Further investigation of hydrogen flame colour

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1 Introduction

Flame colour, as one of the most important fundamental study of combustion, has been carried on along centuries. Among several kinds of combustible gaseous fuels, hydrogen has been focused on due to its unique advantages, such as renewable, high efficiency, non-toxic, etc.. Although hydrogen flame colour was firstly described as "faint reddish brown" by W. F. Barrett in 1872 [1], the misconception about if the hydrogen flame colour is invisible still has not been well addressed until today. In details, water (H_2O) is the only chemical product after the combustion of hydrogen and oxygen, of which the light emitted by water molecules is mainly in the infrared regime and hard to be observed by human eyes. But, from Schefer's investigation, it is proved that hydrogen flame can be observed, that the blueish hydrogen flame emission from the Space Shuttle Main Engine (SMME) has been determined [2]. The continuous wave region detected in hydrogen flame spectrum, defined as "blue continuum" [3], is considered as the cause of hydrogen blue flame colour without demonstrating the actual physical cause. Whereas, in many real applications, the orange/yellow flame colour of hydrogen combustion, which is an absolutely different colour, is often observed. A good example is shown in Fig. 1 that the hydrogen flame of a NASA Delta IV rocket launch presented bright yellow reddish colour during the ignition phase before taking off. Obviously it can be seen that the flame colour is more yellowish than a normal hydrocarbon flame. A possible reason for such different-colour-phenomenon could be that the yellow colour of the flame mainly came from the combustion of sodium in the air while the burning of gaseous hydrogen fuel. Sodium has spectral lines of 589 nm and 589.6 nm in the visible range, which generate yellow colour. Since the rocket launch site is close to the sea coast, the amount of sodium in the air can be considerably higher than normal level, then resulting that more yellow colour was observed from the combustion of hydrogen. Besides the yellow light, red colour can also be seen in the flame in Fig. 1. However, there is still no clear explanation of the source of red flame in hydrogen combustion. In this study, possible causes of reddish colour of hydrogen flame are analysed, and hypothesis is verified by designed experiments.

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Figure 1: NASA Delta IV rocket launch [4]

Hydrocarbon gas diffusion flame, such as methane and propane, presents orange or red colour with some weak blueish emissions. It has been proved that the orange flame colour is due to the emission of soot generated in the combustion process [5]. However, the combustion process of hydrogen does not involve any soot, which can further deny the possibility of soot's orange light emission. As an interesting but yet unsolved challenge, great efforts have been made by researchers for determining the reason behind this phenomenon. For example, Gaydon supposed that the reddish colour of hydrogen flame may come from airborne dust, mainly sodium [6].

Among many hypothesises, the hydrogen $H - \alpha$ spectrum is one of the tops. In details, such spectrum is relatively close to the proverbial sodium colour, which may lead to an overlook with reddish colour. As a possible reason of such reddish colour appeared in blue hydrogen flame, the $H - \alpha$ is further introduced based upon Bohr atom model. When the electron energy level of hydrogen falls from n=3 to n=2, $H - \alpha$ will be emitted in visible red light colour (656.3 nm) [7] and possibly leading to the reddish colour of hydrogen flame.

However, an alternative potential cause of the faint colour of hydrogen flame can be due to the existence of water vapour, which is produced during the combustion process [8]. Referring to Kitagawa, water vapour has a vibration-rotation absorption band 651.68 nm and is proximity to hydrogen emission band. Oxygen burning in hydrogen flame spectrum taken by Gaydon in the range of 610 nm to 730 nm shows clear emission band heads at around 645 nm and 652 nm. He also suggested that these bands are due to the vibration-rotation bands of water [3].

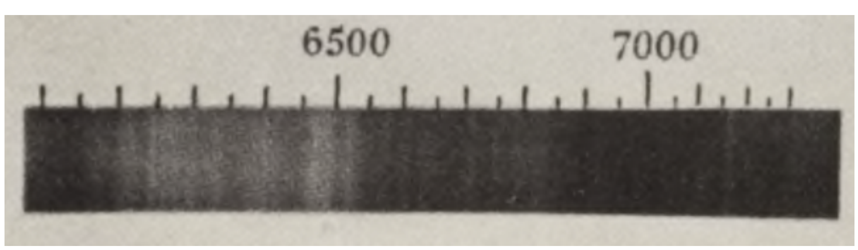

Figure 2: Flame spectrum of oxygen burning in hydrogen in the range of 610 nm to 730 nm, captured by Gaydon [3]

2 Experiment

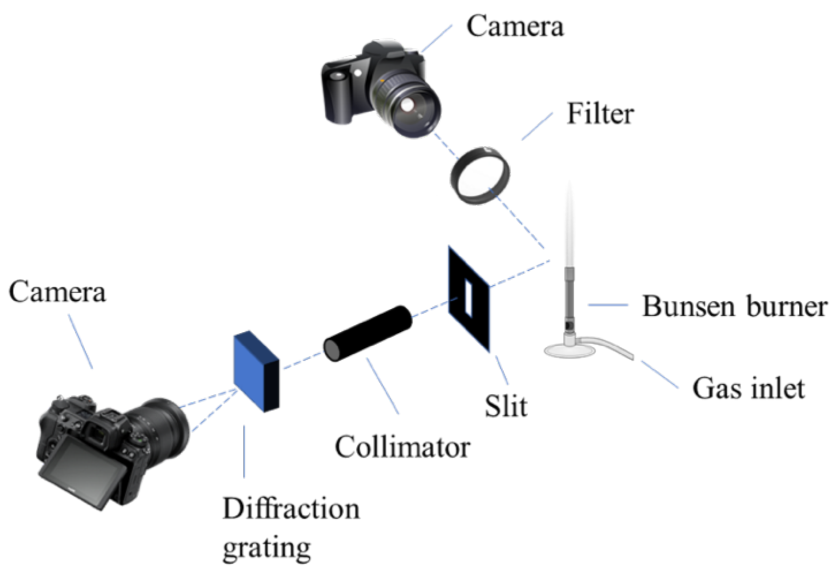

Figure 3: Experimental Apparatus setup for hydrogen diffusion flame investigation.

In order to analyse the cause of hydrogen flame colour, the experiments of capturing hydrogen flame colour spectrum have been conducted, where the set-up is presented in the Fig. 3. Two methods were used to identify the emission band of the flame, including utilization of a narrowband filter and observations by a spectroscopic imaging system. A narrowband filter (model Baader Planetarium 2458383R) was used to allow the wavelength of 649.3 nm to 663.3 nm pass only to visualize the hydrogen flame. The flame images were compared with the unfiltered images. A diffraction grating of 1200 lines/mm was used to obtain spectral data. Images were taken by a canon camera (Model Canon 1200D) with long exposure time settings. The spectrum obtained was compared to data available in the literature. The setup which was used in the experiment enabled long exposure images. Long exposure images were essential to capture both the filtered images and spectrum.
The hydrogen gas used in the experiment had a grade of ultra-high purity (UHP) grade (99.999%). The Bunsen burner gas outlet diameter was measured as 8 mm. The flow of hydrogen was metered using a calibrated volume flow meter. Hydrogen was supplied at a volumetric flow rate of 5.6L/min, measured under standard conditions of 20℃ and 1 atm.

3 Results

The images of diffusion hydrogen flame captured from experiments are presented in the Fig. 4 and 5. In details, the Fig. 4 shows unfiltered hydrogen flame with 1/15 second exposure time, and the Fig. 5 shows narrowband $H-\alpha$ filtered hydrogen flame with 4 seconds exposure time. It can be seen that, with the $H-\alpha$ filter, the reddish flame is clearly shown. Sodium emits double bands ("D-line") at 589 nm and 589.6 nm in the spectrum, which is out of the range of the $H-\alpha$ filter used in this experiment.

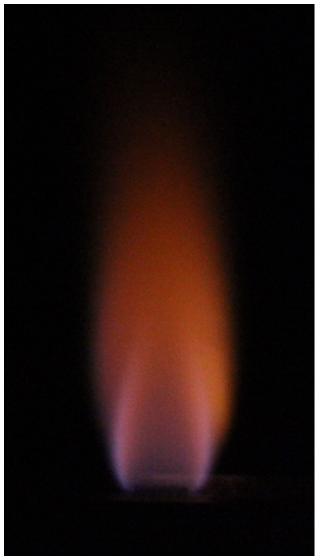

Figure 4: Hydrogen flame from a Bunsen burner, unfiltered, 1/15 seconds exposure time

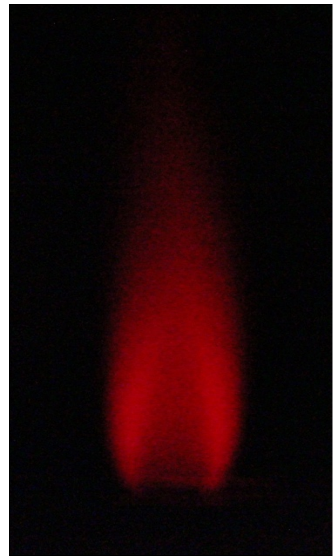

Figure 5: Hydrogen flame from a Bunsen burner, $H-\alpha$ filter added , 4 seconds exposure time

Furthermore, the spectrum of hydrogen diffusion flame are analyzed and presented in the Fig. 6. Two most intense peaks determined were at 589.3 nm and 656.5 nm. The maximum intensity occurred at 589.3 nm emission band and is due to sodium. There should be two sodium lines of 589 nm and 589.6 nm. They are only can be seen as a single line due to limited experimental resolution. The emission band peaks at 656.5 nm which matches the wavelength of $H-\alpha$ emission band. Hydrogen molecules have very high diffusivity and are able to easily diffuse into the combustion zone to generate H radicals during combustion. And those H radicals may emit $H-\alpha$ light when the electron falls back to n=2 energy level.

Therefore, it is likely for $H-\alpha$ existing in a hydrogen flame. There is another less obvious peak at 652.9 nm, which is close to one of the water vibration-rotation spectrum band (652.4 nm) [9]. It could also be noticed that there are two peak lines in the red colour range, and their wavelength are 658.8 nm and 660.6 nm respectively. The cause of these two emission lines has not yet been explained by any research. The colour of $H-\alpha$ emission combined with flame colour of sodium, and two other unknown emission lines forms the visible reddish colour of diffusion hydrogen flame. Although the colour of hydrogen diffusion flame is a complex combination, $H-\alpha$ emission definitely plays a non-negligible role.

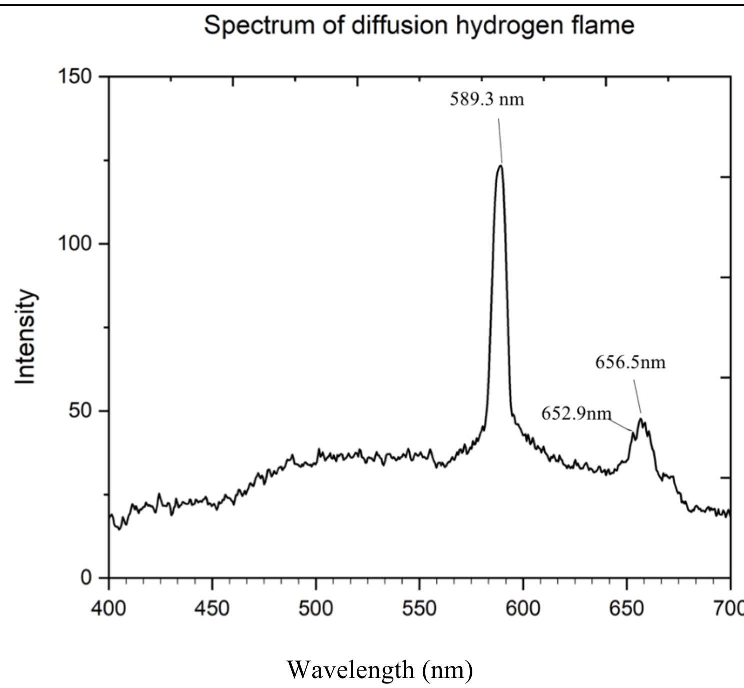

Figure 6: Spectrum of diffusion hydrogen flame

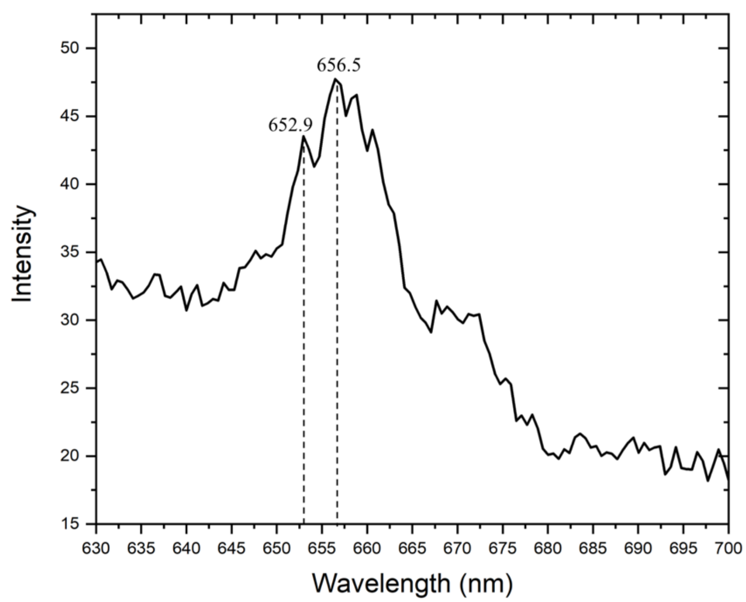

Figure 7: Detailed Spectrum of diffusion hydrogen flame in the range of 630 nm to 700 nm

4 Conclusion

Spectrum and the filtered photography of hydrogen flame highlights that $H-\alpha$ importantly contributes to the reddish flame colour. The minute existence of sodium particles in the air can have strong emission lines in the spectrum under hydrogen combustion temperature. Moreover, there are four emission lines in the range of the $H - \alpha$ fliter band. Although background noise does exist, the peaks still can be easily observed. These peaks remain consistence in all 5 trials. The peak at 652.9 nm might belongs to the vibration-rotation band of water vapour. Another peak at 656.5 nm is highly likely to be the $H - \alpha$ emission line. Therefore, it may be concluded that water vapour and $H - \alpha$ emission might play non-negligible roles in the faint reddish colour of a diffusion hydrogen flame. More experiments will be conducted to confirm the existence of $H - \alpha$ emission in hydrogen flame, then further improve the diagnostics of equivalence ratio in hydrogen combustion and sun flare monitoring.

References

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