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Investigation On Fuel Injection Sprays Of Water-In-Diesel Emulsion and Using Shadow Imaging

Mhadi A. Ismael, A. Rashid A. Aziz
Center for Automotive Research and Electric Mobility
Universiti Teknologi PETRONAS,
Perak, Malaysia
Telephone, +60112678600
mhadi_g03348@utp.edu.my

Morgan Heikal, Cyril Crua
Advanced Engineering Centre,
University of Brighton,
Brighton BN2 4GJ, United Kingdom
Telephone: +44(0)1273 642326
m.r.heikal@brighton.ac.uk

ABSTRACT

This paper highlight the potential usefulness of water-in-diesel emulsions when exposed to high-temperature and thereby, reduces the NOx and PM emissions simultaneously. In addition, an improving of the air-fuel mixing process by means of micro-explosion. Although the high-injection pressure has a significant effect on the spray characteristics and fuel mixing process, however, observation of micro-explosion in the spray is rarely addressed. In this study, an emulsion made with 5%, 10% and 15% of water by volume were investigated at injection pressure of 500 bar. The experiments were conducted in a constant volume chamber under evaporative condition. A high-speed camera coupled with a long-distance microscope was used to magnify and visualize the spray droplets micro-explosion in the spray. The raw images of spray were then analysed using a purpose-built image processing algorithm to identify both spray penetration length and dispersion angle. Our measurements indicated that the differences in water content (10%w and 15%w) suggest an increase in both spray penetration length and cone angle due to fuel evaporation and micro-explosion. The spray droplets at the end of injection showed a clear micro-explosion. The spray breakup was enhanced with the increase of water content.

Keywords

Keywords: Water in diesel emulsion; Spray characteristics, Spray droplets, Micro-esplosion; Puffing.

1. INTRODUCTION

In the new global warming, diesel fuel has become a central issue for emission pollutants. As a fuel base solutions, there is a growing body of literature that recognizes the critical role played by admission of water into diesel engine in the reduction of nitrogen oxides (NOx) and particulate matter (PM) [1]–[3]. The NOx reduction can be explained by the present of water in the diesel fuel leads to absorb the heat of combustion, consequentially, lower exhaust gas temperature [4]–[6]. Several methods have been proposed to classify the use of water into the engine cylinder, including through injection into the pathway [7], direct injection of water into the combustion chamber [8], and emulsification of water and diesel prior to injection into the chamber [9]–[11]. Although the direct injection method strategies facilitating the control of water to fuel ratio [12], however, the main challenge faced by many researchers is that the engine was suffering from wear and degraded combustion [7]. The water emulsified diesel is found to be the better option of these. In fact, the multi-component fuel with different boiling point lead to secondary atomization by means of micro-explosion phenomena [13]. Micro-explosion is the rapid breakup of droplets into smaller droplets due to explosive boiling of the water inside the oil causes the disruption of the primary drops and hence a secondary atomization. The secondary drops evaporated faster and mixed with the ambient air [14].

Recently, literature has emerged that offers contradictory findings on the break specific fuel consumption (BSFC) and brake thermal efficacy (BTH) regarding the emulsified fuel prior to injection into diesel engine. Some researchers [15]–[17] reported an increase in BSFC due to the lower calorific value of the emulsions. This is can be attributed to the replacement of amount of diesel to the equal amount of water added in the emulsion. While others showed a significant increase in BTH due to their better combustion characteristics [18]. Contradictory to the previous findings, some authors [9], [19] observed remarkable reduction in BSFC and increase of thermal efficiency in water in diesel emulsion in comparison with that of diesel fuel. The reduction in BSFC may be contributed from the distribution of dispersed water droplets in the base fuel, as it can affect the occurrence and strength of micro-explosion [20]. In line with this, it has been reported that an increase of the engine effective efficiency up to 20% and 25% reduction of NOx emission in case of large dispersed water droplets size [21]. However, with a small dispersed water droplet size, the BSFC reduced by 5.55% compared to 3.89% in case of large dispersed droplet size [9].

All these inconsistent and contradictory can be attributed to the complicated combustion behaviours of emulsified fuels. Micro-explosion has been identified as a major contributing factor to the combustion of emulsified fuels. To prove the existence of micro-explosion phenomena, several factors can explain this observation inside an engine. An observation of a longer ignition delay and a shorter combustion duration in the case of water in diesel emulsion fuel comparted to neat diesel. Some researchers observed an increase in the ignition delay [22], [23]. The longer ignition delay can be attributed to the lower volatility and higher viscosity of the dispersed phase [24]. While the shorter combustion reaction may be contributed from the effects of micro-explosion phenomena [18]. The longer ignition delay is often favourable for fuel burn simultaneously to enhances the pressure and heat release. In addition, the distribution of water

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dispersed size was found to be related to amount of water in the emulsion [25]. The dispersed droplet size was increasing with the increase of water content, and the optimum water content in the emulsion in order to get a high strength of micro-explosion and high stability of the emulsion was found to be 10% [26]. Whilst with 10% water content, slight reduction in combustion pressure was found [4], [11], [27], and increased by 5% at full engine load with15% water content [28]. On the other hand, in spite of much difficult about the role of micro-explosion, however, single droplet experiments are often used to facilitated the observation of this behaviour, and its well reported that the water content and its distribution are among the most important factors [14], [26], [29]–[34].

However, in an operating engine, the distribution of the dispersed droplet size during the spray have been classified depending on injection pressure. In this trend, about the effect of fuel injection equipment on the distribution of water droplet size was carried out by some authors [35]. A significant decrease in the water droplets size were found at high injection pressure (1500bar), however, some water content in the emulsion were evaporated during the injection. Furthermore, direct evidence of micro-explosion in the spray combustion under real engine conditions has rarely been captured in the chamber reactor experiments. Together, these studies indicate that the need to understand about the effect of water in the fuel on spray penetration length and its dispersion angle. Beside those characteristics, spray droplets micro-explosion should be highlighted.

This study therefore set out to assess the effect of water content and high-injection pressure on spray characteristics. For this purpose, an optical constant volume combustion chamber was developed to visualize the spray images. Firstly, a high speed camera was used to capture the full spray characteristics. Secondly, the high speed camera coupled with a long distance microscope to capture the possibility of spray droplets micro-explosion. The current study will clarify several aspects of existing micro-explosion during the spray and its effects on the engine emission and combustion which are in consist in the previous reports.

2. EXPERIMENTAL SETUP AND PROCEDURE

The fuel used in the current study was an emulsion of 5%w, 10%w and 15%w water (by volume), neat diesel and span 80 as an emulsifiers dosage. The emulsion preparation and its properties are discussed in the authors previous work [35].

The experiments were carried out in an evaporating condition using a common rail injection system. The injection pressure was 500 bar. The schematic of the experiment setup is shown in Figure 1, which is composed of a constant volume chamber, high-pressure fuel injection system, shadowgraph imaging system and data acquisition system.

2.1 Constant volume chamber

A constant volume chamber was developed and used for the spray visualization (Figure 1). The chamber has a cylindrical structure with two optically accessible windows. The diameter of the window is 100 mm. the spray penetration can reach 60 mm excluding the length of the injector tip nozzle and bottom of the glass window. A ceramic electric heater was mounted on the cylinder wall to heat the chamber. Two thermocouples (K-type) were used to measure the temperatures on the surfaces of the chamber as well as gas temperature located at the center inside the chamber. The chamber wall temperature was set to 900 K. The surrounding gas (air) temperatures was measured at the axial distance of the injector tip along the spray axis, and the temperature was 873±3 K. Consisting with the previous measurement [55], the chamber walls and surrounding gas temperatures were 973 K and 850 K respectively.

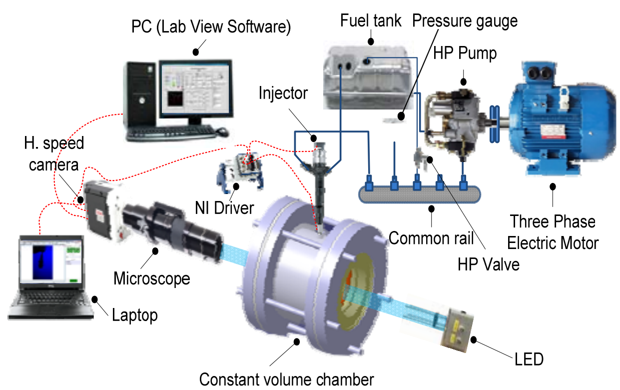

Figure 1. Schematic diagram of the experimental system setup.

2.2 Optical system and resolution

In this study, two different arrangements of optical systems were conducted to acquire detailed of the full spray and spray boundary at high-injection pressure. In the first optical setting a high-speed video camera (Phantom Miro M310) and Multi LED (LT-V8-15) for illumination were positioned opposite to each other to visualize the shadow of the full spray. The camera was set to resolution of 64 × 296 pixels and 74, 074 fps. Based on the calibration scale, the final optical scale is 0.24 mm/pixel.

In the second setup, a long-distance microscope (Infinity K2), zoom lens (CF1 objective) was coupled with the high-speed camera and a custom-built illumination system were used for focusing in spray droplets (Figure 2). It was decided that the best method to adopt a suitable images with a desired frame rate, both a high intensity and a short duration light source must be applied [36], [37]. A pulsed ELD system was developed, which consisted of a high power (blue Phatlight) operated with current of 5A. The National Instrument (NI) modules reconfigurable cRIO-9076 acts a real-time processor for communication, signal processing and a used-programmable LabView FPGA. A developed programme running on LabView software was used to control the pules and synchronize the signal of LED light, camera exposure and injection timing. The LED light duration was set to 40 µs, to be match with camera frame rate. An oscilloscope was used to measure and set the time when LED is on (using the pules width), and it was set to 2µs. Overall, the effective specific setting of the camera resolution and exposure time, fps and the period time are 192×504pixels, 2µs, 14,522fps, 77.86µs respectively. The optical scale was 0.028mm/pixel. The experimental condition is shown in Table 1.

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Table 1. Experimental conditions.

Test fuels	Ambient temperature	Injection pressure	Injection duration	Injector temp.	Nozzle diameter
Diesel, 5%w, 10%w, and 15%w (v/v)	873K	500, 750, 1000 bar	2ms	380K	0.2mm

2.3 Spray measurements

The evaporative raw images captured by the high-speed Phantom Miro (M310) camera were then analyzed using a purpose-built MATLAB image processing algorithm to automatically detect the spray penetration and spray dispersed angle simultaneously. The global image thresholding method is often used for spray image segmentation [38], [39]. An automatic thresholding algorithm was used to segment the spray boundary from the spray shadow (Figure 2). The spray tip pentation was defined as the distance from the injector nozzle orifice to the spray boundary along the axial distance. The dispersed spray angle was defined as angle corresponds to the triangle whose area is equal to the projected area of the spray boundary from the injection nozzle to the spray half of spray tip penetration. The spray angle measured using the following equation:

$$\theta = 2\arctan\left[\frac{A}{(S/2)^2}\right] \quad (1)$$

Where A is the projected area and S is the penetration length. In order to represent the statistical analysis, the mean, median and standard deviation were calculated for both the spray penetration length and dispersion angle. In each case, three videos were processed together and median, mean and standard deviation were calculated. The accuracy of measurements of spray tip penetration was estimated to be ±0.3 mm. The end of injection was not defined well, therefore a cut-off at frame 40 was used for all the cases (t = 526.5µs).

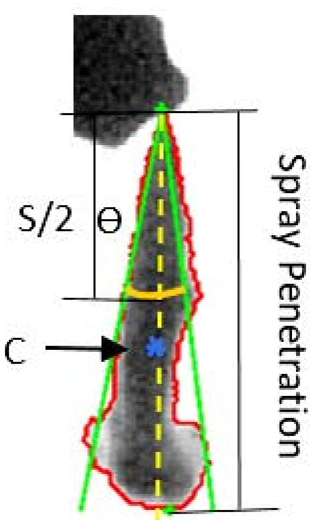

Figure 2. Snap shot of the Matlab image processing shows the definition of spray penetration length and dispersion angle measurement.

3. Results and discussion

In this section we present the effect of both the water concertation and injection pressure of water in diesel emulsion on spray tip penetration and spray cone angle. We have also discussed the spray droplets puffing and micro-explosion during the injection.

3.1 Effect of water content on the spray penetration

A typical spray images (Figure 3) of water in diesel emulsion made with 0%, 5%, 10% and 15% water content and 500 bar injection pressure. The structure of the spray is consistent with previous study [40]. It should be noted that, admission water into diesel fuel leads the emulsion to be more viscous than regular diesel [34], [35], [41]. Therefore, it is resistance to shear flow become higher than pure diesel. In fact, most fuels viscosity unlike with the temperature increases. Similarly, some researchers observed the same behavior for surface tension on initial spray formulation and structure [36], [37]. By comparing the images in Figure 3, qualitatively, all the spray images are similar. However, at the begging the spray head structure for the emulsions were a wider compared with neat diesel fuel. It has been reported that the emulsion undergoes break and phase separation at a temperature higher than 50 ºC [42], this is cause the structure of emulsion to be changed. Actually, in an operating engine, although the pressure is high in the injector, however, its temperature is close to ambient temperature due to heat transfer between the injector nozzle and the fuel. This is may cause the water in the fuel to be changed into superheated steam.

Concerning the spray penetration (Figure 4), it is clear that the emulsified fuels penetrated furthest, however, for 5%w, the penetration rate was close to the pure diesel. That is mainly because the water content in the emulsion were subjected to insensitive shear flow during passing the injection equipment, thus, causes some water to be lost during the injection [35]. With the increase of water content in the emulsion, a longer spray penetration was observed. This is can be attributed to two resions: Firstely, the density and viscosity were higher in the emulsions compared to neat diesel as shown in Table 1 in Ref. [35]. With the increasing of fuel spray density, a more initial spray momentum will be retained before spray breakup. While the viscosity increases the resistance of fuel to breakup [43]. Secondly, a probable explanation is that the frequency of micro-explosion was found to be higher in case of 10% and 15% water content [32].

Furthermore, in the quantitative analysis of spray penetration (Figure 4) shows the difference between spray penetration of diesel, 5%, 10% and 15% which is not obvious before 100 µs. This is may be due to the spray momentum at the initial stage not retain its momentum as expected. In addition, the heat exchange between the spray and the ambient gas at the initial spray period is determined by contact time and area [44].

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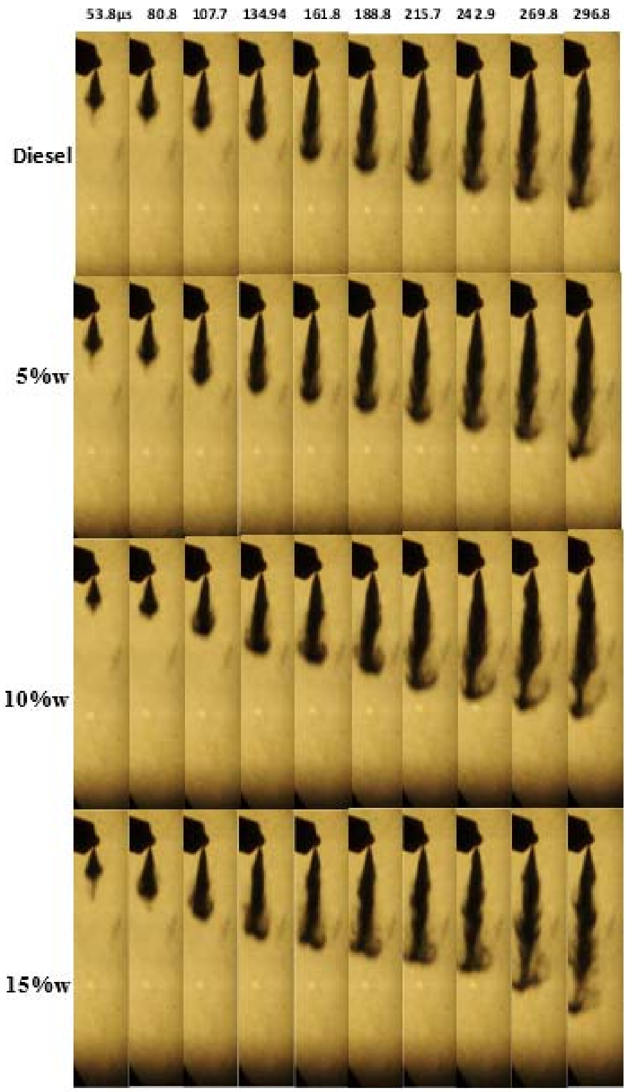

Figure 3. Images of 5, 10 and 15% water content at 500bar injection at 873K.

As time elapsed (100 µs onward), a longer spray penetration for 10%w and 15%w were obviously observed compared to the neat diesel and 5%w. Again, these variations in penetration mainly due to differences in water content as well as the droplet size distribution. Both those factors enhance the strength of micro-explosion and thereby, could accelerate the spray penetration and breakup. As can be seen in the images (Figure 3), the spray tip become brighter for 10 %w and 15%w, and low bright for 5%w and darker for neat diesel. As the spray moves downstream, the near spray boundary is first evaporated by contact of hot gaseous, and this leads the spry tip become brighter. A similar behavior was observed for 20%w and 30%w in the previous work [40].

In order to further reveal the effect of emulsified fuels on spray evaporation and micro-explosion, Figure 5 shows the spray dispersion angle for all examined fuels. Although the emulsified fuels penetrated faster, however, their spray cone angles were also higher. It can be seen that an initial fluctuation appeared during the spray transition before its fully developed, which causes the dispersion angle to be higher at the begging of spray. Also, the dispersion angle for emulsified fuels were higher than that of pure diesel. However, for non-evaporating condition, the emulsions dispersion angle were found to be decreases due to an increase of dynamic viscosity of the emulsion [40], [45]. Note that the specific heat capacity and heat of vaporization of water are higher comparted to those of neat diesel. According to cooling theory, those are expected to cause the dispersion angle to decrease with the increase of water content. For the present experiment, the spray dispersion angle of 5%w for the emulsions is consisting with the previous theory. However, in the cases of 10%w and 15%w were completely different. A combined qualitative and quantitative analysis reveal that an increase of the cone angle resulted from breakup process by micro-explosion phenomena. Due to the optical limitation to magnify the fuel droplets in a high density fuel, however, in the next section further experimental carried out with a microscopy lens.

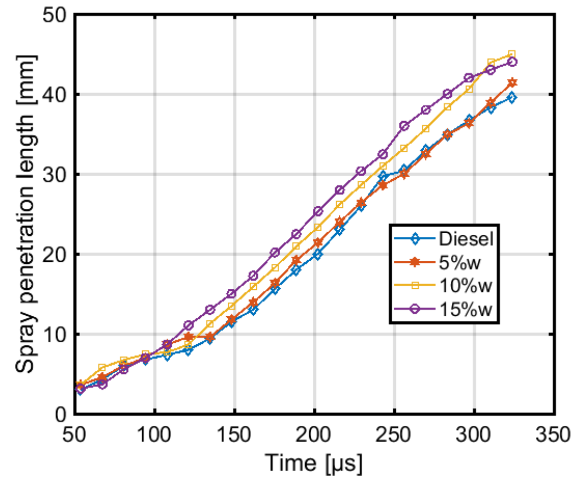

Figure 4. Spray penetration length of 0%, 5%, 10% and 15%water content at injection pressure of 500bar and 873K.

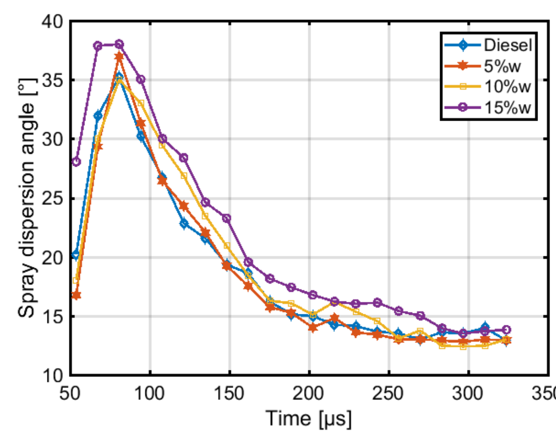

Figure 5. Spray dispersion angle of 0%, 5%, 10% and 15%water content at injection pressure of 500bar and 873K.

3.2 Observation of droplet micro-explosion in high injection spray

So far, in the literature there has been little discussion about the microscopic spray behavior during the high injection pressure [37]. However, in water emulsified diesel due the volatility

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differences between the water and diesel makes it difficult to observe the droplet micro-explosion and it behavior in diesel-like condition. In the percent work, attempts have been made to capture the spray droplets. Firstly, the high speed camera was attached with a long-range microscopy to magnify the spray droplets. Secondly, only the area just downstream of the injector was focused. It has been thought that the intensity of micro-explosion was found to be higher in the upstream region [46]. In our experiments, only the droplets at the end of injection were clearly captured (the smallest droplet size was 20 µm). The microscopic evaluations of spray behavior for 10% water content are given in Figure 6. The spray droplets were not obvious before 0.943ms, due to both high spray velocity and with higher density. However, the development of spray, spray breakup and evaporation were very clear for emulsified fuel. Figure 7 shows the magnified spray droplets at 1 ms (tracked area in Figure 6). Very clear individual droplets (droplet 1 and 2) showing micro-explosion and puffing respectively, and generate very fine droplets at different location and evaporated. In the single isolated droplet experiments, droplet puffing is often observed before a complete micro-explosion [41]. The spray droplets size was found to be increased due evaporation of dispersed water before the micro-explosion. This behavior has never been seen during the droplets of pure diesel. These findings indicating that the emulsion fuels have the ability to improve the air-fuel mixture even through high-injection pressure and thereby enhances the thermal efficiency.

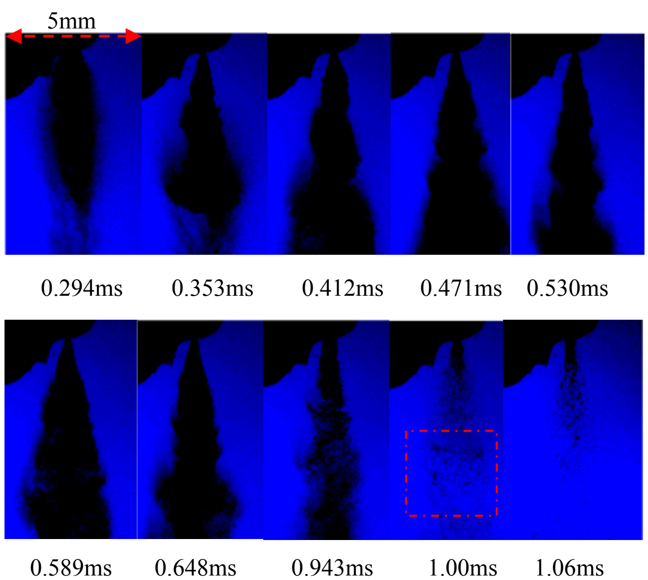

Figure 6. Microscopically visualized spray intial formulation of emulsified fuel (10% water content) injected at 500 bar.

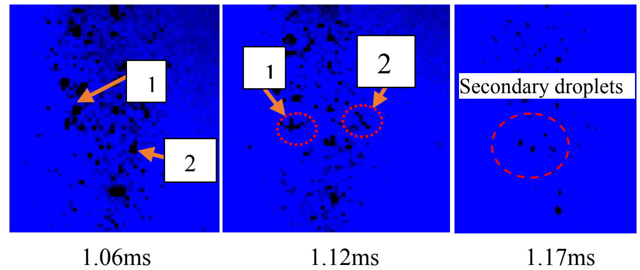

Figure 7. Spray droplet observation behavior in the spray.

4. Conclusion

An experimental study was conducted to examine the effect of water in diesel emulsion (5%w, 10%w and 15%w by volume) on spray characteristics and spray droplet behavior in a high-temperature environment. The measurements of the spray summarized in the following:

1. Both the spray penetration length and dispersion angle increased for emulsions of 10%w and 15%w. However, for 5%w was close to neat diesel due the evaporation of water during the injection.
2. A clear droplet micro-explosion was observed at the end of injection. This phenomenon is thought to be affected in both spray penetration length and dispersion angle which are favorable for air-fuel mixing process.

As a result of this study, differences in the water content in the emulsion, and injection pressure may contribute to some of the disagreements in the literature regarding the BSFC and BTE on engine combustion.

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