COMPARATIVE STUDY OF NUSSELT NUMBER FOR A SINGLE PHASE FLUID FLOW USING PLATE HEAT EXCHANGER

by

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In this study, the plate heat exchangers are used for various applications in the industries for heat exchange process such as heating, cooling and condensation. The performance of plate heat exchanger depends on many factors such as flow arrangements, plate design, chevron angle, enlargement factor, type of fluid used, etc. The various Nusselt number correlations are developed by considering that the water as a working fluid. The main objective of the present work is to design the experimental set-up for a single phase fluid flow using plate heat exchanger and studied the heat transfer performance. The experiments are carried out for various Reynolds number between 500 and 2200, the heat transfer coefficients are estimated. Based on the experimental results the new correlation is developed for Nusselt number and compared with an existing correlation.

Key words: *Nusselt number, Reynolds number, chevron angle, plate heat exchanger*

Introduction

Plate heat exchanger is a heat transfer device which is used to exchange heat energy between two or more fluids. Plate heat exchanger is transfer the heat from either single phase or multiphase by forced convection purely based on temperature difference. The various applications of plate heat exchanger are in process industries, power plants, petrochemical industry, waste heat recovery systems, cryogenics, refrigeration and air condition systems, and biomedical industry. The plate heat exchangers are broadly classified in to two types; a direct contact heat exchanger and an indirect contact heat exchanger. The two fluids are mixed together in direct and the heat transfer take place in the direct contact heat exchanger, such as open feed water heater, desuperheater, *etc*. The two fluids are separated by wall, the heat flow from higher temperature fluid to low temperature fluid across the wall in the indirect contact heat exchanger. The plate heat exchanger used in present work is an indirect contact type heat exchanger. The major advantages of plate heat exchanger is the heat received from the hot fluid to cold fluid through the wall as pure parallel or counter flow arrangement which leads a high effectiveness of plate heat exchanger which cannot occur in other type of heat exchangers [1, 2].

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The plate exchanger mainly consists of thin, rectangular pressed sheet metal plates with peripheral gasket and clamped together in a plate and frame, sometimes it may name as plate and frame heat exchanger. The plates are manufactured by stamping or embossing a corrugated on the sheet and a special gasket grooves are provided for gasket which avoids the leakage in between the plates and make the channel. The ports are provided in the end plate for inlet and outlet for hot and cold in U-arrangement [3].

Plate heat exchanger

Heat transfer analysis for single phase water in plate heat exchanger using U-type counter flow heat exchanger. It has been analyzed with three different chevron plate arrangements. Test were conducted test for Re > 1000 and 30 < *b* < 60. The result gives the significant effects of both parameters like chevron angle and surface enlargement factor. It is found that the Nusselt number increases two to five times higher than the flat plate pack [4].

Further, test were conducted on plate heat exchanger the results shown that the inclined discrete rib plate can enhanced 20-25% heat transfer for the same flow rate [5].

Tests are also conducted on corrugated plate heat exchanger using single phase water to water condition and various combinations of chevron angles and the Reynolds number from the range of 500-2500 and the Prandtl number from 3.5-6.5. The results shown that the Nusselt number increases with increase of Reynolds number and chevron angle. The test was conducted on corrugated plate heat exchanger in commercial plate heat exchanger for symmetric and mixed chevron angle and found that the Nusselt number is a function of Reynolds number, Prandtl number and chevron angle [6].

Focke *et al*. [7] were conducted study on plate heat exchanger and estimated that, the effect of corrugation inclination angle and developed the Nusselt number correlations.

Akturk *et al*. [8] were conducted test on gasketed plate heat exchanger and estimated the Nusselt number correlation using coefficient pilot method.

Experimental set-up

Figure 1 shows the experimental set-up of plate heat exchanger. It consists of vertical plate heat exchanger, pump, thermo start with heating coils, hot fluid tank, by-pass valve arrangement, flow regulating valve, rotometer, thermocouple with display unit, U-tube manometer, radiator with fan, coolant pump, and cold fluid tank.

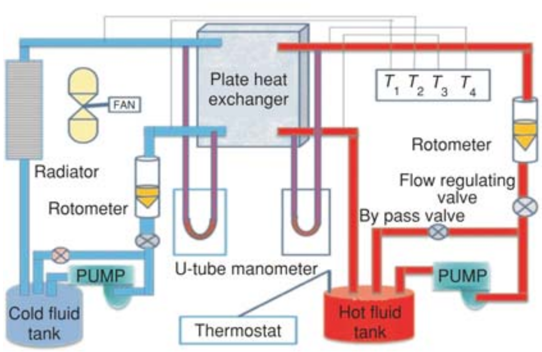

Figure 1. Experimental set-up of plate heat exchanger

The plate heat exchangers are provided with four ports to connect for hot and cold fluid inlet and outlet connections are shown in fig. 2. The U-arrangement flow of fluid is used and all the ports are provided in front of the heat exchanger, and it is shown in the fig. 3. In the hot side circuit the hot fluid from the hot fluid tank is pumped through the flow regulating valve and rotometer to the plate heat exchanger. The hot fluid leaves from bottom side of the port and the fluid is delivered to the hot fluid tank. The constant temperature is maintained in the hot fluid tank with the help of thermostat. The thermostat and the temperature sensor are used in the hot tank which controls the input supply of the heating coil. The inlet and outlet temperature of the hot fluid is measured using rod type thermocouple.

The cold side circuit the cooling water is pumped through the flow regulation valve. The rate of flow is adjusted using the by-pass valve and flow regulating valve accurate setting in the rotometer. The coolant enters from bottom side of the port in the heat exchanger and the coolant are discharged from the upper port and connected to the radiator. With the help of cross flow heat exchanger (radiator) with copper fined tube, the water gets cooled and it is collected in cold tank. The temperature of coolant is measured with the help of rod type thermocouple.

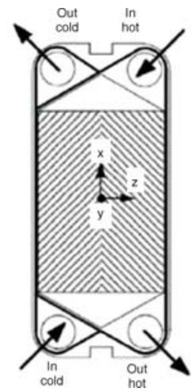

Figure 2. Plate with four port

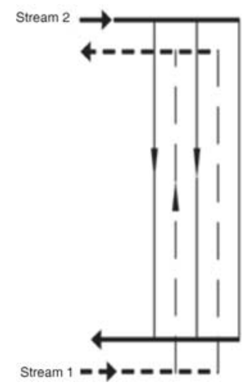

Figure 3. Flow arrangement inside the channel

Parts of plate heat exchanger

The plate heat exchanger consists of frame plate, pressure plate, carrying bar (top and bottom), heat transfer plates with gasket, and foot angle.

The heat transfer plates are made up of AISI316 materials. Five heat transfer plates are used to make four channels to the fluid that is, two channels for hot fluid flow and two channels for cold fluid flow. All the four ports are provided in front of the frame plate. The gasket is used to make the fluid to flow in alternative plates. The heat transfer plates are kept in between the frame plate and pressure plate by using U-flow arrangement in the vertical plate heat exchanger. Flow is resisted by closing the port available in the last heat transfer plate. The plate heat exchanger is fixed with help of foot angle which is provided in the front side to hold the plate heat exchanger in the stand. The entire heat exchanger including, hot fluid tank, pipe lines is fully insulated to avoid the heat losses.

Specification of plate heat exchanger

Flow direction	: Vertical counter flow
Flow arrangement	: U-type
Width of the plate, w	: 100 mm
Vertical distance between the ports	: 480 mm
No. of plate	: 5
No. of channel, n	: 4
Channel spacing, b	: 3.5 mm
Effective surface area, A	: 0.14 m^2
Plate material	: AISI 316
Plate thickness	: 0.6 mm
Surface enlargement factor, ϕ	: 1.25
Chevron (or) Herringbone angle, β	: 60^o
Port diameter, d	: 30 mm
Gasket material	: NBR
Number of V groove on plate	: 33

Terminology used in plate heat exchanger

– *Chevron angle*

The chevron angle various from 22°-65° in all cases. It is a inclined angle projected with reference to the width of the plate.

– *Surface enlargement factor*

It is the ratio of developed length to protracted length.

– *Mean channel spacing*

It is the actual channel gap available for the flow or the gap between the two plate $b = p - t$.

– *Channel flow area*

It is the actual gap available for the fluid flow or the actual cross-sectional area across the horizontal cross-sectional area of a single channel in vertical plate heat exchanger $Ax = bw$.

– *Channel hydraulic diameter*

It is the ratio of four times the minimum flow area to the wetted perimeter.

Experimental procedure

The water is heated in the insulated tank and allow for steady-state condition. The pump is operated to allow the hot fluid in the plate heat exchanger through the rotometer and the flow rate is fixed by adjusting the flow control valve. Similarly the coolant water is allowed to flow in the plate heat exchanger through the valve until reaching the steady-state condition. The flow rate for hot fluid, coolant, inlet and outlet temperature for water and coolant are recorded. By varying the flow rate of coolant after obtaining the steady-state condition the same parameters are recorded. The following assumptions are considered to conduct the experiments in a plate heat exchanger under steady-state condition.

– No phase changes occur in the heat exchanger.
– Heat losses are negligible.
– There is no heat addition or rejections in the heat exchanger expect the actual transfer.
– The fluids have constant specific heats.
– The fouling resistance is negligible.

Governing equation and computation procedure

The fundamental heat transfer eqs. (1) and (2) are used to find the heat transfer in the experiments:

$$Q = \dot{m}_{\mathrm{h}} C_{p\mathrm{h}} (T_{\mathrm{hin}} - T_{\mathrm{hout}}) \tag{1}$$

$$Q = \dot{m}_{\mathrm{c}} C_{p\mathrm{c}} (T_{\mathrm{cout}} - T_{\mathrm{cin}}) \tag{2}$$

When all the fluid properties are evaluated at bulk temperature.

To determine the overall heat transfer coefficient, the following equation to be considered:

$$\Delta T\ Lm = \frac{(T_{\mathrm{hin}} - T_{\mathrm{cout}}) - (T_{\mathrm{hout}} - T_{\mathrm{cin}})}{\ln \dfrac{T_{\mathrm{hin}} - T_{\mathrm{cout}}}{T_{\mathrm{hout}} - T_{\mathrm{cin}}}} \tag{3}$$

The heat transfer Q is determine from the equation:

$$Q = UA\Delta TLm \tag{4}$$

Channel Reynolds number can be find by using channel mass velocity, equivalent diameter and dynamic viscosity:

$$\text{Re} = \frac{G_{\text{ch}} D_{\text{e}}}{\mu} \tag{5}$$

$$D_{\text{e}} \cong 2b \tag{6}$$

$$G_{\text{ch}} = \frac{\dot{m}_{\text{ch}}}{N_{\text{cp}} bLw} \tag{7}$$

Nusselt number can be determined by a coefficient pilot method:

$$\frac{1}{U} = \frac{1}{h_{\text{c}}} + \frac{1}{h_{\text{h}}} + \frac{1}{k} \tag{8}$$

Nusselt number is the ratio of temperature gradients by conduction and convection at plate surface is defined in eqs. (9) and (10):

$$\text{Nu} = \frac{hD_{\text{h}}}{K} \tag{9}$$

where

$$D_{\text{h}} = \frac{2b}{\phi} \tag{10}$$

In most of the plate heat exchanger [9] the correlation of Nusselt number is a function of Reynold number, Prandtl number, and the ratio of dynamic viscosity at bulb to wall temperature is given in eq. (11)

$$\text{Nu} = C\,\text{Re}^{a}\,\text{Pr}^{b}\left(\frac{\mu}{\mu_{\text{w}}}\right)^{0.14} \tag{11}$$

By equating the eq. (9 and 11) the convection heat transfer coefficient is derived and the given in eq. (12):

$$h = \frac{K_{\text{f}}}{D_{\text{h}}} C\,\text{Re}^{a}\,\text{Pr}^{b}\left(\frac{\mu}{\mu_{\text{w}}}\right)^{0.14} \tag{12}$$

The coefficient b is taken as 1/3 for simplify the calculation.

The coefficient a always lie in between 0 and 1, so it is found by trial and error method and it is applied in order to determine the value of C.

By using eqs. (8) and (12) to find the constant C and a to generate the new Nusselt number correlation.

Result and discussion

The data obtained from the experimental study are used to find the characteristics of chevron plate. The experiment is conducted for various range of Reynolds number between 500 and 2200 under the steady-state condition.

Figure 4 shows that the power of Reynolds number with average and C average deviation in percentage. The graph are plotted to find the average C and a value using the change of C

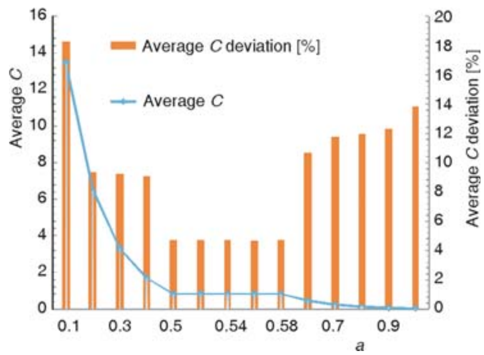

Figure 4. Coefficient a *vs.* C values and its percen derivation from average

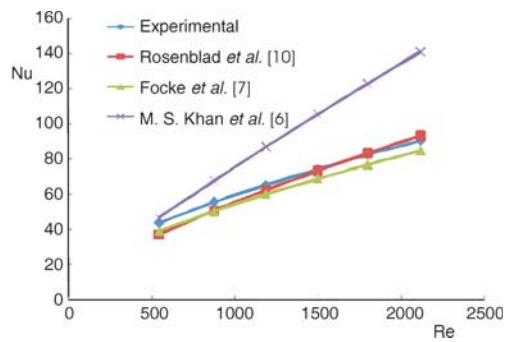

Figure 5. Comparison of new Nusselt number correlations with other correlations

average deviation in percentage. From the figure it has been found that *C* and *a* are 0.8 and 0.56, respectively. Hence, the coefficient of heat transfer plate can be calculated:

$$Nu = 0.8\,Re^{0.56}\,Pr^{0.333}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{13}$$

The correlation developed from the present study is given in eq. (13) and it is compared with the various correlations shown in tab. 1.

Table 1. Nusselt number correlations in literature and the range of Reynolds number and chevron angle

Reference	Chevron angle θ	Re	Correlation
Rosenblad *et al.* (10)	60	60 < Re < 2415	$Nu = 0.289\,Re^{0.697}\,Pr^{0.33}$
Focke *et al*. [7]	60	Re < 44000	$Nu = 0.44\,Re^{0.647}\,Pr^{0.5}$
M. S. Khan *et al*. [6]	60	500 < Re < 2500	$Nu = 0.1449\,Re^{0.8414}\,Pr^{0.35}\,(\mu/\mu_w)^{0.4}$

Figure 5 shows that a new correlation of Nusselt number (present work) is similar to Focke *et al*. [7] and Rosenblad *et al*. [10] The experimental correlations are very close to Focke and Rosenblad. It is observed that the Rosenblad correlations, the Nusselt number is minimum for low Reynolds number value and reaches maximum Nusselt number for high Reynolds number value. The Nusselt number increases with increase in flow rate when compared with Focke correlations. The Khan *et al*. [6] correlations are similar to Focke and Rosenblad, during low flow rate, the Nusselt number deviated linearly with increase of Reynolds number.

Conclusion

Experiments are conducted on a single phase fluid flow plate heat exchanger for various flow rates in range of Reynolds number between 500 and 2200 to obtain the new Nusselt number correlations. The new Nusselt number correlation is $Nu = 0.8\,Re^{0.56}\,Pr^{0.333}(\mu/\mu_w)^{0.14}$ for chevron angle of 60°. From the experiment investigations it is concluded that the Nusselt number is a function of Reynolds number and which increase with increasing of Reynolds number.

Nomenclature

A – effective heat transfer surface area, [m^2]
A_x – horizontal cross section of single channel, [m^2]
b – corrugation depth or mean channel spacing, [m]
Ch – channel
c_p – specific heat, [kJkg^{-1}K^{-1}]
D_e – equivalent diameter of flow passage, [m]
D_h – hydraulic diameter, [m]
G_{ch} – mass velocity of channel, [kgm^{-2} s]
h – convective heat transfer coefficient, [Wm^{-2}K^{-1}]
k – thermal conductivity, [Wm^{-1}K^{-1}]
m – mass flow rate, [kgs^{-1}]
Nu – Nusselt number
N_{cp} – Number of channel
Pc – corrugation pitch, [m]
Pr – Prandtl number
p – pitch of the plate
Q – heat load, [W]
Re – Reynolds number
T – temperature, [K]
ΔT – log-mean temperature difference, [K]
t – plate thickness, [m]
U – overall heat transfer coefficient, [Wm^{-2}K^{-1}]
W – width of the channel

Greek symbols

β – chevron or corrugation angle
μ – dynamic viscosity, [kgm^{-1}s^{-1}]
ϕ – surface enlargement factor

Subscripts

avg – average
c – cold stream
h – hot stream
in – inlet fluid condition
out – outlet fluid condition
w – wall

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