RELATIONSHIP BETWEEN NUSSELT AND REYNOLDS NUMBER IN DIRECT CONTACT HEAT TRANSFER BY CONDENSATION OF LIGHT HYDROCARBONS IN WATER

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ABSTRACT

The experimental Reynolds and Nusselt numbers were measured for the direct contact heat transfer by condensation of n-pentane, n-hexane and n-heptane single bubbles in water. The physical properties of water were taken at the measured temperature, while those of the light hydrocarbons were taken at their saturation temperature. The velocity and the change in the dimensions of the resulting two-phase bubble were measured using a high-speed camera of 120 frames/s.

INTRODUCTION

Direct contact heat transfer by condensation of single bubble of light hydrocarbon in an immiscible liquid happens when the temperature of the continuous phase (i.e. water) is lower than the dew point of the dispersed phase (i.e. light hydrocarbon). The vapor bubble of the light hydrocarbon condenses to a two-phase bubble as it passes through the continuous phase and the condensation process continues until an almost a full liquid drop is formed.

The industrial application of direct contact heat transfer includes desalination, geothermal heat recovery, emergency cooling sprays of nuclear power reactors, etc.

The process of heat transfer between the dispersed phase and the continuous phase mainly happens by the latent heat of condensation.

Sideman and Hirsch (1964) conducted preliminary studies of the condensation of single vapor bubble in an immiscible liquid media. They used motion pictures of isopentane bubble rising in water to find the transfer mechanism involved in the latent heat transport.

In 1966, Sideman pointed to the presence of air in the bubble, which caused a decrease in the rate of heat transfer.

In 1967, Sideman and Isenberg studied this phenomenon and presented a theoretical study to find the bubble growth and the time dependency of heat transfer coefficient.

Moalem-Maroon and Sideman (1973) presented a theory of the effects of the constant and radius-dependent translation bubble velocity on the collapse of a single bubble.

Jacobs, Fannar and Beggs (1978) presented a study of the collapse of a bubble of saturated vapor rising through a cold continuous immiscible liquid with analytical solution. The study took into account the internal resistance to heat transfer.

A closed periodic condensation-evaporation cycle of a two-phase vapor-liquid bubble driven by gravity in an immiscible continuous phase with a vertical temperature profile was presented by Moalem-Maroon, Sokolov and Sideman in 1979.

Sudhoff. Plischke and Weinspach in 1982 presented a general study on the direct contact heat transfer with change of phase and presented an analytical solution for single bubble.

An experimental and theoretical study of the condensation and the collapse of single bubbles of n-pentane in an immiscible liquid were conducted by Simpson, Beggs and Fannar (1982).

Lavania and Johnson (1987) presented a study of direct contact heat transfer during the condensation of a vapor bubble in an immiscible liquid with a model to heat transfer.

Terasaka, Sun, Prakoso and Tsuge (1999) published a study on the measurement of heat transfer coefficient for direct contact condensation during two-phase bubble formation.

The aim of the work consisted:

1. Measuring the changes in the velocity of the two-phase bubble.
2. Measuring the changes in the dimensions of the two-phase bubble.
3. Studying the relationship between the experimental Nusselt and Reynolds numbers due to the process of condensation.

EXPERIMENTAL WORK

The different experimental fluids studied were n-pentane, n-hexane and n-heptane as dispersed phase in water as continuous phase.

The experimental apparatus, as shown in Fig.(1), consisted of a QVF column of one meter long and (0.1) meter in diameter situated in a rectangular container filled with water to ensure a constant temperature bath and to minimize the visual distortion during filming by high-speed camera of 120 frames/s.

The column was filled with water at 15°C (this temperature can be kept constant using continuous steps of subcooling) . It was equipped with calibrated thermocouples to measure the change in the temperature of the continuous phase. The dispersed phase was introduced through a nozzle at the bottom of the column. Two different diameter nozzles were used so that two different starting bubble diameters as (0.3) and (0.2) cm were ensured.

The vapor of the dispersed phase was generated in a three-knecked round-bottomed QVF flask. The liquid dispersed phase was heated in the flask where adequate quantity of heat was introduced to ensure the complete formation of a vapor bubble and to prevent back condensation. The flask was connected by a heated copper tube through which the vapor passes to the column.

As the vapor bubble enters the column through the nozzle, it begins to condense forming a two-phase bubble with the condensate forming the lower part of the bubble and the remaining vapor in the upper part of it.

To measure the change or the decrease in the dimensions of the two-phase bubble and its velocity, a high-speed camera of 120 frames/s was used. The video timer showed the time related to each picture on the screen and from the measured position of each bubble, the velocity was calculated.

The shape of the two-phase bubbles was spherical and their radii were measured.

As the two-phase bubble was formed the condensate forms the lower part of the bubble with a sickle shape. The vapor phase forms an ellipsoidal or spherical shape. The vertical and horizontal radii of the vapor phase were measured. A schematic representation of the two-phase bubble is shown in Fig. (2) (Basma A. Abdul Majeed, 2002).

A digital camera equipped with a 3.5″ floppy disk, which can be used in a personal computer, was also used to get clear photographs of the two-phase bubble. Figures (3) and (4) show two different bubbles (Basma A. Abdul Majeed, 200).

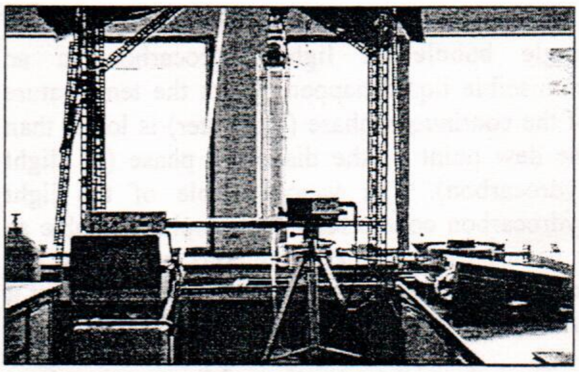


Fig. (1) Photograph of the apparatus

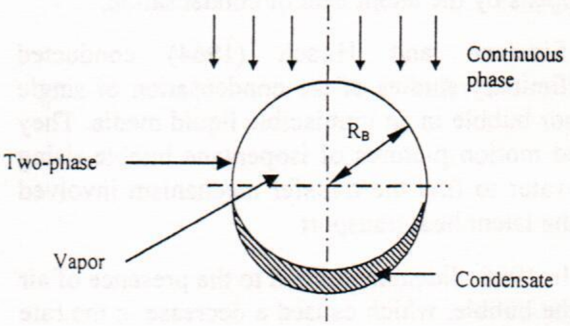


Fig. (2) Two phase bubble

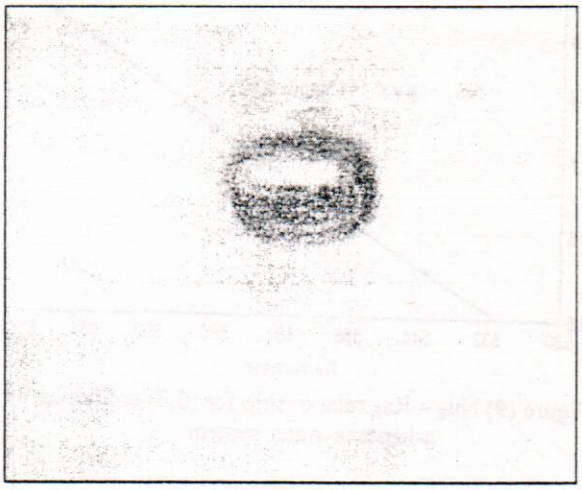
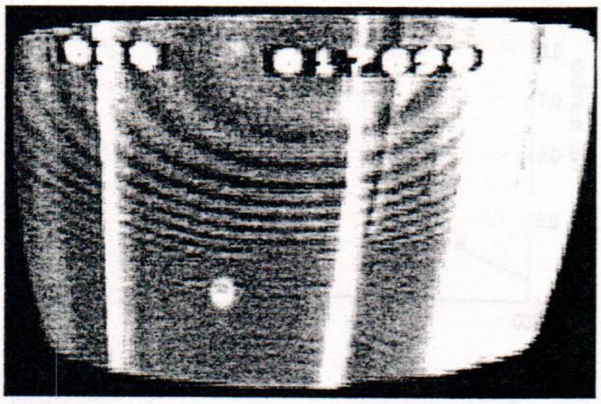


Fig. (3) Two phase bubble



Fug. (3) Two phase bubble projected on high-speed camera

The instantaneous experimental heat transfer coefficient corresponds to each reading of the thermocouple. The values of ΔT together with the corresponding radius of the two-phase bubble are given in Table (1) and (2) respectively. The heat transfer coefficient can be calculated using Eq. (1):

$$h_E = \frac{L_{fg}\rho}{\Delta T}\frac{1}{A_B}\frac{dV_B}{dt} \qquad (1)$$

The volume of the two-phase bubble is calculated from Eq.(2), while its area is calculated from Eq. (3) as follows:

$$V_B = \frac{4}{3}\pi R_B{}^3 \qquad (2)$$

$$A_B = 4\pi R_B{}^2 \qquad (3)$$

$\frac{dV_B}{dt}$ represents the change of volume of the two-phase bubble with time taken from the enlarged photographs relative to each thermocouple reading. These values are calculated by graphically differentiating the volume with respect to time.

The values of the horizontal and vertical radii of the vapor phase are shown in Table (1) and (2). The volume of the two-phase, its area, the change in volume with time and its velocity are given in Table (3) and (4).

The values of Nusselt number were calculated using Eq.(4):

$$Nu_E = \frac{h_E(2R_B)}{k} \qquad (4)$$

The values of Reynolds number were calculated using Eq.(5) as follows:

$$Re_E = \frac{U\rho(2R_B)}{\mu} \qquad (5)$$

The values of ReE and NuE are shown in Table (5). Figures (5)-(10) show the behavior of Nusselt-Reynolds numbers, Basma Abbas Abdul Majeed, 2002.

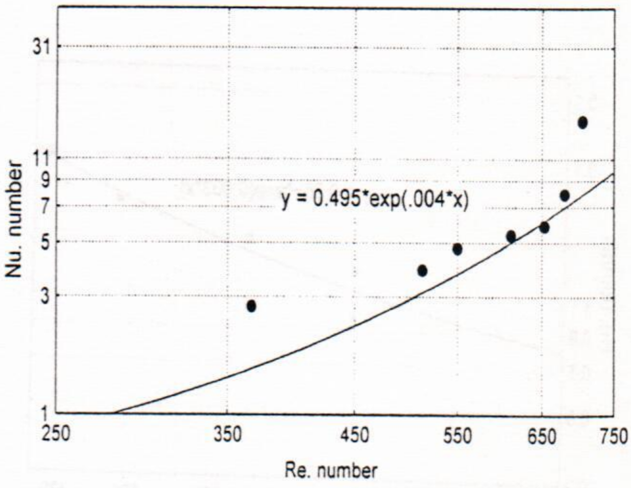


Figure (5) $Nu_E - Re_E$ relationship for (0.3) cm radius, n-pentane-water system

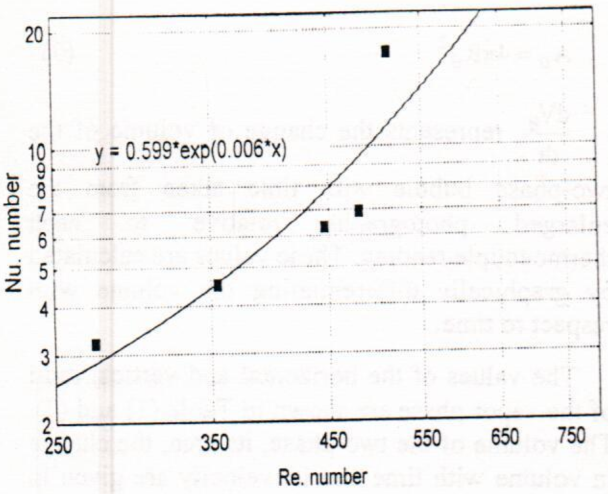


Figure (6) $Nu_E - Re_E$ relationship for (0.2) cm radius, n-pentane-water system

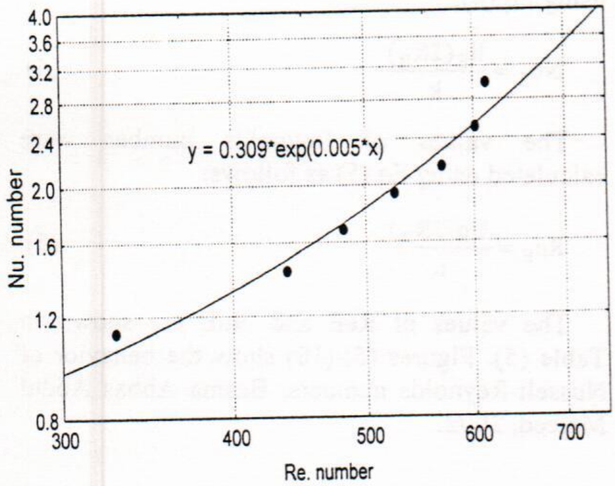


Figure (7) $Nu_E - Re_E$ relationship for (0.3) cm radius, n-hexane-water system

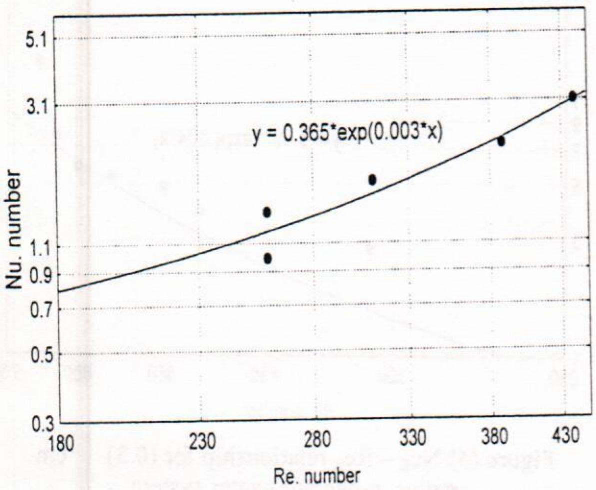


Figure (8) $Nu_E - Re_E$ relationship for (0.2) cm radius, n-hexane-water system

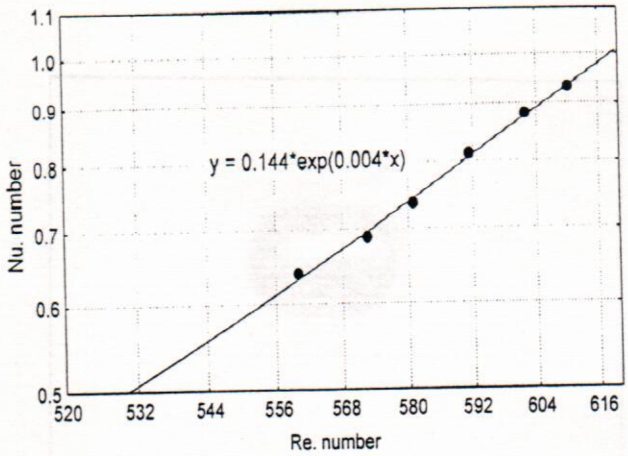


Figure (9) $Nu_E - Re_E$ relationship for (0.3) cm radius, n-heptane-water system

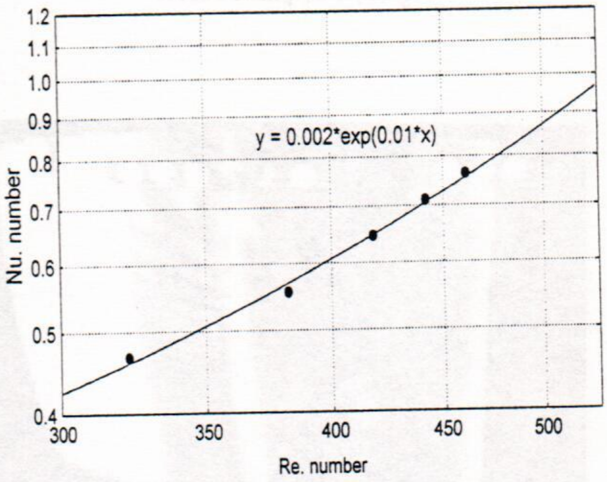


Figure (10) $Nu_E - Re_E$ relationship for (0.2) cm radius, n-heptane-water system

RESULTS AND DISCUSSION

The change in the dimensions of the two-phase bubble is clear. As the vapor bubble of the dispersed phase enters the column through the nozzle, it begins to condense forming a two-phase bubble. It ascends through the column and it is subjected to more condensation. The temperature of the continuous phase increases. The velocity of the bubble at the nozzle is considered to be zero. It reaches a maximum value at the location of the thermocouple, then its value remains constant.

Referring to Figures (5) to (10), the value of Nusselt number depends on the heat transfer coefficient, radius of the two-phase bubble and the thermal conductivity of the water. The Nusselt number shows a decrease in its value since both the radius and the heat transfer coefficient decrease. The decrease in the radius is obvious since the bubble is subjected to continuous condensation causing a shrinkage in its size.

At high values of vapor content, i.e., at the beginning of the condensation process, the heat transfer coefficient acquires high values.

As the process of condensation continues, the condensate increases leading to an increase in the resistance to heat transfer rate. Generally speaking, the heat transfer behavior can be explained firstly by a somewhat turbulent behavior of the two-phase bubble, where the primary condensation process takes place. As the two-phase bubble continues its transfer to a liquid drop, the heat transfer rate decreases. Reynolds number decreases with the decrease in the bubble dimensions, i.e., with the continuous condensation.

When considering the figures shown and the tables corresponding to them, the system of n-pentane in water proves to give the highest values of Nusselt number compared to that of n-hexane or n-heptane in water.

CONCLUSIONS

1. There is a continuous change in the dimensions of the two-phase bubble and its velocity.
2. A clear proportional relationship exists between the two dimensionless groups Nusselt and Reynolds numbers.
3. The most appropriate system used is the n-pentane single bubble in water because the higher carbon atoms hydrocarbons give poor heat transfer rates.

NOMENCLATURE

AB	area of the two-phase bubble, m2
a	horizontal radius of the the vapor phase, m
b	vertical radius of the vapor phase, m
hE	experimental heat transfer coefficient, kW/Km2
k	thermal conductivity of water, W/mK
Lfg	latent heat of condensation, kJ/kg
NuE	Nusselt number
RB	Radius of the two-phase bubble, m
ReE	Reynolds number
t	time, s
VB	volume of the two-phase bubble, m3
U	velocity of the two-phase bubble, m/s
ΔT	difference between the temperature of the water and the saturation temperature of the dispersed phase, K
ρ	density of the water, kg/m3
μ	viscosity of the water kg/ms.

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Table (1)

	0.3, cm			
	R_B*10^2 m	$a*10^4$ m	$b*10^4$ m	ΔT, K
n-pentane	0.288	5.0	5.0	0.3
	0.278	5.0	4.5	0.6
	0.267	4.5	4.0	1.0
	0.250	4.5	3.0	1.4
	0.225	3.5	2.5	2.0
	0.210	3.0	2.0	2.6
	0.150	3.0	2.0	3.0
n-hexane	0.28	5.0	5.0	1.7
	0.275	5.0	4.8	2.0
	0.26	5.0	4.8	2.4
	0.24	5.0	4.5	2.8
	0.22	5.0	4.2	3.3
	0.20	5.0	4.2	3.7
	0.18	4.8	4.0	4.1
n-heptane	0.295	11.0	6.0	2.0
	0.292	10.0	6.0	2.7
	0.288	9.2	6.0	2.9
	0.283	9.0	6.0	3.2
	0.278	9.0	5.8	3.6
	0.274	8.6	5.8	3.9
	0.268	8.6	5.5	4.3

Table (2)

	0.2, cm			
	R_B*10^2 m	$a*10^4$ m	$b*10^4$ m	ΔT, K
n-pentane	0.163	4.0	3.0	0.2
	0.153	3.0	2.0	0.4
	0.142	2.7	1.8	0.5
	0.113	2.0	1.5	1.1
	0.087	2.0	1.5	1.4
n-hexane	0.17	6.0	2.8	1.8
	0.15	5.5	2.8	2.2
	0.12	4.0	2.8	3.0
	0.10	4.5	2.8	3.6
	0.10	4.5	2.5	4.2
n-heptane	0.193	5.0	5.0	2.5
	0.185	5.0	4.8	2.8
	0.175	4.8	4.8	3.1
	0.160	4.8	4.5	3.4
	0.135	4.5	4.5	4.5

Table(3)

	0.3, cm			
	A_B*10^5 m^2	V_B*10^8 m^3	$dV_B/dt*10^6$ m^3/s	U, m/s
n-pentane	10.4	10.0	0.048	0.14
	9.7	9.0	0.047	0.14
	9.0	7.8	0.056	0.14
	7.9	6.6	0.067	0.14
	6.4	4.8	0.076	0.14
	5.5	3.9	0.074	0.14
	2.8	1.4	0.044	0.14
n-hexane	9.9	9.2	0.035	0.12
	9.5	8.7	0.034	0.12
	8.5	7.4	0.033	0.12
	7.2	5.8	0.032	0.12
	6.1	4.5	0.030	0.12
	5.0	3.4	0.026	0.12
	2.8	1.4	0.017	0.12
n-heptane	10.9	10.8	0.02	0.105
	10.7	10.4	0.02	0.105
	10.4	10.0	0.02	0.105
	10.1	9.5	0.02	0.105
	9.7	9.0	0.02	0.105
	9.4	8.6	0.02	0.105
	9.0	8.1	0.02	0.105

Table (4)

	0.2, cm			
	A_B*10^5 m^2	V_B*10^8 m^3	$dV_B/dt*10^6$ m^3/s	U, m/s
n-pentane	3.3	1.8	0.020	0.14
	2.9	1.5	0.015	0.14
	2.5	1.2	0.016	0.14
	1.6	0.6	0.020	0.14
	1.0	0.3	0.014	0.14
n-hexane	3.63	2.06	0.023	0.11
	2.83	1.41	0.018	0.11
	1.81	0.72	0.015	0.11
	1.26	0.42	0.012	0.11
	1.26	0.42	0.010	0.11
n-heptane	4.7	3.0	0.01	0.105
	4.3	2.7	0.01	0.105
	3.4	2.3	0.01	0.105
	3.2	1.7	0.01	0.105
	2.3	1.0	0.01	0.105