the normalized equations are,
For heat transfer rate,

$$Q_n(h) = -0.0288\, h^5 + 0.1253 h^4 + 0.0628 h^3 - 0.8643\, h^2 + 1.304\, h$$

For pressure drop,

$$P_n(h) = 0.3333\, h$$

Giving equal weights to both heat transfer rate and pressure drop ($w_1 = w_2 = 0.5$), the composite objective function is,

Maximize: $F(h) = -0.0144\, h^5 + 0.0626\, h^4 + 0.0314\, h^3 - 0.43215\, h^2 + 0.48535\, h$

The plot of the objective function is shown in figure 11

Maximizing the objective function we get h = 0.7 mm corresponding to maximum value. Therefore the optimized heat condition for the heat exchanger is at 0.7 mm extrusion height. The heat transfer rate and pressure drop at this point are listed in table 12.

V. Conclusion

The following points can be concluded from the study:

1. The heat transfer rate increases 40% to 75% in cylindrical extrusion plate compared to flat plate while the increase is lot more in chevron plate at 135%.
2. While the heat transfer rate is more in chevron plate, the pressure drop associated with it is also very high, a 187% increase compared to flat plate. For cylindrical extrusion plate the pressure drop increases only 6% to 39%.
3. A non-parametric anova test shows that the heat transfer rate and pressure drop in cylindrical extrusion plate varies significantly with extrusion height.
4. The optimized condition for the cylindrical extrusion plate heat exchanger, giving equal weights to heat transfer rate and pressure drop, is found to be at an extrusion height of 0.7 mm.
5. At this optimized condition the heat transfer rate is increased by 48% compared to flat plate and the pressure drop increased by a mere 8.5%.

Symbols and nomenclature

Symbols	Description
ρ_{nf}	Density of the nanofluid
Φ	Concentration of the nanoparticles in the nanofluid
ρ_b	Density of base fluid
ρ_p	Density of nanoparticles
C_{Pnf}	Specific heat of nanofluid
C_{Pb}	Specific heat of base fluid
C_{Pp}	Specific heat of nanoparticles
m_{cf}	Mass flow rate of cold fluid
m_{hf}	Mass flow rate of hot fluid
T_{Co}	Temperature of cold fluid at outlet
T_{Ho}	Temperature of hot fluid at outlet
ΔP	Pressure drop
P_i	Pressure at inlet
Q	Heat transfer rate

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