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Technical Note

Effects of the inclination angle on pool boiling in an annulus

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Abstract

To identify effects of the inclination angle on pool boiling heat transfer an experimental study has been executed. For the test a single tube of 30 mm diameter and an annulus of 12.7 mm gap size submerged in the saturated water at atmospheric pressure have been considered. The inclination angle changes heat transfer much. The change of the inclination angle from 0° to 45° results in 29.8% and 11.2% decrease in the heat transfer coefficient at 40 kW/m^2 for the single tube and the annulus, respectively. For the single tube, no specific changes in heat transfer are observed as the inclination angle increases up to 15° whereas the angle for the annulus is 30°. The major heat transfer mechanisms are considered as the intensity of liquid agitation and bubble coalescence due to the enclosure by the outer tube.

1. Introduction

The mechanism of pool boiling heat transfer has been studied for a long time since it is closely related with the designs of more efficient heat exchangers and heat removal systems [1]. To determine the required heat transfer area as well as to evaluate the system performance overall heat transfer coefficients applicable to the systems are needed. Since pool boiling heat transfer coefficient is usually the governing factor in determining overall heat transfer coefficients through the heat exchanging tubes of the heat exchangers, many researchers have studied about it. Through the review on the published results it can be concluded that one of the efficient ways to increase the heat transfer rate can be suggested to utilize the inclination angle (θ) of the heated surface. Although many researchers have investigated the effects of several design parameters on pool boiling heat transfer for the past several decades, results for the effects of inclination angle are relatively small. Two practical approaches have been employed to obtain effects of the inclination angle on pool boiling heat transfer for the heated surface of wire, plate, and tube, as follows: (1) the inclination angle itself and (2) combined effects with other design parameters (see Table 1).

Stralen and Sluyter [2] performed a test to find out boiling curves for platinum wires in the horizontal and vertical position at atmospheric pressure. They concluded that the horizontal type was more effective than the vertical type both in the natural convection and boiling regions. The peak heat flux for the horizontal position is 45% higher in comparison to the corresponding value for the vertical position. The major cause of the reduction in heat transfer for the vertical position is due to the formation of large vapor slugs. The coalesced bubbles are distributed over the entire heating surface for a vertical wire and this behavior differs from that for a horizontal wire, where bubble coalescence is generally restricted to nearby nuclei.

Githinji and Sabersky [3] reported interesting results related with the inclination angle of a plate like a narrow strip. They changed the orientation from horizontally facing upward, to vertical, and to horizontally facing downward. They observed the importance of the gravity on pool boiling heat transfer. For the surface facing downward heat transfer coefficients decrease much as the heat flux (q'') increases due to the bubbles coalesced on the surface.

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Nomenclature

D	diameter of the heated tube	T_W	tube wall temperature
h_b	boiling heat transfer coefficient	V	supplied voltage
I	supplied current	ΔT_{sat}	tube wall superheat ($=T_W - T_{sat}$)
L	heated tube length	θ	inclination angle from the vertical
q''	heat flux		
T_{sat}	saturation temperature		

Table 1
Summary of the previous and present works about inclination angles

Author	Test section	Liquid	Major parameters
Stralen and Sluyter [2]	Single wire	Water	Inclination angle (0°, 90°)
Nishikawa et al. [4]	Flat plate	Water	Inclination angle (0–175°)
Jung et al. [6]	Flat plate	R-11	Inclination angle (0–180°) Enhanced surfaces
Fujita et al. [7]	Parallel plates	Water	Inclination angle (0–175°) Gap size Flow area confinement
El-Genk and Bostanci [9]	Flat plate	HFE-7100	Inclination angle (0–180°)
Kang [11]	Single tube	Water	Inclination angle (0–90°) Tube diameter
Present work	Single tube annulus	Water	Inclination angle (0–45°)

Nishikawa et al. [4] studied heat flux and wall superheat (ΔT_{sat}) on a flat plate oriented at an angle, that varied from a horizontal, upward-facing position to the near-vertical position in the water. According to them, boiling heat transfer coefficients are increased with an increase of the inclination angle at the low heat flux region less than 100 kW/m^2 and inclination effects become negligible as the heat flux on the surface increases more than 100 kW/m^2. The difference in the effect of surface configuration over the whole region of nucleate boiling is presumed as a change in heat transfer mechanisms between low heat fluxes and high heat fluxes. In addition, they explained the heat transfer mechanisms for the low heat fluxes and high heat fluxes as the inclination angle changes. One year later, Lienhard [5] explained the loss of orientation dependence at higher heat fluxes using the Moissis–Rerenson transition.

Jung et al. [6] performed some experiments for inclined plates and R-11. Through the tests of two metal coated surfaces and a flat copper surface were subjected to heat fluxes up to 180 kW/m^2 with surface orientations varying from horizontally facing upward, to vertical, and to horizontally facing downward. They report tendencies similar to the Nishikawa et al.'s result [4]. For all surfaces investigated, the superheat decreases by 15–25% as the inclination angle changes in the relatively low heat flux range (i.e., 10–40 kW/m^2). Beyond this heat flux range, however, the superheat remains constant regardless of the surface orientation. Some more studies about plate are reported by Fujita et al. [7]. Fujita et al. studied the combined effects of inclination angle and gap size between two plates. According to the outputs, the effect of the inclination angle is closely related with the gap size. The general trend is similar to the Nishikawa et al.'s result [4]. However, decreasing the gap size much narrower (0.15 mm for the case) the boiling behavior does not change with the inclination angle. Howard and Mudawar [8] studied effects of the inclination angle on the critical heat flux (CHF). Recently, El-Genk and Bostanci [9] studied effects of the inclination angle of a copper specimen shaped as a plate on pool boiling of HFE-7100 for application to the design of an electric chip.

Although some authors have studied effects of the inclination angle on pool boiling heat transfer along with the effects of geometry, pressure, and surface conditions, no detailed studies have been performed for tubes until Chun and Kang [1] studied the effect of tube orientation on pool boiling heat transfer in combination with tube surface roughness. According to Chun and Kang [1], the slope of q'' versus ΔT_{sat} curve of the vertical tube becomes smaller than that of the horizontal tube as the surface roughness decreases. Two years later, Kang [10] carried out an experimental parametric study of a tubular heat exchanger to determine effects of the tube inclination angle on pool boiling heat transfer. The results obtained by Kang [10] at three inclination angles ($\theta = 0°$, 45°, and 90°) have a large effect on pool boiling heat transfer. Moreover, he identified that the result for a tube is much different from those for a flat plate. The effect of inclination angle is more strongly observed in the smooth tube and if a tube is properly inclined ($\theta = 45°$ for the case) enhanced heat transfer is expected in comparison with the horizontal and the vertical positions. Some more detailed study for the inclination angle has performed by Kang [11] considering different tube diameters and inclination angles.

Summarizing the works, it can be said that effects of the inclination angle on pool boiling heat transfer closely depend on the heating surface geometry. As Cornwell and Houston [12] suggested nucleate boiling on a tube differs considerably from that on a flat plate. The same is true for the wire. One of the important parameters in pool boiling is the gap size. As Fujita et al. [7] already observed the gap size can differentiate the tendency of heat transfer on an inclined surface. Therefore, the annular space in combination with the inclination angle can be a good design parameter to be investigated. Up to the author's knowledge, no previous results concerning to this effect have been published yet. As such, the present study is aimed at the determination of effects of the tube inclination angle on pool boiling heat transfer (1) to identify the combined effects of an annulus and (2) to investigate the potential areas for improvement of the thermal design of the heat exchangers.

2. Experiments

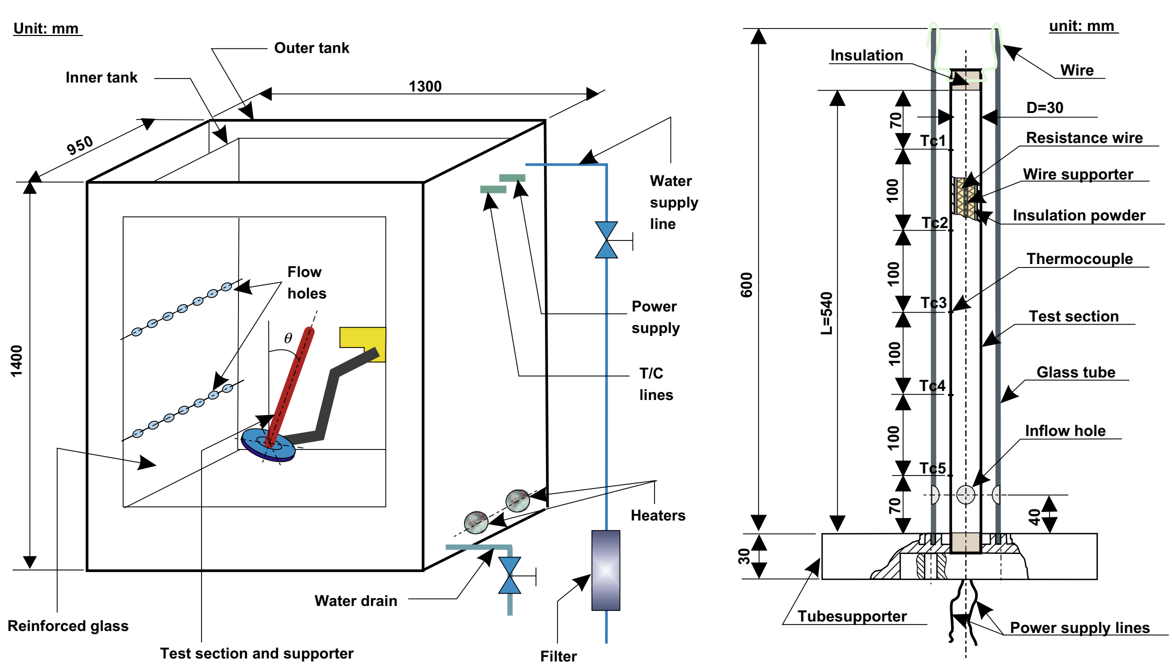
A schematic view of the present experimental apparatus and an assembled test section is shown in Fig. 1. The water tank (Fig. 1a) is made of stainless steel and has a rectangular cross section (950 × 1300 mm) and a height of 1400 mm. The sizes of the inner tank are 800 × 1000 × 1100 mm (depth × width × height). Four auxiliary heaters (5 kW/heater) are installed at the space between the inside and outside tank bottoms. The heat exchanger tubes are simulated by a resistance heater (Fig. 1b) made of a very smooth stainless steel tube (tube diameter $D = 30$ mm and the heated length $L = 540$ mm). The surface of the tube is finished through a buffing process to have a smooth surface. Electric power of 220 V AC is supplied through the bottom side of the tube.

The tube outside is instrumented with five T-type sheathed thermocouples (diameter is 1.5 mm). The thermocouple tip (about 10 mm) is brazed on the tube wall. The water temperatures are measured with six sheathed T-type thermocouples brazed on a stainless steel tube that placed vertically at a corner of the inside tank. All thermocouples are calibrated at a saturation value (100 °C since all tests were done at atmospheric pressure). To measure and/or control the supplied voltage and current, two power supply systems are used. The capacity of each channel is 10 kW. For the tests, the heat exchanging tube is assembled vertically at the supporter (Fig. 1a) and an auxiliary tube supporter is used to fix a glass tube (Fig. 1b). To make the annular condition, a glass tube of 55.4 mm inner diameter and 600 mm length are used. Accordingly, the annular gap size is 12.7 mm. The inclination angle is measured from the vertical position as depicted in Fig. 1a.

After the water tank is filled with water until the initial water level is reached at 1100 mm, the water is then heated using four pre-heaters at constant power. When the water temperature is reached at a saturation value, the water is then boiled for 30 min to remove the dissolved air. The temperatures of the tube surfaces (T_W) are measured when they are at steady state while controlling the heat flux on the tube surface with input power.

The heat flux from the electrically heated tube surface is calculated from the measured values of the input power as follows:

$$q'' = \frac{VI}{\pi DL} = h_b \Delta T_{sat} = h_b (T_W - T_{sat}) \tag{1}$$



(a) water tank (b) assembled test section

Fig. 1. Schematic diagram of the experimental apparatus.

where V and I are the supplied voltage (in volt) and current (in ampere), and D and L are the outside diameter and the length of the heated tube, respectively. T_W and T_{sat} represent the measured temperatures of the tube surface and the saturated water, respectively.

The error bounds of the voltage and current meters used for the test are ±0.5% of the measured value. Therefore, the calculated power (voltage × current) has ±1.0% error bound. Since the heat flux has the same error bound as the power, the uncertainty in the heat flux is estimated to be ±1.0% neglecting the uncertainty of the geometric size. The measured temperature has uncertainties originated from the thermocouple probe itself, thermocouple brazing, and translation of the measured electric signals to digital values. The possible maximum uncertainty of the measured temperatures is defined by adding the above errors, giving a value of ±0.3 °C.

3. Results and discussion

Fig. 2 shows plots of q'' versus ΔT_{sat} data obtained from the experiments. In the figure the inclination angle θ denotes inclination from the vertical direction. The inclination of the heated tube changes heat transfer characteristics. As the inclination angle increases the tube wall superheat increases for the given heat flux. The difference between the results of the different inclination angles are much clearly observed for the single tube comparing to the annulus. For the 15° inclination from the vertical no specific changes in the curve slope is observed regardless of the geometric condition. For the annulus the inclination angle of no meaningful heat transfer change extends to $\theta = 30°$. However, the gradual increase in the inclination angle results in the decrease in heat transfer. The change of θ from 0° to 45° results in 29.3% (from 4.1 to 5.3 °C) increase of ΔT_{sat} for the single tube while only 11.6% (from 4.3 to 4.8 °C) increase is observed for the annulus as the heat flux is 50 kW/m^2. These discrepancies in the general tendency suggest that there should be somewhat different mechanisms affecting on heat transfer between the single tube and the annulus as the inclination angle varies.

To find out some causes to the difference in tendency between the single tube and the annulus the heat transfer coefficients have been calculated by Eq. (1) and the results are shown in Fig. 3. Two heat fluxes of 40 and 80 kW/m^2 have been considered. For the single tube, no specific changes in the heat transfer coefficient are observed as the inclination angle increases from 0° to 15°. As the inclination angle increases more than 15°, sudden decrease in the heat transfer coefficient is observed. When the annulus is considered no meaningful change in the heat transfer coefficient is observed as the inclination angle increases to $\theta = 30°$ regardless of the heat flux. After then, sudden decrease in the heat transfer coefficient is observed. Anyhow, the increase in the inclination angle from 0° to 45° results in the decrease of the heat transfer coefficient. At $q'' = 40$ kW/m^2 the change rates are 29.8% (from 10.4 to 7.3 kW/m^2) and 11.2% (from 9.8 to 8.7 kW/m^2) for the single tube and the annulus, respectively.

The major cause for the tendency is considered as the intensity of liquid agitation. In nature, bubbles detached from the heated surface flows up to the free surface of water due to the buoyancy of the bubbles. For the single tube the intensity of liquid agitation decreases as the inclination angle increases. For the vertical tube (i.e., $\theta = 0°$) bubbles generated at the bottom side of the tube length moves up along the tube surface. During the movement bubbles coalesce with the other bubbles. Thereafter, big size bubble slugs have been developed and, then, these result in active liquid agitation around the heated tube.

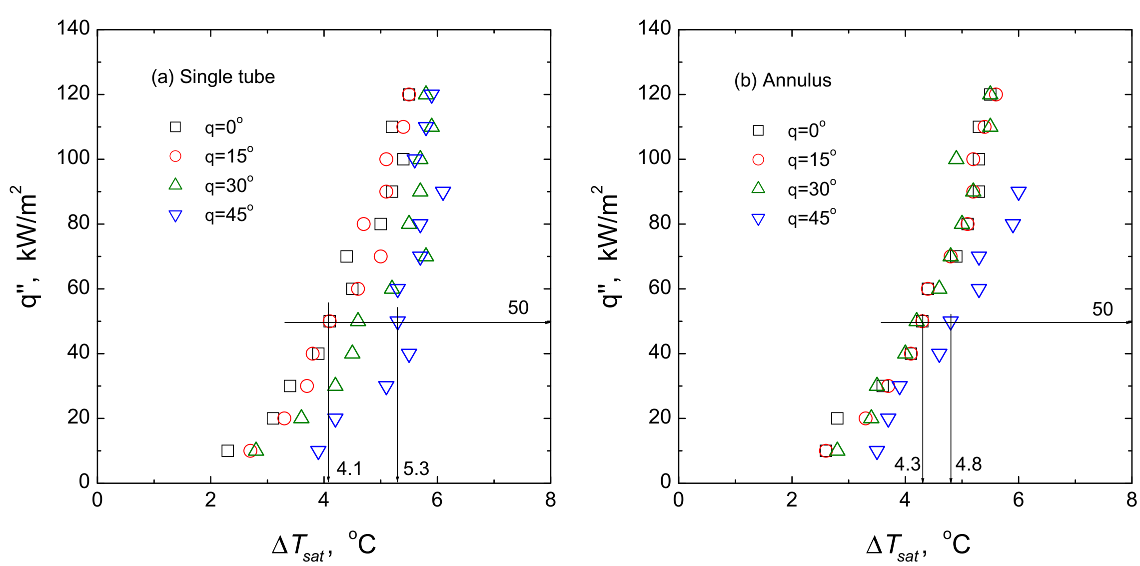


Fig. 2. Curves of q'' versus ΔT_{sat}.

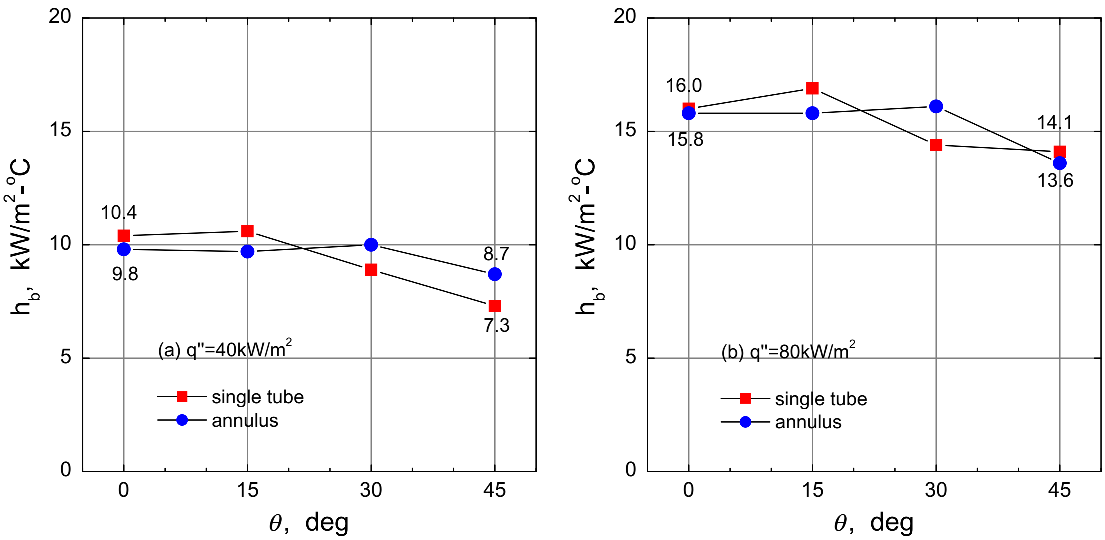


Fig. 3. Curves of h_b versus θ as a function of the heat flux.

As the inclination increases, bubbles detached from the heated surface move directly up to the water level and have less chance to glow to a large size bubbles through the coalescing process with other bubbles. Therefore, gradual decrease in the heat transfer coefficient is resulted in. As the inclination angle is 15° liquid agitation is still active to increase heat transfer. As the heat flux increases, a tendency of heat transfer deterioration at $\theta = 0°$ is observed because the large size bubble slugs prevent the access of the relevant liquid to the heated surface (see Figs. 2 and 3b). When the annulus is under consideration, the effect of liquid agitation continues to maintain until the inclination angle gets at 30°. For the annulus the bubbles detached from the heated surface do not move up to the free surface of water because the outer glass tube prevents the departure of bubbles from the annular space. The coalesced bubbles move up along the annulus space, and generate active liquid agitation around the tube surface. Therefore, the heat transfer coefficient has a similar value as the inclination angle changes from 0° to 30°. More increase of the inclination angle results in heat transfer decrease. However, the cause of the decrease in heat transfer for the annulus is somewhat different from the single tube. The reason of the decrease for the single

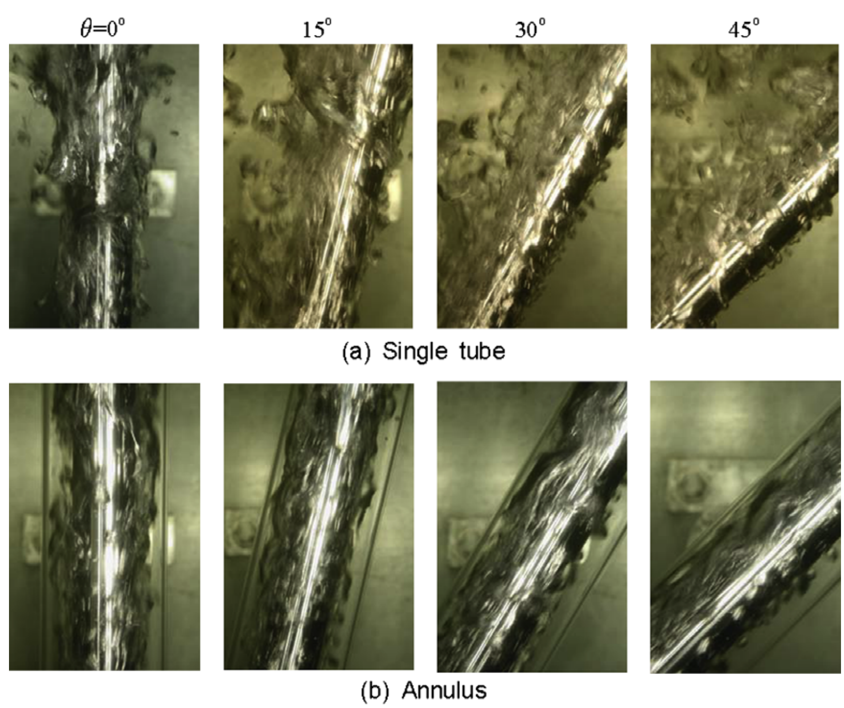


Fig. 4. Photos of saturated pool boiling at $q'' = 80$ kW/m^2.

tube is the decrease in the intensity of liquid agitation as mentioned before. However, the reason for the annulus is the prolonged stay of the bubbles around the heated surface. If an annulus is inclined at a certain angle bubbles should move along the annular space. The consequence is that the driving force of the bubbles toward the water level caused by the buoyancy decreases in proportion to $\cos\theta$. Subsequently, the total traveling time along the heated surface is increased. Thereafter, the possibility of much bigger size bubble generation is expected. Moreover, bubbles are not uniformly distributed in the inclined annular space. The bubbles are gathering around the upper region of the space. After all, the generation of bigger size bubbles and the non-uniformity of bubbles result in heat transfer decrease in the annulus. To observe the generation and agitation of bubbles some photos of boiling are shown in Fig. 4 as the inclination angle changes. Those photos are taken at around the mid-point of the tube length. Photos of the single tube and the annulus at $q'' = 80\ \mathrm{kW/m^2}$ are shown. The detached bubbles for the single tube move freely upward whereas bubbles in the annulus are enclosed by the outer glass tube and move along the tube length.

4. Conclusions

An experimental study has been carried out to identify effects of the inclination angle on pool boiling heat transfer of a tube. For the test a single tube of 30 mm diameter and an annulus of 12.7 mm gap size submerged in the saturated water at atmospheric pressure have been considered. Main conclusions of the present experimental results are as follows.

(1) The inclination angle results in much change in heat transfer. The change of θ from 0° to 45° results in 29.3% (from 4.1 to 5.3 °C) increase of ΔT_{sat} for the single tube while only 11.6% (from 4.3 to 4.8 °C) increase is observed for the annulus as the heat flux is $50\ \mathrm{kW/m^2}$.

(2) For the single tube, no specific changes in the heat transfer coefficient are observed as the inclination angle varies from 0° to 15°. When the annulus is considered no meaningful change in the heat transfer coefficient is observed as the inclination angle increases up to $\theta = 30°$ regardless of the heat flux.

(3) The causes for the tendencies are considered as the difference in the intensity of liquid agitation and bubble coalescence due to the enclosure by the outer tube.

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