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# Effect of geometric parameters of liquid-gas separator units on phase separation performance

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**Abstract**−Five liquid-gas separator units were designed and constructed based on a new concept of a validated high-performance condenser. Each separator unit consiss of two united T-junctions and an apertured baffle. The separator units have different header diameters or different baffles with different diameters of the liquid-gas separation hole. The phase separation characteristics of the units were investigated at inlet air superficial velocities from 1.0 m/s to 33.0 m/s and water superficial velocities from 0.0015 m/s to 0.50 m/s. The experimental results showed that the liquid height, liquid flow rate through the separation hole, and liquid separation efficiency increased with increased header diameter and decreased diameter of the separation hole. The geometric structures of the separator units affected the phase separation characteristics by influencing the liquid height in the header and the liquid flow rate through the separation hole.

Keywords: Two-phase Flow, Phase Separation, Separator, Geometric Parameter, Condenser

## INTRODUCTION

Heat transfer enhancement of heat exchangers has elicited scientific interest in both academic research and industry. Parallel flow heat exchangers are commonly used because they have better thermal performance than conventional heat exchangers [1]. The decrease in mass flow rate in each tube because of multi-passages reduces the frictional pressure drop, but the heat transfer coefficient is also reduced.

Another issue in multi-passage flow is the uneven two-phase distributions of the working medium that occur in different tube passes and different channels of the same tube pass of the parallel flow heat exchanger [2]. Numerous attempts have been made to improve the working medium distribution, which can be classified into two types. The first type involves the induction of intensive mixing of the two phases, such as by adjustment of the placement of baffles or distributors [3,4]. However, these methods often fail to produce uniform distribution over the entire operating conditions [5]. The other approach is to separate the refrigerant vapor or liquid before the flow distributions and allow only one phase working medium into the heat exchanger. The concept was first validated by Beaver et al. [6]. Zhang et al. recently demonstrated that gas-rich flow is uniformly distributed into the primary distribution branches after removal of most of the liquid in the mixture [7].

An innovative idea was proposed to design a new kind of high-performance condenser using several simple liquid-vapor separators. This kind of liquid-vapor separation condenser (LSC) would automatically separate liquid from vapor working medium during condensation. Thus, the working medium remains high in vapor quality in all tubes (or channels), which enhances the heat transfer of in-tube condensation. The improvement of working medium quality will also help improve the flow distribution. The high performance of an air-conditioning system with an LSC was validated by our previous experiments and the results showed that the system performance was comparable with a traditional system, whereas the heat transfer area of the LSC was only 67% of the traditional condenser. Moreover, the performance of the air-conditioning system varied with the diameter of the header of the LSC and the diameters of the liquid-vapor separation holes in the baffle located at the header for liquid-vapor separation. The geometric parameters would influence the liquid-vapor distribution in the LSC. However, the effect of the geometric parameters on the liquid-vapor separation performance was still unclear.

The liquid-vapor separator is the key unit used in the LSC. Fig. 1 shows a simple liquid-gas separator. During condensation of the

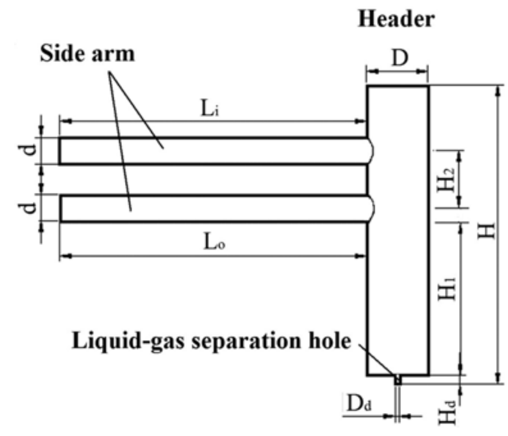


**Fig. 1. Schematic of a separator unit.**

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working medium, liquid-vapor mixture flows into the upper arm. Under the designed working conditions, liquid would accumulate above the apertured baffle at the bottom of the header and then flow through the hole in the baffle, while the vapor is blocked by the flooded baffle and forced to flow through the lower arm. Thus, liquid and vapor are separated in the header and then enter the next flow passage separately.

The separator appears like two combined T-junctions except for the apertured baffle. Thus, the literature on T-junction separators was surveyed. Extensive studies have been conducted on multiphase flow distribution characteristics in T-junctions, while considering the effects of working conditions and geometric parameters [10-17]. However, these studies cannot be applied to our liquid-vapor separators because of the effect of the apertured baffle. The liquid-gas separation performance of our liquid-gas separator would be effectively influenced by the liquid height in the header, which was influenced by the diameter of the separation hole in the baffle and the diameter of the header.

Therefore, the effect of geometric parameters of the separator on its phase separation performance should be studied. In this study, the phase separation characteristics of five liquid-gas separators with different geometric parameters were investigated. The effects of the diameter of the header and the separation hole of the separators on the liquid level in the header and the phase separation efficiency were analyzed and the separation characteristics discussed. The results may be helpful to optimize similar compact separators.

## EXPERIMENTAL SYSTEM

### 1. Separator Unit

The detailed structure of the separator used in this study as a basic separation unit of the innovative condenser is illustrated in Fig. 1. Schematic of a separator unit. Water-air mixture flows into the upper arm to simulate the condenser and the two phases are separated in the header. Gas will flow out through the lower arm, whereas liquid will flow down through the hole at the bottom of the header. Then, the liquid and gas enter the flow passage below (not shown in Fig. 1). The separation unit was manufactured with acrylic resin to allow visual observation. The outside surface of the header (main vertical pipe) had a rectangular cross-section to minimize refraction errors on flow observation. Two parallel horizontal side arms were connected to the vertical cylindrical header on the same side. The top end of the header was sealed to avoid upward flow. An apertured baffle with a small hole in the center for liquid-gas separation was set at the bottom of the header. The detailed geometries of the five separators are shown in Table 1. Separators A, B and C have the same size of separation hole but different header diameter; whereas separators A, D, and E have the same header diameter but different diameter of the separation hole. The choice of these head diameters and sizes of separation holes was based on the capillary force and pressure analysis and experiments in our previous work [18] to make sure that the hole at the bottom of the header should be filled with liquid while the liquid would not flood over the lower arm at the tested gas and liquid superficial velocities.

**Table 1. Geometric parameters of the separator units**

| Parameter | Value (mm) | | | | |
|---|---|---|---|---|---|
| Side arm inner diameter d | 6 | | | | |
| Upper arm length $L_i$ | 70 | | | | |
| Lower arm length $L_o$ | 70 | | | | |
| Header height H | 60 | | | | |
| Pitch of arm tubes $H_2$ | 14 | | | | |
| Lower arm height from the bottom of the header $H_1$ | 35 | | | | |
| Depth of the hole in the baffle $H_d$ | 2 | | | | |
| | A | B | C | D | E |
| Header inner diameter D | 14 | 17 | 20 | 14 | 14 |
| Diameter of the liquid-gas separation hole $D_d$ | 1.0 | 1.0 | 1.0 | 1.5 | 2.0 |

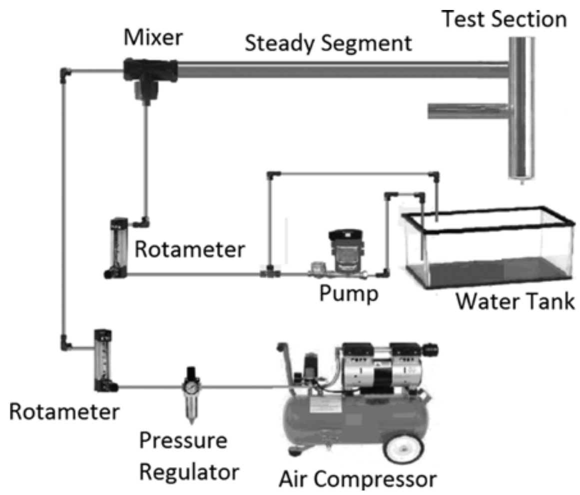


**Fig. 2. Schematic of the experimental system.**

### 2. Test System

The test system used is schematically shown in Fig. 2. Air flow was supplied by an air compressor with pressure adjusted by a pressure regulator. Water flow was pumped from a water tank. In each test, the air and water inlet flow rates were maintained constant by valves and measured by rotameters before entering the mixer. Then, the mixture of the two phases flowed into a horizontal acrylic resin pipe with 2.0 m length and 6.0 mm diameter to become fully developed before flowing into the upper arm of the separator unit. The pressure difference between the static pressure in the header and the atmosphere was measured by a pressure meter.

Phase separation was measured at air superficial velocities from 1.0 m/s to 33.0 m/s and water superficial velocities from 0.0015 m/s to 0.50 m/s at the upper arm inlet. The inlet liquid superficial velocity $u_{l,in}$ and gas superficial velocity $u_{g,in}$ in the upper arm are defined as follows:

$$u_{1,\,in} = \frac{4G_l}{\pi d^2} \tag{1}$$

and

$$u_{g,\,in} = \frac{4G_g}{\pi d^2} \tag{2}$$

where $G_l$ and $G_g$ are the volumetric flow rates of liquid and gas, respectively.

Under certain conditions, water accumulated at the bottom of the header and flowed through the hole of the baffle, whereas air was blocked by the flooded baffle and forced to flow through the lower arm. In this way, the two phases were completely separated. In other situations, the liquid level in the header was higher than $H_1$ and some liquid would flow into the lower arm with air; consequently, the two phases were only partially separated. The separated liquid (liquid through the baffle hole) was collected over a period of time and weighed by an electronic balance with a precision of 0.0001 g to determine the separated liquid flow rate. The outlets of the lower arm and the baffle hole were connected to atmosphere.

Gas cannot flow through the hole when the liquid-gas separation hole is filled with liquid but only through the lower arm, whereas liquid flows through the hole and sometimes through the lower arm at flooding situations. Liquid separation efficiency $\eta$ is defined as the ratio of mass flow rate of liquid through the liquid-gas separation hole m, which is called the separated liquid flow rate, to the total inlet mass flow rate $m_0$ of liquid in the upper arm:

$$\eta=\frac{m}{m_0} \tag{3}$$

The mass flow rates during each test were recorded after the liquid level in the header was maintained for 1 min.

The experimental uncertainties of the separated water flow rate, the inlet water flow rate, and the inlet gas flow rate were estimated to be ±2.0%, ±1.4%, and ±1.5%, respectively.

## RESULTS AND DISCUSSION

### 1. Effect of Header Diameter

Fig. 3 shows that the height of liquid film h in the header increased with the increase in liquid superficial velocity. The liquid film height of separator C with larger header diameter (D=20 mm) was higher than separator A (D=14 mm) and B (D=17 mm) at the same air superficial velocity (7.9 m/s) and liquid superficial velocity (0.029-0.044 m/s). Only four experimental data of separator C are present because the liquid level would flood over the lower arm at the liquid superficial velocity of 0.049 m/s. If the header diameter was further increased, the liquid level would flood over the lower arm at even lower liquid superficial velocity, which would limit the application of the separator.

The result that the liquid level height increased with the header diameter is contrary to our previous assumption that the liquid height would be lower in a larger header at the same liquid superficial velocity. The analysis of the forces that influence the liquid height follows.

The forces that drive the liquid to flow out through the hole in the baffle include the static pressure in the header $p_{hd}$, the dynamic pressure of the gas flow $p_g$, and the liquid flow $p_l$; the resistance is the capillary pressure and the atmospheric pressure.

The dynamic pressure of the gas flow $p_g$ and liquid flow $p_l$ are as follows:

$$p_g=\rho_g u_g^2/2 \tag{4}$$

$$p_l=\rho_l u_l^2/2 \tag{5}$$

where $\rho_g$ and $u_g$ are the density and superficial velocity of gas in the header, respectively.

The static pressure in the header is difficult to measure because of the instability pressure field in the small volume of the header. Thus, the pressure $p_m$ adjacent to the water-air mixer, which is called the mixed pressure, was measured for evaluation. The mixed pressure for all the five separators was comparable. Thus, only the mixed pressure of separator A was recorded. Fig. 4 shows the pressure difference between the mixed pressure and the atmospheric pressure $p_{at}$. The static pressure in the header $p_{hd}$ can be evaluated to be proportional to the mixed pressure as follows:

$$p_{hd}\propto\frac{p_m d^2}{D^2} \tag{6}$$

The capillary force is proportional to the surface tension $\sigma$ of the liquid and inversely proportional to the diameter of the baffle

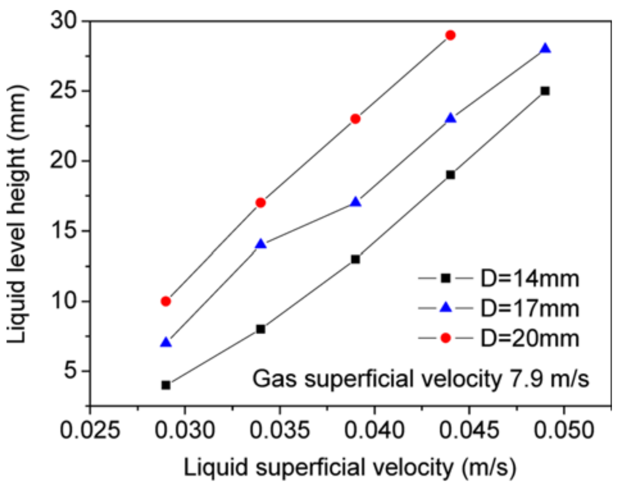


**Fig. 3. Liquid levels for different header diameters (separator A, B and C).**

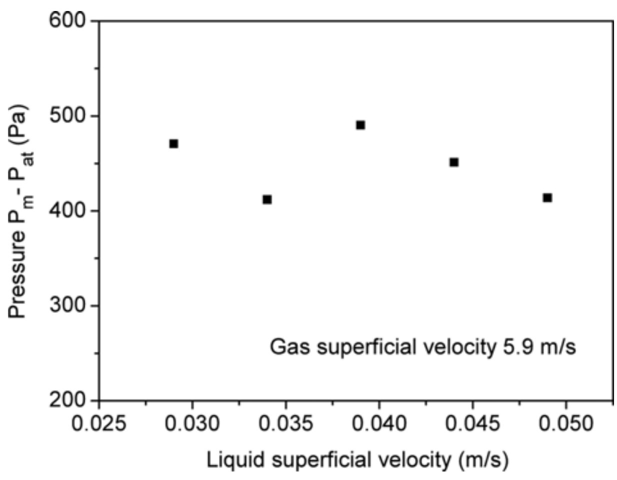


**Fig. 4. Pressure difference between the mixed pressure and atmospheric pressure for separator A.**

hole and thus can be evaluated by $\sigma/D_d$. A modified Weber number is introduced to estimate the ratio of driving force and resistance force of the liquid to flow through the separation hole

$$We=\frac{\rho_g u_g^2/2+\rho_l u_l^2/2+\Delta p+\rho_l gh}{\sigma/D_d} \quad (7)$$

where $\Delta p=p_{hd}-p_{at}$ is the pressure difference between the static pressure in the header $p_{hd}$ and the atmospheric pressure $p_{at}$.

$$\Delta p=p_{hd}-p_{at} \quad (8)$$

Based on Eqs. ((6)) and ((8)), the static pressure in the header $p_{hd}$ is decreased when the header diameter D is increased. Moreover, the pressure difference $\Delta p$ that pushes liquid to flow out through the baffle hole decreased. All the parameters remained stable for a steady flow condition including the Weber number. Therefore, Eq. ((7)) can be used to predict that the liquid height h will increase when $\Delta p$ is decreased because of the increased header diameter D. This prediction is verified in Fig. 3.

Fig. 5 shows that the flow rate of liquid through the hole at the bottom of the header increased with the increase of liquid superficial velocity. The separated liquid flow rate of separator C with larger header diameter was higher than those of separator A and B at the same air and liquid velocity. Since the diameter of the baffle hole of the separator A, B and C was the same, the difference between the separated liquid flow rates is thought to be due to the difference in the liquid height. It can be found from Fig. 6 that the separated liquid flow rate increased approximately linearly with the liquid height.

Fig. 7 shows that the liquid separation efficiency of separator C with larger header diameter was higher than 90% at the tested conditions, whereas the liquid separation efficiency of separator A and B was approximately 7%-18% lower than that of separator C at the same air and liquid velocity. Thus, the liquid separation efficiency should be higher according to Eq. ((3)) because the separated liquid flow rate of separator C was higher at the same inlet liquid and gas flow rate.

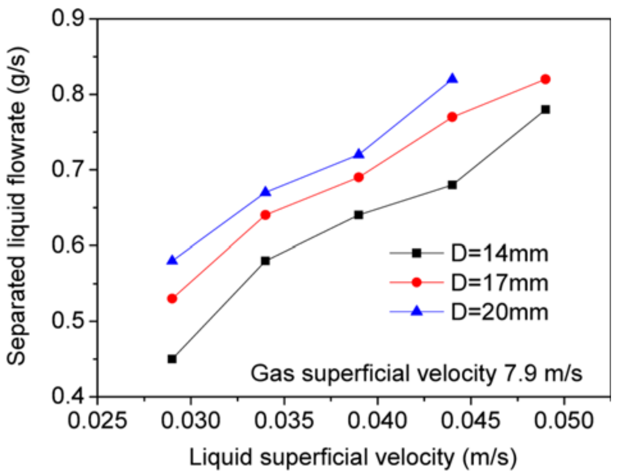


**Fig. 5. Separated liquid flow rate for different header diameter (separator A, B and C).**

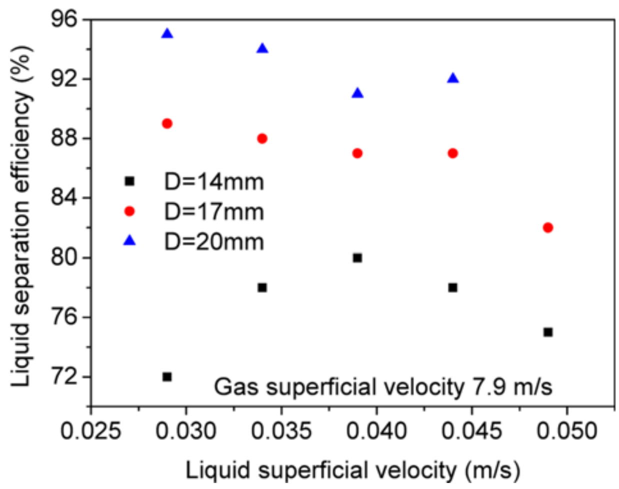


**Fig. 7. Liquid separation efficiency for different header diameters (separator A, B and C).**

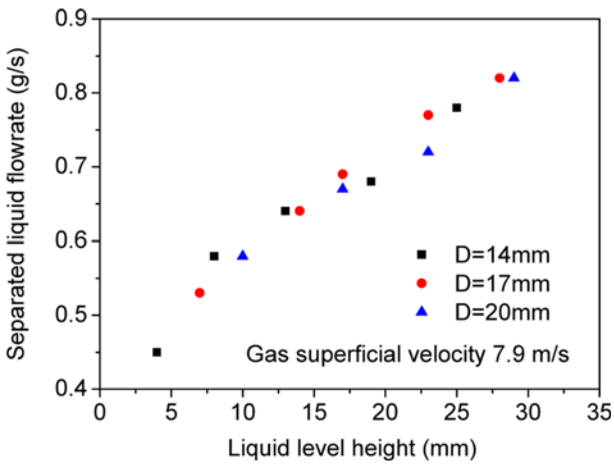


**Fig. 6. Separated liquid flow rate versus liquid level height (separator A, B and C).**

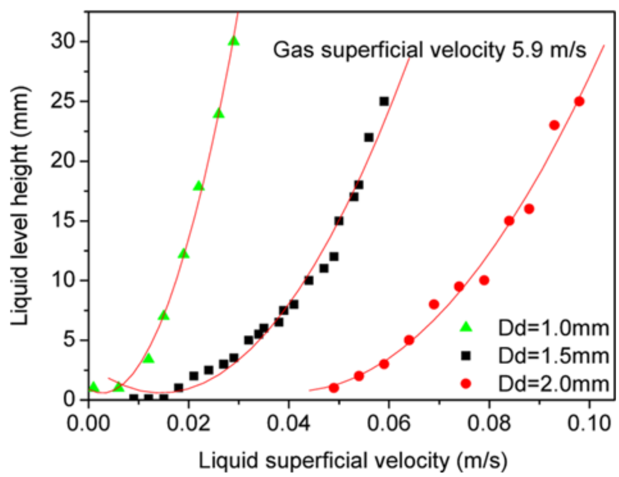


**Fig. 8. Liquid level height for different diameters of the liquid-gas separation hole (separators A, D, and E).**

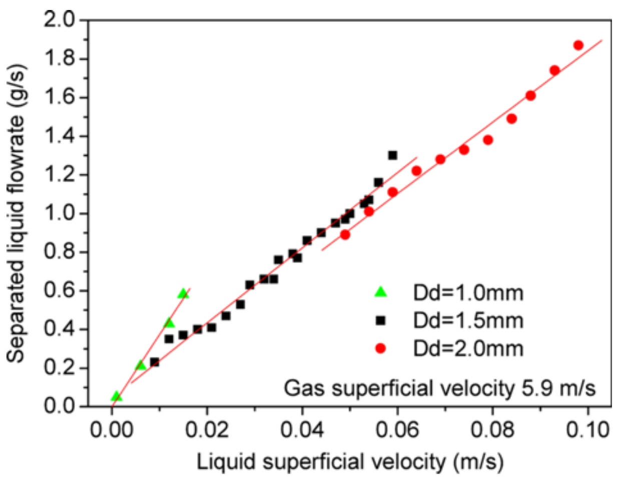


**Fig. 9. Separated liquid flow rate for different diameters of the liquid-gas separation hole (separators A, D, and E).**

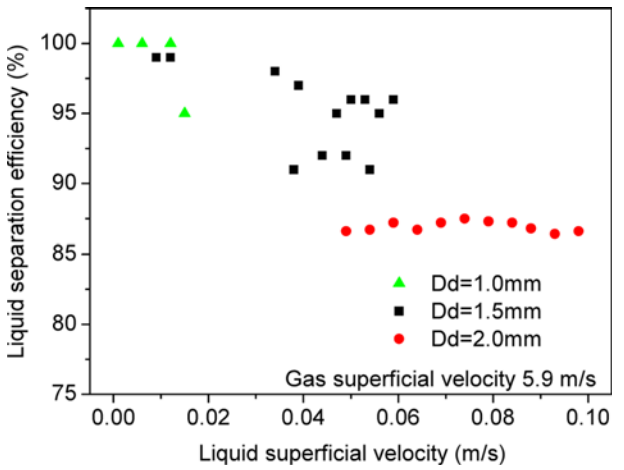


**Fig. 10. Liquid separation efficiency for different diameters of the liquid-gas separation hole (separators A, D, and E).**

**2. Effect of Diameter of the Liquid-gas Separation Hole**

Fig. 8 shows that the height of liquid film in the header increased when the liquid superficial velocity increased for each separator with different baffle hole. A comparison of separators A, D, and E reveals that the liquid film height increased when the diameter of the liquid-gas separation hole decreased at the same gas and liquid superficial velocity. This result can be explained by Eq. ((8)), i.e., a larger diameter $D_d$ of the baffle hole results in less resistance and higher liquid height.

Fig. 9 shows that the separated liquid flow rate increased linearly when the liquid superficial velocity was increased for each separator. A comparison of separators A, D, and E reveals that the separated liquid flow rate increased when the diameter of the liquid-gas separation hole decreased at the same air and liquid superficial velocity.

Fig. 10 shows that the liquid separation efficiency of the separator was lower for larger diameter of the liquid-gas separation hole. Figs. 8 and 9 show that the liquid level height and separated liquid flow rate of separator with larger separation hole was lower, which may have caused the lower liquid separation efficiency.

## CONCLUSIONS

Five separator units for liquid-gas separation used in innovative liquid-vapor separation condensers were constructed and the phase separation characteristics were investigated. The main conclusions are as follows:

(1) The liquid height, flow rate through the separation hole, and separation efficiency increased when the header diameter increased and the diameter of the separation hole decreased.

(2) A modified Weber number was introduced and found to be suitable for analyzing the phase separation characteristics, including the unexpected result that the liquid height increased when the header diameter increased at the same inlet conditions.

(3) The geometric parameters of the separator units influenced the phase separation performance by influencing the liquid height in the header. The liquid height increased, the liquid flow rate through the separation hole increased, and the liquid separation efficiency increased for larger header diameter and smaller diameter of the separation hole.

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