EXPERIMENTAL INVESTIGATION OF DIRECT-CONTACT HEAT TRANSFER IN ISO-PENTANE/WATER SYSTEMS

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ABSTRACT

The present experimental investigation deals with the phenomenological study of direct-contact heat exchange for iso-pentane/water system. The test section consisted of a cylindrical perspex column, in which distilled water was to be confined. Liquid iso-pentane drops were injected into the hot water filled column through special distributors located at the bottom of the column. Various operating and design parameters were investigated and their effects on the overall performance of the heat transfer process were deduced. The experimental runs were planned using the central composite rotatable design method. It has been found that the volumetric heat transfer coefficient values fall with an increase in the inlet temperature of water, also small-diameter nozzles associated with faster nozzle velocities, and smaller droplets, yield higher volumetric heat transfer coefficient. In addition, iso-pentane was found to yield a slightly higher volumetric heat transfer coefficient compared with n-pentane.

Keywords: direct-contact heat transfer, bubble column, heat exchanger, iso-pentane.

INTRODUCTION

Direct-contact heat exchange is a process whereby two fluids pass in direct-contact with each other to facilitate heat transfer. The heavier fluid enters at the top of the column and flows downward. A lighter fluid is admitted at the bottom and flows upward in the column. Obviously the flow is driven by gravity effects. One of the fluids (generally either one of them) can play the role of the continuous fluid, while the other takes the role of the dispersed fluid. The latter is usually dispersed by some type of spray header (droplet spray nozzle) (Brickman & Boehm, 1994).

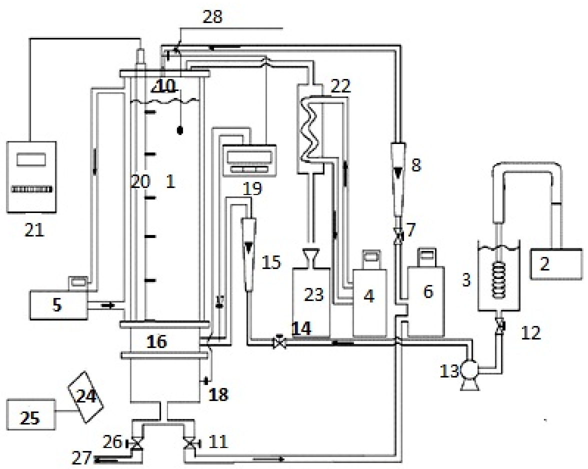
Direct-contact heat transfer between two immiscible liquids has the advantages of (a) eliminating metallic heat transfer surfaces, which are prone to corrosion and fouling, (b) relative simplicity of design, which utilizes natural buoyancy to create a counter flow through a column, (c) higher heat transfer rates (relatively high performance), (d) ability to operate at relatively small temperature driving forces, (e) low capital cost, and (f) lower pressure drop. The practical applications are found in water desalination, production of electricity from low or moderate temperature heat sources in geothermal brines or solar pond power plants coupled with Rankine cycle, ocean thermal energy conversion, thermal energy storage system, emergency cooling of chemical reactors, and production of steam generation for the Rankine power cycle from the direct-contact vaporization of water with lead-bismuth eutectic in Pb-Bi/ water reactor (PBWR) (Brickman & Boehm, 1995), (Battya et.al., 1982, 1983), (Seetharamu & Battya, 1989), (Buongiorno et.al., 2001).

Terasaka and Tsuge (Terasaka & Tsuge, 1993) studied the bubble volumes and shapes formed from a constant-flow nozzle submerged in a liquid. They photographed the bubble shapes during bubble formation with a high-speed video camera, using different liquids in N_2 gas such as tap water and 68 Wt% glycerol. (Sideman et al. 1965) investigated the spray column with fixed dispersed phase flow rates and different diameters of orifices using the n-pentane / sea water system. The results show that the smaller the droplets, the smaller the optimal volume, and the larger the volumetric heat transfer coefficient. (Sideman and Gat. 2004) measured the volumetric heat transfer coefficient and column heights required to vaporize pentane in water. Volumetric heat transfer coefficients were in the range of 8,000 to 20,000 kJ/m hr. C, and the results show that the coefficients decrease with increasing driving force. (Ghazi,1991) investigated the direct heat transfer for air- water system and concluded that water temperatures appear to have little or no effect on the overall heat transfer coefficient.

(Brickman and Boehm, 1994) studied the liquid-liquid direct-contact heat exchangers for the purpose of finding the design that brings the temperature difference between the two fluids to as a small value as possible, using oil-water system. They confirmed that a longer column and smaller droplet size yield an increase in effectiveness. (Özbelge and Shahidi, 1999) studied the direct-contact heat transfer between water and oil in co-current flow through a horizontal concentric annulus. They compared conventional heat exchangers with direct-contact heat exchangers (DCHX), and concluded that DCHXs have many advantages, especially in an annular geometry, because the unequal shear stresses exerted on the liquid drops, located in the annulus, by the inner and outer pipe surfaces induce the deformation of drops and their break-up into droplets, thus an enhancement of heat transfer is obtained. (Dammel and Beer, 2000) studied the rise and evaporation of furan drop (dispersed phase) in a second less volatile immiscible liquid of aqueous glycerol (continuous phase) of higher density and a temperature above the saturation temperature of the dispersed phase, and investigated the motion of the interfaces. (Nagayoshi et al., 2002) conducted a study on heat and mass transfer characteristics of air bubbles and hot water in direct contact. Hanna et al., (2003) conducted a parametric

analysis on a three phase direct-contact system consisting of n-pentane and water. (Ribeiro & Lage, 2004) used an air-water system for measuring liquid temperature, bubbling height, evaporation rate, gas hold-up and bubble size distributions in a direct-contact evaporator for four gas superficial velocities in both homogeneous and heterogeneous bubbling regimes, revealing some interesting features of transient non-isothermal bubbling. (Ribeiro & Lage, 2005) also characterized the gas-liquid direct-contact evaporators by bubbling of a superheated gas through a solution to be concentrated).
(Adams and Pinder, 1972) obtained the average heat transfer coefficients for the evaporation of the drops of iso-pentane and cyclopentene in different glycerin-water solutions. (Chughtai & Inayat, 2010) conducted a numerical simulation of direct-contact condensation from a supersonic steam jet in subcooled water and compared the findings of the computational fluid dynamics simulations with published experimental data which showed good agreement thus validating their model.

EXPERIMENTAL SET-UP
The experimental system is shown schematically in Fig.1. It consisted of a test section, hot water supply system, cooling supply system, dispersed phase supply system, and dispersed phase distributor.



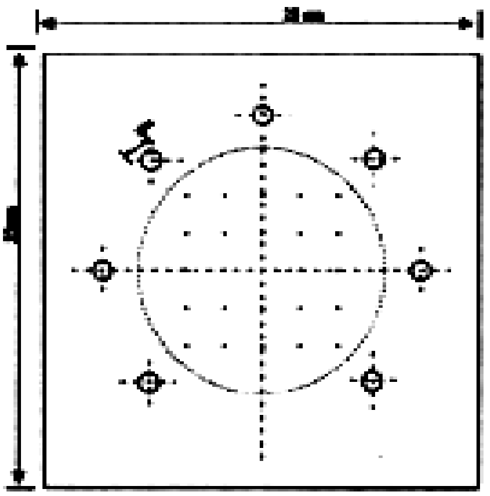
1. Direct – contact heel exchanger
2. Submerged cold coil
3. Cylindrical storage tank
4. Cooling bath
5. Jaconet bath
6. Water bath
7.11,12,14,26 ball valves
8. Water rat meter
9.17.18 serocr (thermocouples
10. water distnbutcx
13.pump
15.Iso-pentane rotamerer
16.Iso-nentane distbetar
19.21.Mub-channel reoo rare
20.Set of thermocouples
22.Conderser
23.Coleation starage tank
24.Digital camera
25.Computer (p3)
27.Discharge line of water
28.Steel bar camera calibration

Fig.1. Schematic diagram of the experimental apparatus

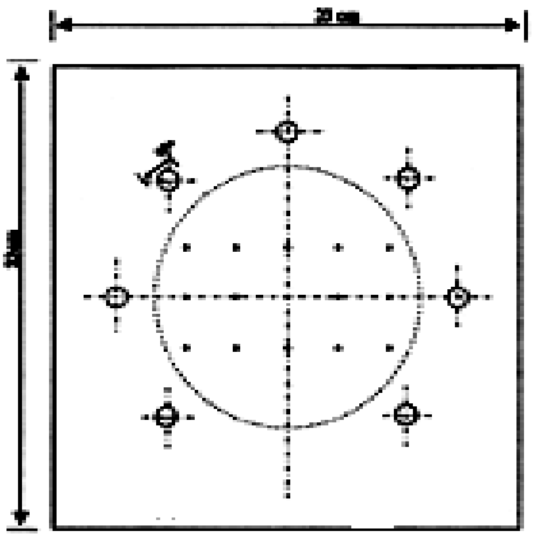
The test section consists of a cylindrical Perspex column of 17 cm inside diameter and 1m length, in which the test fluid, water, is to be confined. A cylindrical Perspex-made water jacket with a variable working temperature was used as a fixed-temperature water bath. The jacket contributed to minimizing the heat losses from the test column by circulating water around the test column. The top and bottom ends of the test column were closed with Perspex plates. The water was supplied at the top of the test column through the distributor located at the center of the test column and flows downward to exit through the bottom by a constant-temperature circulating bath equipped with a thermostatically controlled electric heater. The optimum water height in the column was found to be around 85cm. The water flow rate was measured by using a calibrated rotameter. The temperature of inlet water was measured by calibrated sheath copper - constantan thermocouple (9), inserted at the top of the inlet water line, and the temperature of outlet water was measured by a similar thermocouple (17), inserted below the distributor section.
The iso-pentane entered the test column at constant temperature of 30^{o}C from the bottom through a distributor and flows upward in droplet form. Its flow rate was measured by using a calibrated rotameter. The flow rates of the continuous phase (water), and dispersed phase (iso-pentane) were manually controlled by using a stainless steel ball valves mounted in the liquid lines.
The temperature of the iso-pentane was measured by a calibrated, sheath copper - constantan thermocouple (18) inserted before the distributor. The thermocouples (9), (17), and (18) were connected to a multi-channel temperature recorder. Six calibrated sheath copper-constantan thermocouples were inserted along the length of the column on its left side with a spacing of 17 cm from each other. These thermocouples were connected to a multi-channel temperature recorder of the same type above. The iso-pentane vapor was collected at the top of the test column, and condensed in a vertical condenser by circulating cooling ethanol/water mixture. The condensate was collected in a storage tank to be reused in the experiments. A digital camera with a speed of 30 Frames per second was used in the experimental work to obtain the two-phase bubble size, and the level of any two-phase bubble along its path from the position of the initial drop.
Hot water was supplied to the test column by a constant temperature circulating bath equipped with a thermostatically controlled electric heater. Cold ethanol-water mixture was supplied to the condenser at the top of the test column by a constant temperature circulating bath equipped with a thermostatically controlled chiller.
The dispersed phase was stored in a vessel of QVF glass, which was a cylindrical vessel of 25 liter capacity. This vessel was supplied with submerged cold coil of the chiller unit. The dispersed phase was iso-pentane fed by a pump from the cylindrical

vessel located approximately 0.5m above the ground level.

Two types of distributors were used in the experiments as shown in Fig.2. Distributor (A) was made of Teflon coated Aluminum plate of 5 mm thickness in which 25 orifices of 1 mm diameter each were drilled according to a square in-line arrangement of 2 cm pitch. Distributor (B) was based on the same design with 15 orifices of 2 mm diameter each and a pitch of 2.5 cm.



Disrbrtor (A) No. of orifice = 25
Orifice diameter = 1mm
Pitch = 2cm



Disrbrtor (B) No. of orifice = 15
Orifice diameter = 2mm
Pitch = 2.5cm

Fig.2. Design details of iso-pentane distributors

DATA ANALYSIS

Data were acquired by direct measurement Enlarged consecutive pictures were developed from the fast and high resolution camera films For these measurements, all the drops, as well as the vapor phase bubbles, were taken as of ellipsoidal shape. The instantaneous equivalent spherical diameter was calculated from the measured horizontal and vertical diameters as well as the diameter of a steel ball suspended inside the test section for calibration purposes (Raina et.al., 1984), (Simpson et.al., 1974)

$$d_D = \left| D_0^3 + \left(\frac{M-1}{M}\right)\left(d_h^2 d_y\right)\right|^{\frac{1}{3}} \qquad (1)$$

By assuming no heat losses from the test column, and knowing inlet and outlet temperatures of water and iso-pentane, the logarithmic mean temperature difference could be calculated, as well as the heat transfer rate, and the volumetric heat transfer coefficient using the following relationship:

$$q = m_0 C_{pc} (T_{ci} - T_{c0})\, m_d^{\cdot} \lambda_d + (T_{d0} - T_{di}) m_d^{\cdot} C_{pd} = U_V V \Delta T_{Lm} F \qquad (2)$$

in which the superheating effects were neglected and the correction factor F is taken equal to 1.

RESULTS AND DISCUSSION

The experimental results are given in Figs. 3 to 8 in which the meanings of code numbers are as given in Table 1. Each figure includes two charts: one for distributor (A) labeled A and another one for distributor (B) labeled B.

Table 1. Working range of coded and corresponding real variables.

Coded level	Inlet temperature of water (^{o}C)	Water volumetric flow rate (cm^3/s)	Iso-Pentane volumetric flow rate (cm^3/s)
-1.732	30	9.8	0.9636
-1	31.7	18.13	1.167
0	34	29.42	1.445
1	36.3	40.83	1.722
1.732	38	49	1.927

Fig.3 shows the influence of inlet temperature of water on the droplet radius. Droplet radii increase with increasing inlet temperature of water for the two distributors (A) and (B), because of the increase in inlet temperature of water leading to an increase in the logarithmic mean temperature difference (ΔT_{Lm}) and an increase in the vapor portion in the two-phase bubbles moving along the length of column. This is attributed to the increase in size of the two-phase bubbles. Similar conclusion was reached by (Simpson et al., 1974) and (Sideman and Taitel,

1964) who used a system consisting of butane drops in brine.

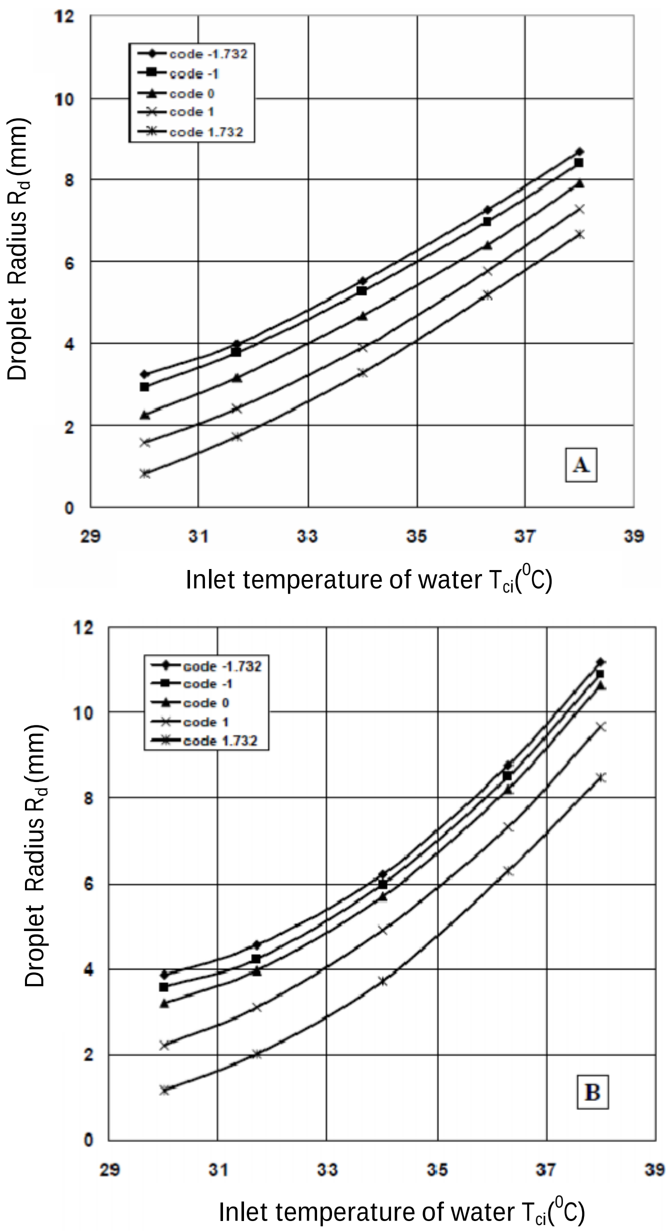


Fig.3. Variation of droplet radius with inlet temperature of water

Fig.4. shows the effect of inlet temperature of water on the volumetric heat transfer coefficient The volumetric heat transfer coefficient decreases with increasing inlet temperature of water due to the increase in the logarithmic mean temperature difference (driving force), and the increase in the overall resistance to heat transfer. Similar results are reported by (Sideman et al., 1965), (Sideman & Gat, 1966) and (Sideman & Taitel, 1964).

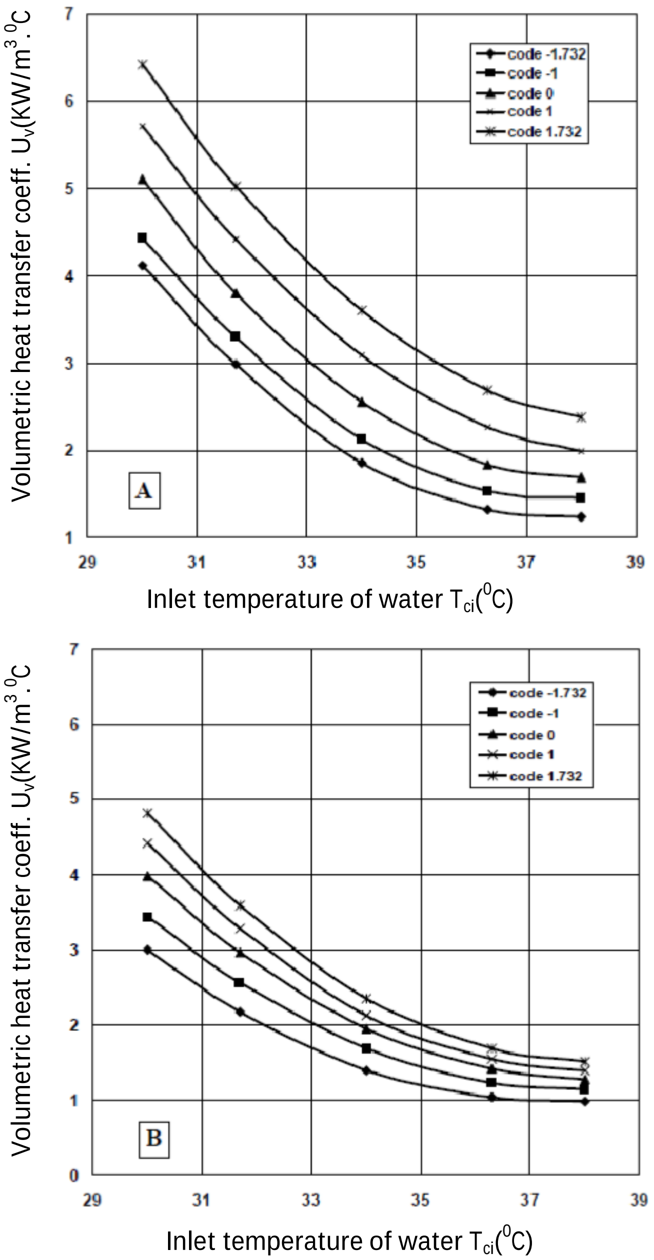


Fig.4. Variation of volumetric heat transfer coefficient with inlet temperature of water

Values of the droplet radius are plotted against the water volumetric flow rate in Figs.4 for distributors (A) and (B), respectively. The droplet radius decreases with increasing water volumetric flow rate for both distributors. Such a decrease is attributed to the increase in the deformation of the two-phase bubbles in the iso-pentane (break-up of two phase bubbles), thus the rate of coalescence decreases. This will result in a smaller two-phase bubble size, and larger interfacial area for direct-contact heat transfer. Similar results were reported by (Shahidi and Özbelge, 1995) using a system of two immiscible liquids.

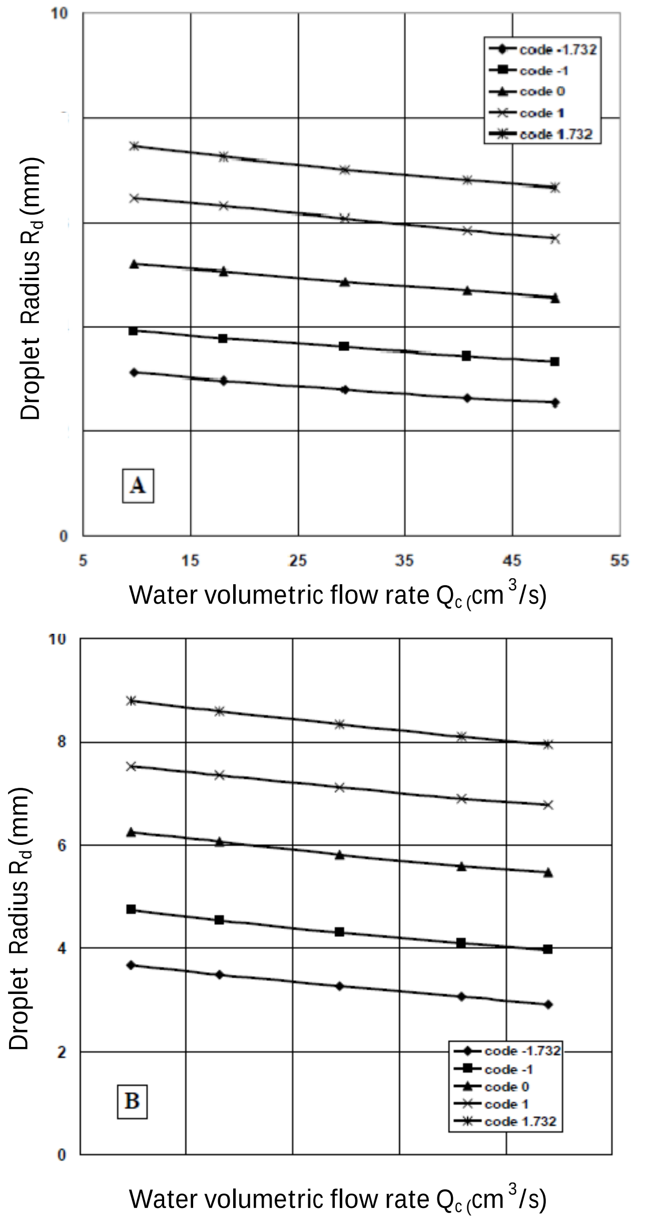


Fig.5. Variation of droplet radius with volumetric flowrate of water

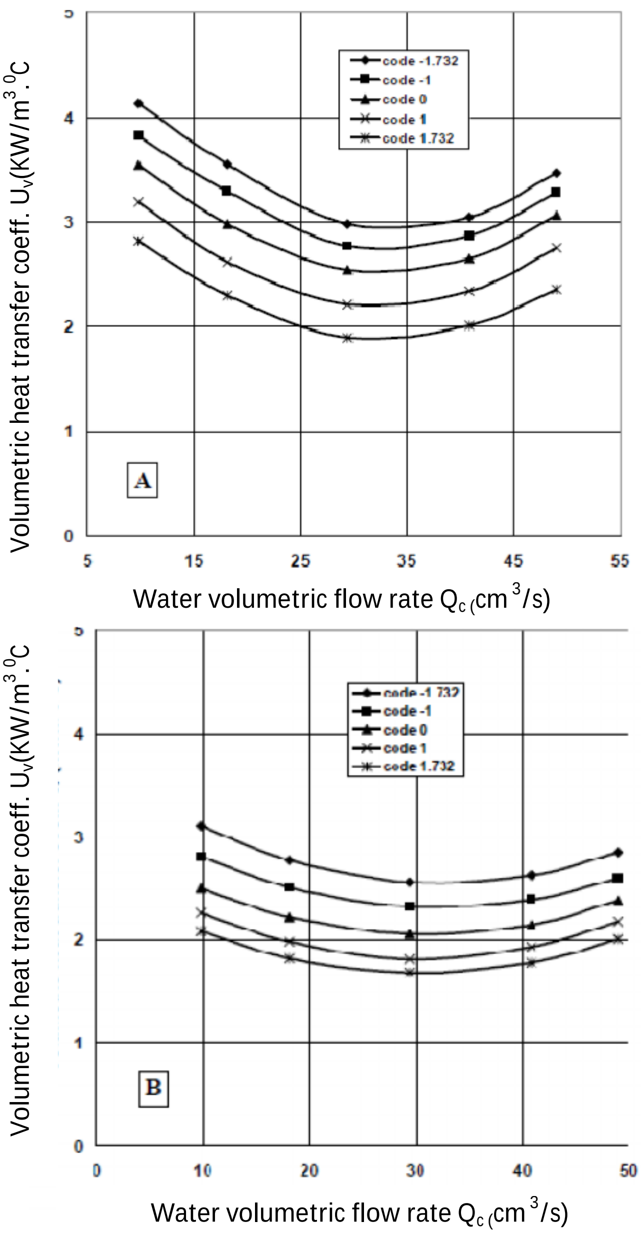


Fig.6. Variation of volumetric heat transfer coefficient with volumetric flowrate of water

The results shown in Fig.5, representing the variation of the volumetric heat transfer coefficient with the water flow rate, indicate, clearly, two operating ranges. In the first range, the volumetric heat transfer coefficient decreases with increasing water volumetric flow rate because of increasing rate of coalescence compared with the rate of break-up in this range. In the second range, the volumetric heat transfer coefficient increases with increasing water volumetric flow rate because of the formation of smaller droplets, which have less tendency to coalesce and high tendency to break-up. Increasing in break-up of the two-phase bubbles will increase the effective heat transfer area per unit volume of the heat exchanger, and, as a result, the volumetric heat transfer coefficient. Such a behavior is reported by (Sideman et al., 1965).

Fig.6 shows the influence of iso-pentane flow rate on droplet radius. Droplet radius decreases with increasing iso-pentane flow rate for both distributors (A) and (B), because a more significant deformation of iso-pentane droplets in the flow direction (break-up of two phase bubbles), leads to small two-phase bubbles size, (Özbelge & Shahidi, 1999).

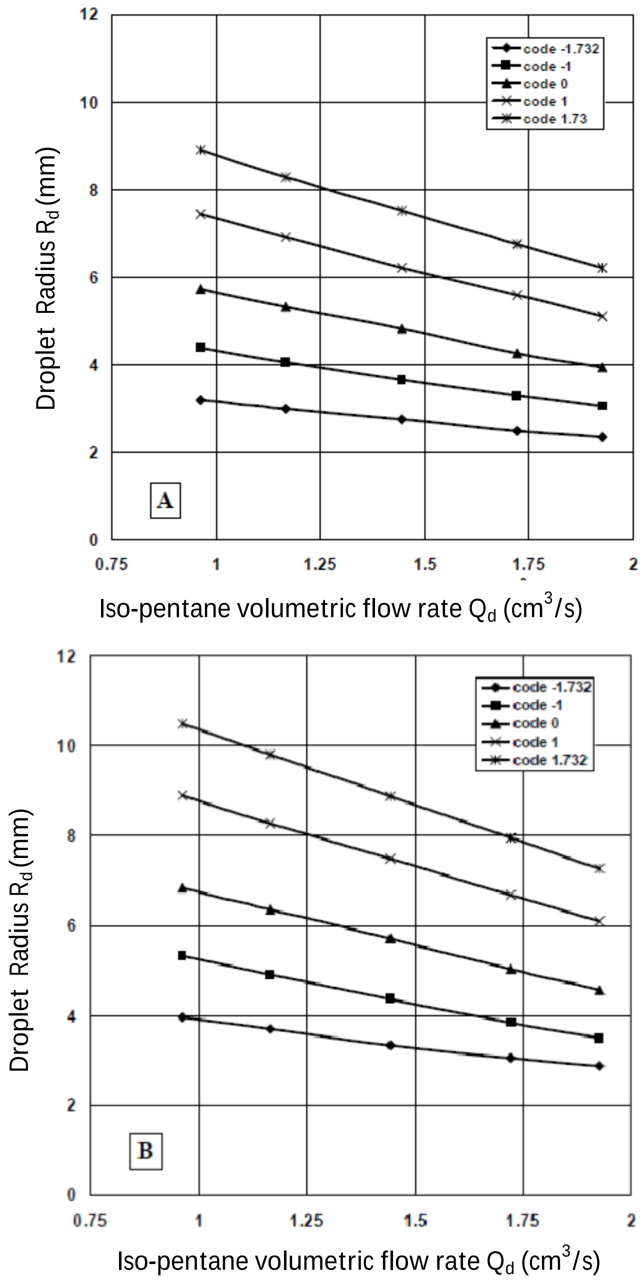


Fig.7. Variation of droplet radius with volumetric flowrate of iso-pentane

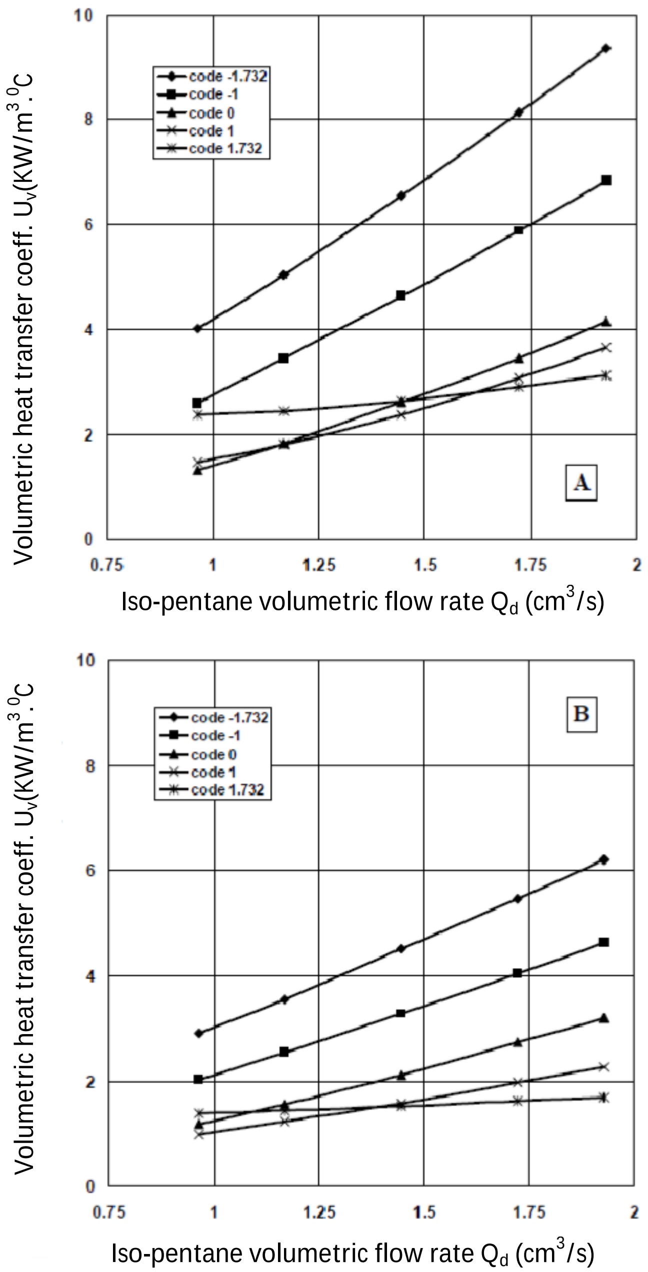


Fig.8. Variation of volumetric heat transfer coefficient with volumetric flowrate of iso-pentane.

The effect of iso-pentane volumetric flow rate on the volumetric heat transfer coefficient is shown in Fig.7. The volumetric heat transfer coefficient increases with increasing iso-pentane flow rate for both distributors (A) and (B). This increase is attributed to the fact that smaller bubbles are formed in higher iso-pentane flow rate. These small bubbles have large interfacial areas leading to high volumetric heat transfer coefficients. Similar trends are reported by (Sideman et al., 1965), Nagayoshi et.al., 2002) and (Shahidi & Özbelge, 1995).

A complete second-order polynomial regression analysis of the results was conducted using standard statistical software. Three variables were considered in the investigations, namely, the inlet temperature water, the continuous phase, e.g. water, volumetric flow rate, and the dispersed phase, e.g. iso-pentane, volumetric flow rate for both distributor designs (A) and (B). The resulting correlations for the droplet radius and the volumetric heat transfer coefficient are:

- Distributor (A):

$$R_d = 2.627572 - 0.463522T_d - 0.0762151Q_0 + 1.023141Q_d + 0.016831T^2_d + 0.000137\,Q^2_0 + 0.013779\,Q^2_d + 0.003062T_dQ_c - 0.047992T_dQ_d - 0.038164Q_cQ_d \quad (3)$$

$$Uv = 63.3236 - 3.63413T_{ci} - 0.405121Q_c + 17.3598Q_d + 0.052008T^2_{ci} + 0.001891Q^2_c + 0.699334Q^2_d + 0.010389T_{ci}Q_c - 0.442591T_{ci}Q_d - 0.052263Q_cQ_d \quad (4)$$

- Distributor (B):

$$R_d = 45.71144 - 3.3060T_{ci} - 0.078543Q_c + 5.910858Q_d + 0.06331T^2_{ci} - 0.001891Q^2_c - 0.963606\,Q^2_d + 0.002706T_{ci}Q_c - 0.139228T_{ci}Q_d - 0.016319Q_cQ_d \quad (5)$$

$$Uv = 42.62726 - 2.38412T_{ci} - 0.13685Q_c + 8.774618Q_d + 0.033075T^2_{ci} + 0.000876Q^2_c + 0.376376Q^2_d + 0.003593T_{ci}Q_c - 0.208444T_{ci}Q_d - 0.031041Q_cQ_d \quad (6)$$

A comparison between the volumetric heat transfer coefficient obtained for n-pentane and iso- pentane is illustrated in Fig.8. The figure shows that using iso-pentane yields a slightly higher volumetric heat transfer coefficient compared with n-pentane. This is probably because of the decrease in driving force due to the lower boiling point of the former.

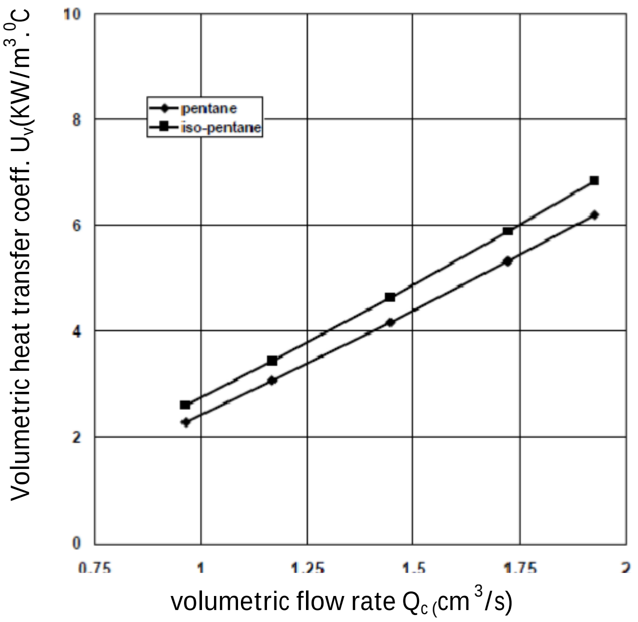


Fig.9. Volumetric heat transfer coefficient for pentane and iso-pentane

Tables 2 & 3 show the regression analysis results for droplet radius and volumetric heat transfer coefficient for both distributors. (A) and (B) which show very good absolute average error, correlation coefficient and standard deviation.

Table 2. Results of regression analysis for droplet radius and volumetric heat transfer coefficient - Distributor (A).

	Droplet Radius	Vol. Heat Transfer Coefficient
Absolute average error	1.1742%	2.52428%
Correlation coefficient	0.99912	0.99804
Standard deviation	0.064836	0.076714

Table 3. Results of regression analysis for droplet radius and volumetric heat transfer coefficient - Distributor (B).

	Droplet Radius	Vol. Heat Transfer Coefficient
Absolute average error	2.13571	3.78032%
Correlation coefficient	0.99556	0.99378
Standard deviation	0.184608	0.096821

CONCLUSIONS

Parametric analysis of direct-contact heat exchanger in a counter-current column of immiscible liquid has been carried out. The results compare favorably with similar results in the literature. The following conclusions can be made:

1. The shape of the two-phase bubbles observed in the present study changed from nearly spherical to ellipsoidal and sometimes to spherical-cap shapes.
2. When the Box-Wilson technique is used, a relationship is found between the process variables T_{Ci}, Q_C, and Q_d, and the design properties R_d, and U_v. The experimental results agree quite well with a polynomial type of correlation.
3. The volumetric heat transfer coefficient values fall with an increase in the inlet temperature of water.
4. Small-diameter nozzles associated with faster nozzle velocities, and smaller droplets, yield higher volumetric heat transfer coefficient.
5. Iso-pentane yields a slightly higher volumetric heat transfer coefficient compared with n-pentane

Recommendations for Future Work

It is highly recommended that further analytical investigations are to be carried out in order to develop techniques that can be used for optimization purposes. It is also recommended to conduct a numerical simulation similar to the one conducted by (Chughtai and Inayat, 2010) on their system.

NOMENCLATURE

C_P specific heat at constant pressure, J/kg ^oC,
d_d droplet diameter of the two-phase bubble, m,
d_h horizontal diameter of the bubble, m,
d_v vertical diameter of the bubble, m,
D_o initial drop diameter, m,
F correction factor
m mass flow rate, kg/s,
M density ratio of liquid density to vapor density of iso-pentane,
q heat transfer rate, kW,
Q volumetric flow rate, m^3/s,
R_d droplet radius of the two-phase bubble, m,
T temperature, ^oC,
U_v volumetric heat transfer coefficient, kW/m.^oC,
V optimum volume of heat exchanger, m^3

GREEK LETTERS

λ latent heat of vaporization, J/kg,
$\Delta T\,l_m$ logarithmic mean temperature difference, ^oC

SUBSCRIPTS

c continuous phase,
d dispersed phase,
i inlet condition,
o outlet condition

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