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Performance Evaluation of Three Phase Spray Direct Contact Heat Exchanger

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Abstract

The present investigation deals with experimental study of three-phase direct-contact heat exchanger, for water-Freon R11 system, where water is the continuous phase (liquid) and Freon R11 (liquid-gas) is the dispersed phase. The test section consisted of a cylindrical Perspex column with inner diameter 8cm and 1.2m long, in which, water was to be confined. Liquid Freon R11 drops were injected into the hot water filled column, through a special design of distributors at the bottom of the column. The liquid Freon R11 drops rose on their way up and evaporated into two-phase bubbles at atmospheric pressure. The study was devoted to express the effect of process variables such as column height, Freon R11 mass flow rate and initial temperature of water on the average percentage holdup, heat transfer rate, volumetric heat transfer coefficient and effectiveness.

The obtained experimental results showed that the average percentage holdup increased with increasing in the process variables. The heat transfer rate increased clearly with increasing in mass flow rate of Freon R11 while it increased very little when column height and initial temperature of water increased, it increased two times when increase the mass flow rate from 1.8 to 5.4 kg/hr. The volumetric heat transfer coefficient was found to decrease with increasing in column height and initial temperature of water, while it was increased with increasing in mass flow rate of Freon R11. The effectiveness was found to increase (maximum 90%) with increasing in column height and decreasing in the mass flow rate of Freon R11 and initial temperature of water. A statistical analysis was performed to get general correlations for the average percentage holdup, heat transfer rate, volumetric heat transfer coefficient and effectiveness as a function of the studied parameters.

Keywords: Direct-Contact Heat Transfer, Heat Exchanger, Freon R11.

Introduction

Direct contact heat transfer can occur whenever two substances at different temperatures touch each other physically. The implication is that there is no an intervening wall between the two substances. The energy transport between the two streams can take place across small thermal resistances.

Direct-contact heat transfer between two immiscible liquids has the advantages as follow:

(a) Eliminating metallic heat transfer surfaces, which are prone to corrosion and fouling.

(b) Relative simplicity of design, 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).

A solar pond power plant operated with a direct contact boiler was thermally analyzed by Sonn and Letan [1]. This study involved six working fluids: butane, pentane, hexane, and Freon R113, R114, R12 with water. The results showed net electrical outputs of 7-9 percent of the heat inputs were obtained for the low pressure fluids, such as pentane, hexane, and R113. Gravity flow of brine to boiler increased these values to 8-11 percent. Battya et al. [2] dealt with experimental investigation of the direct contact evaporation of R-113 in a stagnant column of distilled water. They found the temperature difference required for the complete evaporation of the dispersed phase was depended considerably on the column height. Goodwin et al. [3] studied flooding limits of a large spray column used as a three-phase direct contact heat exchanger (water/n-pentane system). They had given detailed studies of the vessel pressure effects on the flooding limit for the first time. It was found that the pressure at the flooding point varies with the inverse of the pentane flow rate at constant water flow rate and temperature. Celata et al. [4] reported the results of an experimental investigation on direct contact boiling of immiscible liquids (Freon 114-water system). They derived the direct contact boiling efficiency by the evaluation of the fraction of Freon that did not undergo the boiling process during the transit in the test section. Experiments on direct-contact heat exchange between molten metal and water for steam production were conducted by Cho et al. [5]. These experiments involved the injection of water into molten lead bismuth eutectic for heat transfer measurements in 1-D geometry. The results showed the effect of temperature difference between molten metal and water on the heat transfer rate would be expected to depend on the system pressure. Hanna et al. [6] investigated experimental and theoretical phenomenological study of three-phase direct-contact heat exchanger for n-pentane-water system. The n-pentane holdup percentage was found to depend mainly on the n-pentane volumetric flow rate and the nozzle diameter. He derived a theoretical model for the prediction of Nusselt number (Nu_c) in term of Pe. Hyun et al. [7] examined the operation of a liquid-liquid type direct contact heat exchanger in harnessing the solar energy. Two different kinds of working fluid were tested for their thermal characteristics that were immiscible with water. Stability and thermal performance were appeared to improve when the heavier working fluid was dispersed from the top of a direct contact heat exchanger. Thongwik et al. [8] studied the heat transfer characteristic during ice formation of a direct contact heat transfer between carbon dioxide and water mixture. From the experiments, it was found that the effectiveness of the direct contact heat transfer between the carbon dioxide and the water was closed to 100%. Experimental investigation that dealt with the phenomenological study of direct-contact heat exchange for iso-pentane/water system was presented by Zablouk et al. [9]. They found that iso-pentane yield a slightly higher volumetric heat transfer coefficient compared with n-pentane. Nomura et al. [10] described the development and performance of a direct contact heat exchanger using erythritol (melting point: 391 K) as a phase change material (PCM) and a heat transfer oil (HTO) for accelerating heat storage. They showed the latent heat can be rapidly stored under large HTO flow rate and high inlet temperature in the direct contact heat exchanger.

Experimental Work

The experimental system is shown schematically in Fig. 1. It consists of a test section, hot water supply system, and dispersed phase supply system. The test column consists of a cylindrical Pyrex glass column of 80 mm diameter and 1m long , in which the test fluid, water is to be confined, and a cylindrical perspex-made water jacket(type Julabo, Model MP-BRUE/PU), with a working temperature range of (20 to 110) ˚C and a precision of ±0.5 ˚C. A rectangular Perspex water jacket is made concentrically around the inner cylindrical column. The jacket is served as a constant - temperature water bath and also contributed to minimizing the heat losses from the test column by circulating water around the test column and prevented the distortion of the images of the bubbles or drops inside the test column. The bottom cover is fitted with a Teflon orifice distributor from which the dispersed phase is fed.

The hot water supply system is an electrical heater. It consists of a 60 liters electrical heater, water pump and an open tank. Pure water was heated in this system to the desired temperature in the range of 35-55 ˚C and pumped to the test column and circulated to the test jacket by a pump. The dispersed phase supply system is an open-loop. It consists of a dispersed fluid container, regulator valve and needle valve. A regulator valve is used to maintain a constant pressure in the range of 2 to 2.5 bar in the test column. A needle valve is used to control the rate of flow of the dispersed liquid in the range of 1.8 to 5.4 kg/hr. As the dispersed liquid phase (Refrigerant R11) is injected to the test column, it is converted to vapor phase. This vapor phase is drawn from the top end of the test column.

Typical experiments are conducted as follows:

1. Water is heated in the constant temperature heating unit to the desired temperature in the range of 35 to 55 ˚C. Hot water from the constant temperature bath is circulated through the test column. When the water in the test column attains the desired temperature above the dispersed phase saturation temperature (23.7 ˚C for R11), the test column is filled with water to the desired level and the circulation is stopped.
2. The dispersed fluid is injected from bottom by Teflon nozzle with a certain temperature. The pressure of this fluid is measured by gauge pressure.
3. The weight of dispersed phase container is measured before and after the test by digital balance to calculate the mass flow rate of dispersed phase with stop watch.

The test is depicted by digital camera to measure the increasing in water level.

Data Analysis

The experimental measurement of temperatures is an important part of this work because it illustrates the change in actual heat transfer rate and effectiveness of the heat exchanger. By assuming no heat losses from the test column, and knowing inlet and outlet temperatures of dispersed phase (Freon R11), and initial and final temperature of continuous phase (water), one calculates the temperature difference, heat transfer rate, and volumetric heat transfer coefficient from the following heat balance:

$$q = \dot{m}_c Cp_c(T_{ci} - T_{cf}) = \dot{m}_d(h_{d2} - h_{d1}) + q_{loss} \quad \ldots(1)$$

Volumetric heat transfer coefficient is [5]:

$$U_v = \frac{q}{V \times \Delta T} \quad \ldots(2)$$

Where:

$$V = \frac{\pi}{4} D^2 \times H$$

$$\Delta T = T_{cf} - T_{d1}$$

That's where LMTD cannot use to calculate volumetric heat transfer coefficient in stagnant column. But it must use ΔT instead of LMTD.

The overall performance of the direct contact heat exchanger in the present work can be quantified by defining the heat exchanger effectiveness (E), in such a way that it gives the ratio of the actual heat gain (q) of the dispersed fluid to the maximum possible heat transfer from the continuous fluid. Here, the maximum possible heat transfer refers to the case when there is no temperature difference between the two fluids in heat communication. This is only possible when the heat exchanger is infinitely long and maximum possible heat transfer can take place. The expression for the effectiveness (E) could be written as Hyun [7] and Thongwik [8]:

$$E = \frac{h_{d2} - h_{d1}}{h_{max} - h_{d1}} \quad \ldots(3)$$

The average holdup is defined as the ratio of the volume of the dispersed phase to that of the total fluid volume. If H_o is the column height before the injection of the dispersed phase and H is the column height when the dispersed phase escapes as a vapor, the average holdup is given by the following Equation [1] and [5]:

$$\phi = \frac{H - H_O}{H} \quad \ldots(4)$$

Discussion of Results

Three variables are studied in direct-contact heat exchanger: column height, initial temperature of water and dispersed phase mass flow rate for the ranges shown Table 1. For this range, the distributor has 19 holes each 1 mm in diameter.

Figs. 1-3 show the average percentage holdup at different process variables. In general, average percentage holdup increases with increase each one of the variables. Fig.1 shows the change of gas holdup with column height. Average percentage holdup increases with increasing in column height of water due to increasing the bubbles growth. This is due to increasing in time contact which leads to increase in heat transfer and the size of bubbles will be increase.

Table 1: Working range of corresponding real variables

Variable	Range
Column Height (cm)	$5 \leq H \leq 40$
Initial Temperature of Water (˚C)	$35 \leq T_{ci} \leq 55$
Mass Flow Rate of Freon 11 (kg/hr)	$1.8 \leq \dot{m}_d \leq 5.4$

Fig. (2) illustrates the effect of mass flow rate of Freon R11 on the average percentage holdup. When the mass flow rate increases, the number of bubbles will be increased then the average percentage holdup increase.

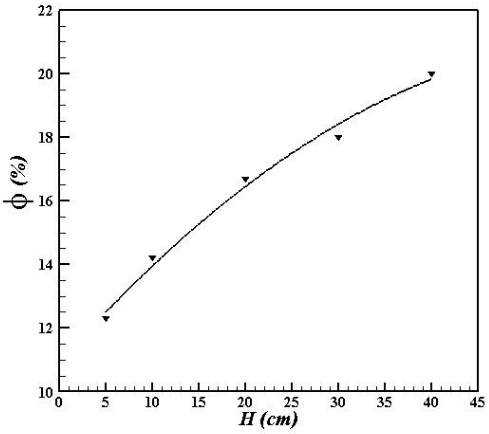

Fig. 1: Variation of ϕ versus H

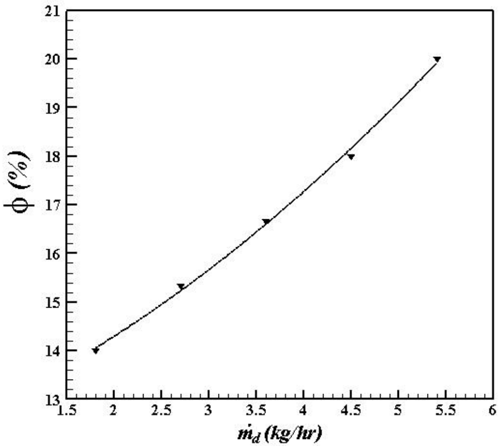

Fig. 2: Variation of ϕ versus $\dot{m}_d$

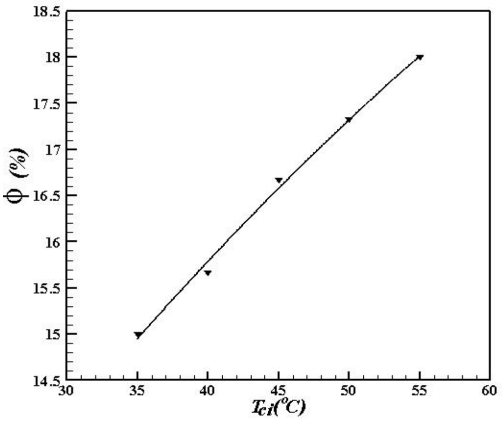

Fig. 3: Variation of ϕ versus T_{ci}

The influence of initial temperature of water on percentage gas holdup is shown in Fig. 3. The increasing in initial temperature means increasing in the temperature difference between the continuous and dispersed phases. That leads to increase in heat transfer between the warm water and gas bubbles and increasing in the size of gas bubbles (increasing the bubbles growth).

Figs. 4-6 show the heat transfer rate at different process variables. Fig. 4 shows the change of the heat transfer rate with column height. It increases very slightly with increasing in column height of water due to increasing in the time contact between the warm water and the dispersed gas bubbles. This increasing in time leads to increase in heat transfer.

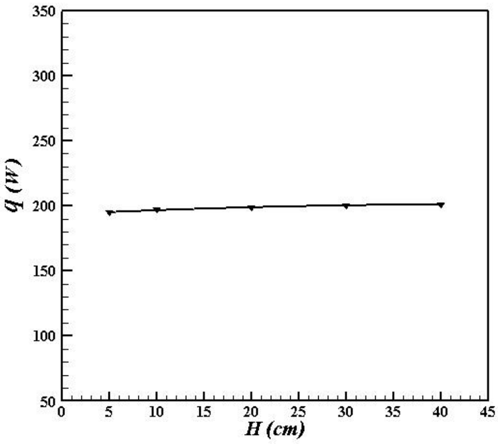

Fig. 4: Variation of q versus H

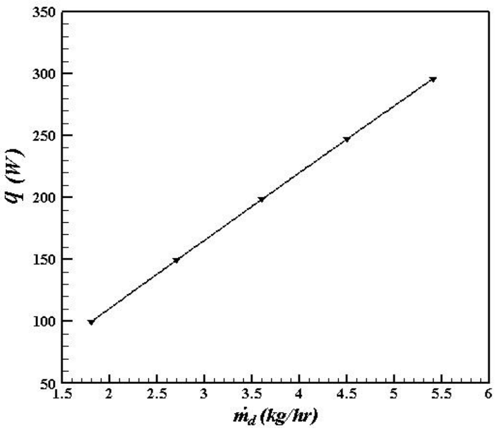

Fig. 5: Variation of q versus $\dot{m}_d$

Fig. 5 illustrates the effect of mass flow rate of dispersed phase on the heat transfer rate. When the dispersed phase mass flow rate increases, the number of bubbles will be increased then the surface area of contact between the water and bubbles is increased. That leads the heat transfer rate increases much.

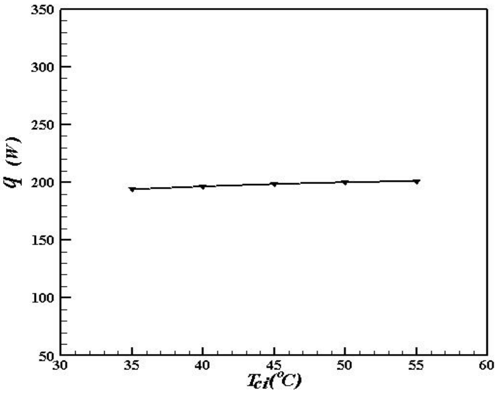

Fig. 6: Variation of q versus T_{ci}

The influence of initial temperature of water on the heat transfer rate is shown in Figs. 6. The increasing in initial temperature means increasing in the temperature difference between continues and dispersed phases. That leads to increase in heat transfer between the warm water and gas bubbles but this increasing is very little.

The results shown in Figs. 7-9 indicate the relation between the volumetric heat transfer coefficient with other variables. The effect of column height on the volumetric heat transfer coefficient is shown in Fig. 7. The surface area of two phase bubble is increased rapidly with column height; this causes a rapid drop in the value of volumetric heat transfer coefficient which is in agreement with Hanna [6] and Vuong and Sadhal [11].

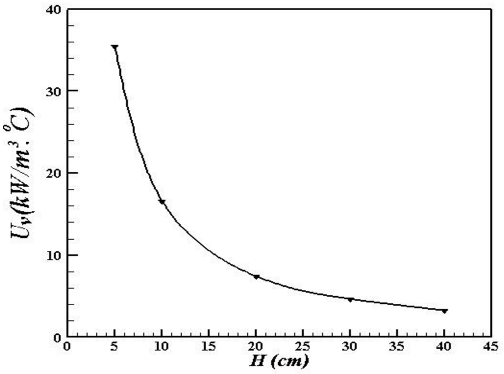

Fig. 7: Variation of U_v versus H

The effect of dispersed phase mass flow rate on volumetric heat transfer coefficient has been demonstrated in the following Fig. 8. Volumetric heat transfer coefficient increases with increasing in mass flow rate of dispersed phase. This increase is attributed to the fact that in higher dispersed mass flow rate, which means higher liquid dispersed phase rate overcomes the increasing of surface area of the two phase bubbles leading to high volumetric heat transfer coefficient, this is reported by Hanna [6].

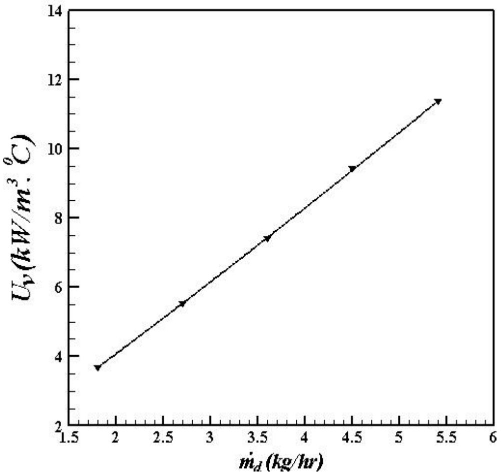

Fig. 8: Variation of U_v versus $\dot{m}_d$

Figs. 9 indicate the effect of initial temperature of water on volumetric heat transfer coefficient. Volumetric heat transfer coefficient decreases with increasing initial temperature of water, due to increase in the temperature difference and that lead to increase in the growth rate of two phase bubbles as mentioned by by Hanna [6].

Figs. 10 show the effect of column height of water on exchanger efficiency. Exchanger efficiency increases with increasing the column height due to the increase of the heat transfer rate between the warm water and bubbles with respect to the maximum heat transfer rate.

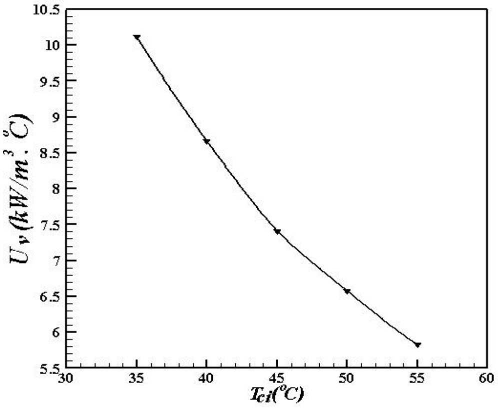

Fig. 9: Variation of U_v versus T_{ci}

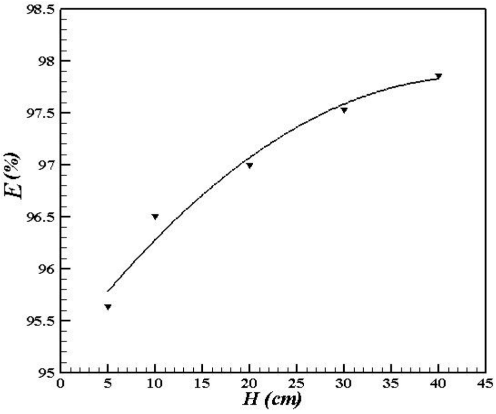

Fig. 10: Variation of E versus H

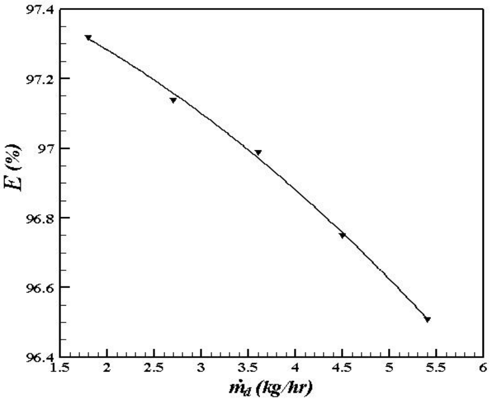

Fig. 11: Variation of E versus $\dot{m}_d$

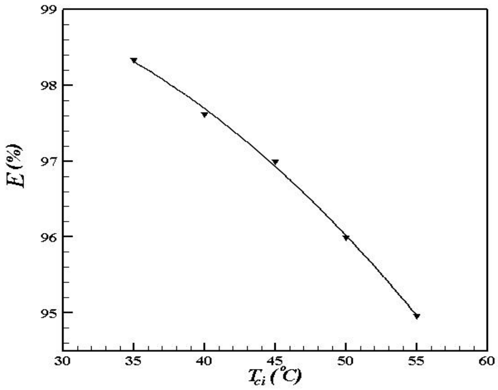

Fig. 12: Variation of E versus T_{ci}

But exchanger efficiency decreases with increasing the mass flow rate of dispersed phase and initial temperature of water due to the increase of the maximum heat transfer rate, as shown in Fig. 11 and Fig. 12 respectively, this is reported by Incropera amd DeWitt [12].

Correlations Equations

The correlation equations for the plotted experimental results are done to know the process variables effect on the average percentage holdup, heat transfer rate, volumetric heat transfer coefficient and exchanger efficiency. These equations are made by using the curve fitting method. This fitting is done by DataFit program version 9. The form of these equations is:

$$\pi = \alpha * H^{\beta} * \dot{m}_d{}^{\gamma} * \Delta T^{\delta} \qquad \ldots(5)$$

ΔT is the difference between initial temperate of water and the inlet temperature of dispersed phase ($\Delta T = T_{ci} - T_{d1}$).

Where: α, β, γ and δ are tabulated in Table 2.

Table 2: Correlations Factors

π	α	β	γ	δ
ϕ	32.34	0.03	0.034	0.037
q	144778.5	0.05	0.017	0.986
Uv	2477754	-1.02	-0.935	0.854
E	0.456	-0.34	0.225	-0.128

*These equations can be used for (water-Freon R11) system and for the following ranges:
$5 \leq H \leq 40$ cm, $20 \leq \Delta T \leq 40$ °C and $1.8 \leq \dot{m}_d \leq 5.4$ kg/hr.

Conclusions

From the analysis, the following conclusions are made:

1- The average percentage holdup increases with increasing in the process variables and distributor geometry except with inlet temperature of Freon R11 it is decreased. Its maximum increase is 85% when the column height increases from 5 to 40 cm.

2- The heat transfer rate increase clearly two times when increase the mass flow rate of Freon R11 from 1.8 to 5.4 kg/hr.

3- The volumetric heat transfer coefficient is affected with change in the column height and mass flow rate of Freon R11 and its maximum value will be at lower column height and higher mass flow rate.

4- The effectiveness increases (maximum 90%) when the column height increase and the initial temperature of water decrease.

Nomenclature

Symbol	Notation
Cp	Specific heat at constant pressure J/kg.K.
D	The diameter of test column cm.
E	Effectiveness (exchanger efficiency).
H	The height of the continuous-dispersed phases (water-R11) cm.
H_o	The height of the clear continuous phase (water) cm.
h_{d1}	Enthalpy of dispersed phase (liquid) at inlet condition kJ/kg.
h_{d2}	Enthalpy of dispersed phase (gas) at outlet condition kJ/kg.
h_{max}	Enthalpy of dispersed phase (gas) at maximum temperature kJ/kg.
$\dot{m}_d$	Mass flow rate of dispersed phase kg/s.
q	Heat transfer rate kW.
q_{loss}	Heat losses from the test column kW.
T	Temperature ˚C.
V	Operating column volume in the test column m^3.

Greek Symbols

ϕ	The average percentage holdup.
ΔT	Temperature difference ˚C.
α, β, γ and δ	Constants

Subscripts

1	Inlet condition
2	Outlet condition
C	Continuous phase
D	Dispersed phase
f	Final condition
i	Initial condition
v	Volumetric

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