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Resolving Visible Emission Lines in Hydrogen Diffusion Flames

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Abstract: The hydrogen diffusion flame is commonly described as difficult to see in the visible range. However, even in controlled laboratory conditions with careful imaging, the flame appears reddish. Previous research has reported a variety of colours generated from hydrogen flames. Some researchers believe that the visible colour is due to sodium in airborne dust. Other studies suggest the flame colour is caused by the vibration–rotation band of water vapour. In addition, $H-\alpha$ emits radiance in the visible range; therefore, the visible colour of the hydrogen flame could be contributed from the $H-\alpha$ emission. Nevertheless, a definitive conclusion to explain the visible reddish colour of the hydrogen flame is lacking. This paper reports precisely instrumented spectroscopic imaging tests, calibration, and data processing in order to resolve the spectral lines in the red colour zone (580–700 nm). This study used a spectrograph and a DSLR camera to capture the spectrum of hydrogen diffusion flames under different co-flow conditions. The values of emission lines in this range were compared with the databases provided by HITRAN molecular spectroscopy and the National Institute of Standards and Technology (NIST). The results of this study show that $H-\alpha$ emission is highly likely to appear in a hydrogen diffusion flame, which contradicts the previous hypothesis. This work may provide new insight into hydrogen-based combustion.

Keywords: hydrogen flame; hydrogen-alpha; spectrum; visible colour; diagnostics

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1. Introduction

Flame colour, as one of the most fundamental characteristics of a flame, has been studied for centuries. Among several kinds of combustible gaseous fuels, hydrogen has been of great research interest due to its unique advantages, such as being renewable and non-toxic. Although the hydrogen flame colour was first described as “faint reddish-brown” by W. F. Barrett in 1872 [1], the misconception about whether the hydrogen flame colour is invisible still has not been well addressed until today. From Schefer et al.’s investigation, it has been proven that the hydrogen flame can be observed at visible wavelengths, and that the blueish hydrogen flame emission from the Space Shuttle Main Engine (SMME) has been determined [2]. The continuous emission region was detected in the hydrogen flame spectrum, defined as the “blue continuum” [3], which is considered the cause of the hydrogen blue flame colour. However, there is still no clear explanation of the source of the reddish flame colour in hydrogen combustion.

The combustion process of hydrogen does not involve any soot, which can further disprove the possibility of soot’s orange light emission. As an interesting yet unsolved challenge, great efforts have been made by researchers for determining the reason behind this visible reddish flame colour of hydrogen. For example, Gaydon supposed that the reddish colour of the hydrogen flame may come from airborne dust, mainly sodium [4].

An alternative potential cause of the faint colour of the hydrogen flame can be due to the existence of water vapour, which is produced during the combustion process [5]. Referring to Kitagawa, water vapour has a vibration–rotation absorption band of 651.68 nm and is in proximity to the hydrogen emission band. Oxygen gas involved in the hydrogen flame spectrum taken by Gaydon (Figure 1) in the range from 610 nm to 730 nm showed clear emission band heads at around 645 nm and 652 nm. He also suggested that these bands were generated by the vibration–rotation bands of water [3].

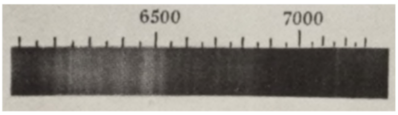

Figure 1. The flame spectrum of oxygen burning in hydrogen in the range from 610 nm to 730 nm, captured by Gaydon [3].

The presence of the hydrogen $H - \alpha$ spectrum is also a possible cause of the reddish flame colour of hydrogen. As a possible reason for such a reddish colour appearing in the blue hydrogen flame, $H - \alpha$ may be considered based upon the Bohr atom model. When the electron energy level of hydrogen falls from n = 3 to n = 2, $H - \alpha$ will be emitted in a visible red-light colour (656.28 nm) [6] and possibly contribute to the reddish colour of a hydrogen flame.

This paper aims to analyse the red band spectrum of a hydrogen–air diffusion flame. In addition, it is the first time that the appearance of $H - \alpha$ in a hydrogen diffusion flame is experimentally verified. The possible contribution of $H - \alpha$ to the reddish flame colour and hydrogen atoms being excited during combustion is investigated with rigorous tests, calibration, and processing.

2. Materials and Methods

In order to analyse the hydrogen diffusion flame colour in the wavelength range from 590 nm to 700 nm, a series of experiments were carried out to capture the hydrogen flame spectrum. Air and oxygen co-flows with different flow rates were applied to further verify the emission lines in the hydrogen diffusion flame spectrum. The setup is presented in Section 2.2 and enables long exposure images. As the spectral intensity of the hydrogen diffusion flame is low in the visible light range, long-exposure images were essential to capture both the flame images and spectrum.

2.1. Methodology

Analysing the flame spectrum is an effective approach to investigate the colour of the hydrogen diffusion flame. A fibre optical spectrometer was utilised in the preliminary experiment; however, its longest integration time was too short. Only sodium lines could be recorded by the fibre optical spectrometer in the hydrogen diffusion flame due to their high emission intensity. Also, it was hard to distinguish weak signals from background noise. Therefore, a spectrograph was used in this work to analyse the flame spectrum.

With regard to hydrogen combustion under ambient air conditions, a number of substances are expected to be produced in the process. Hence, finding out which species are participating in the combustion reaction and investigating the light they emit are necessary for analysing the hydrogen flame colour.

When monochromatic light projects into the spectrograph, the mounted-in diffraction grating diffracts the light into various angles depending on their wavelength. The spectrum of the flame could be obtained based upon this principle. The following shows the data processing and calibration method we used: the spectrum was captured by a camera and recorded in raw format (ARW) to preserve its quality. It was observed that sodium was present in all the studied cases due to its minute presence in the ambient air, resulting in two spectrum lines with significant intensity in the measurements. The theoretical values (in terms of frequency) of these two lines were adopted as a benchmark for calibrating the spectrum samples, i.e., to estimate the wavelengths associated with other measured spectrum lines.

The occurrence of sodium doublet lines is due to the electron transition from different states. The transition from the $P_{3/2}$ state to the S state emits the line at 588.99 nm and the transition from the $P_{1/2}$ state to the S state emits the line at 589.59 nm [7].

The Python processing algorithms (Version 3.11) have high repeatability and accuracy, but there are still some unavoidable errors that exist. One of the primary error sources is considered the post-processing of raw measurements. In the Python processing algorithms, sodium doublet lines were used for calibration. The separation distance between the two lines is 0.597 nm (equivalent to 16 pixels in the image).

The main error comes from the spectrum lines. The width of each line is 16 ± 1 pixels, so the error can be worked out as

$$\text{error 1} = [1/15 - 1/(32 + 17)] \times 0.597 = 0.0276\ \text{nm} \tag{1}$$

The error also comes from the difference between the exact position and the adjacent position of each pixel. In this case, the separation distance between the two lines can be within 17 pixels. Hence, the error could be calculated as

$$\text{error 2} = (1/15 - 1/17) \times 0.597 = 0.0047\ \text{nm} \tag{2}$$

Therefore, the error for the experiment can be determined at approximately ±0.032 nm.

In addition, to ensure the accuracy of the experiment, a purge process by using the corresponding testing gases was carried out by flowing the gas through the whole system before ignition for five minutes. This ensured that all the other gas remaining in the system especially in the flow control system was evacuated and replaced by the experiment gas.

After the wavelength values of these spectral lines were calculated, they were compared with the spectral line database to identify the substances. Hence, the substances that contribute to the colour of the hydrogen flame could be estimated. Furthermore, to further validate the contribution of these substances, the emission lines caused by H_2O, OH, O, and $H - \alpha$ were integrated. The obtained emission lines in the experiment were determined by the values of each pixel in the red channel (R channel) of the captured flame spectrum, and the integration of these emission lines represented the intensity of their R channel values. The integration of these R channel values was positively correlated with the intensity of the emission lines.

An extended exposure time of 20 min was applied for each of the experimental trials when measuring the hydrogen flame spectrum to enhance the sampled data.

Moreover, in order to figure out the "reddish-brown" flame colour, this experiment mainly focused on the analysis of the spectral lines in the range of 580 nm to 700 nm.

2.2. Experimental Setup

The DSLR camera enrolled in this experiment was a Sony-α camera. The ISO range of this camera is from 100 to 16,000, and the sensor is a 24.3-megapixel Exmor APS-C HD CMOS sensor. In this experiment, a DADOS slit spectrograph was connected to the camera directly. The spectroscopic grating used was a 1200 lines/mm blazed reflection grating. The spectral resolution of this grating is 4400, and the line resolution is 1.5 Angstroms [8]. The exposure time of each trial was 20 min, and the ISO used in this experiment was 800. Figure 2 shows the setup of the hydrogen diffusion flame colour experiment.

The burner used in this experiment was a tailor-made Swagelok stainless steel burner. The size of the fuel nozzle was 6 mm in diameter. In this experiment, hydrogen gas flowed through the fuel nozzle, which was in the middle of the burner. Two co-flow types were tested in this study, air and oxygen. The honeycomb design helped stabilise the flame and provided uniform co-flow. The hydrogen and oxygen gas used in the experiment had a grade of ultra-high purity (UHP) grade N5.5 (99.9995% purity). Hydrogen was supplied at a volumetric flow rate of 3 L/min, measured under standard conditions of 20 °C and 1 atm.

Air was compressed air from the outside of the lab. All gas supply pipes' gauge pressures were at 1 bar. Details of the co-flow conditions used in the experiment are listed in Table 1.

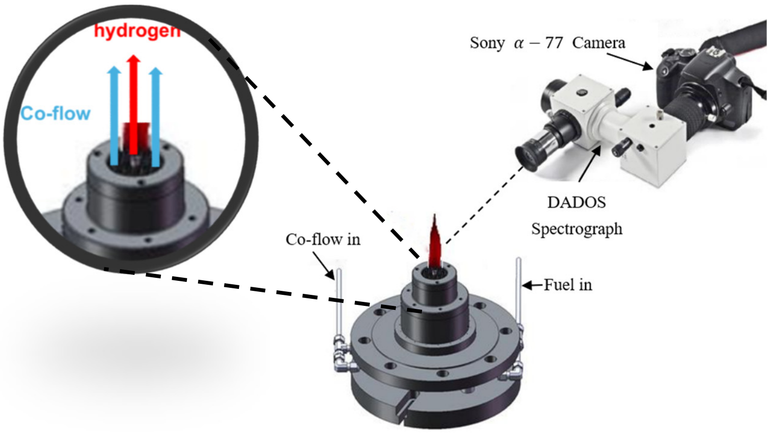

Figure 2. Hydrogen diffusion flame experimental setup with close-up showing the gas flow from the nozzle.

Table 1. Flow rates of hydrogen and co-flow used in the experiment.

Case No.	H_2 Flow Rate (L/min)	Co-Flow Type	Co-Flow Rate (L/min)
1	3.00	None	0.00
2	3.00	Air	6.50
3	3.00	Air	13.0
4	3.00	Oxygen	0.30
5	3.00	Oxygen	0.55

As the intensity of the hydrogen flame was low and the flame colour was extremely sensitive to contamination, a precisely controlled experimental condition was required. The gas pipes used for connecting the gas gauge and the burners were dust-free plastic pipes. All components of the burners used were cleaned carefully in an ultrasonic cleaner before experiments. After these components were ultrasonically cleaned, they were also rinsed with distilled water and air-dried. In addition, the flow control system was also kept clean. The hydrogen flow meter was new and had not been used for other gas. The gas was released before the experiment to eliminate the gas that was left in the gas pipeline before. Also, the experimental gas was discharged for a period of time before each trial according to the equivalent ratio and flow rate required for the experiment. Such measures ensure the purity of the gas during the experiment.

Calibration of the diffraction grating was carried out externally by the manufacturer (Baader Planetarium, Mammendorf, Germany). Calibration of the spectrum was carried out before the experiment with double emission lines of sodium.

The spectrograph is sensitive to light in the visible range, and the intervention of any other visible light source can bring an unexpected emission spectrum. Therefore, this experiment needs to be carried out in a dark environment to eliminate the influence of other light sources in the lab.

Following the above requirement, all light sources were eliminated within the lab when carrying out the experiments, e.g., doors and windows were sealed to prevent light leaks (the lab does not have windows), and all indicator lights were turned off or covered. However, there were still some light sources that could not be turned off or avoided, for example, the light from the door gap. In order to avoid the influence of these lights, a black cloth made of inert material was used to block them. After taking such measures, a spectrum was taken under the same conditions as the experiment to ensure that there were no spectrum lines in the captured image. Hence, a darkroom environment was created.

Besides the spectroscopic image method, a 656.3 nm bandpass filter with a bandwidth of 7 nm (model Baader Planetarium 2458383R) was used to visualise the $H - \alpha$ in the hydrogen diffusion flame.

3. Results and Discussion

The flame images were compared with the unfiltered images. The images of the diffusion hydrogen flame captured from experiments are presented in Figure 3.

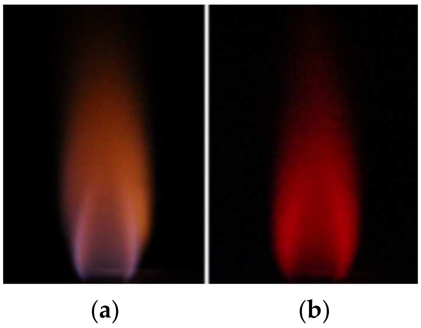
(**a**) (**b**)

Figure 3. Hydrogen diffusion flame from a Bunsen burner: (**a**) unfiltered; (**b**) filtered.

Figure 3a shows unfiltered hydrogen flame with a 1/15 s exposure time, and Figure 3b shows the hydrogen flame with a 4 s exposure time after applying the filter.

It indicates the existence of the potential presence of $H - \alpha$ emission in the hydrogen diffusion flame after eliminating the effects of the sodium emissions.

The spectrum of the hydrogen diffusion flame is presented in Figure 4. The spectrum focuses on the light wavelength ranges from 580 nm to 700 nm. The two most intense lines were determined as 588.99 nm and 589.59 nm, which are considered the sodium doublet lines. Besides the sodium doublet line, a cluster of emission lines is observed in the range from 580 nm to 635 nm, as shown in Figure 4 with a blue rectangle. However, it is unknown what specie(s) these emission lines correspond to, and they are not reported in the literature. At a higher wavelength range in Figure 4, four distinctive emission lines are observed ranging from 650 nm to 660 nm. This is highlighted in a white rectangle in Figure 4. All the spectral lines are located in the red-light range.

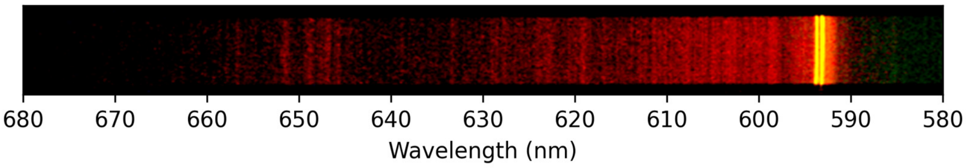

Figure 4. Hydrogen–air diffusion flame spectrum.

Figure 5 shows the detailed spectrum of the hydrogen diffusion flame. It was analysed that the values of the four lines in the range from 650 nm and 660 nm were 652.88 nm, 654.34 nm, 656.58 nm, and 659.90 nm.

According to the records in the HITRAN molecular spectroscopic database [9], H_2 has three intensive emission lines in the range from 650 nm to 670 nm. As shown in Table 2, they are at 656.71 nm, 658.70 nm, and 661.69 nm. Because the values in the HITRAN database are obtained under vacuum conditions, they need to be converted into values under air conditions. Referring to the NIST Engineering Metrology Toolbox, which is based on the Ciddor equation [10,11], these spectral lines mentioned above are equivalent to the wavelengths of 656.53 nm, 658.52 nm, and 661.51 nm in air.

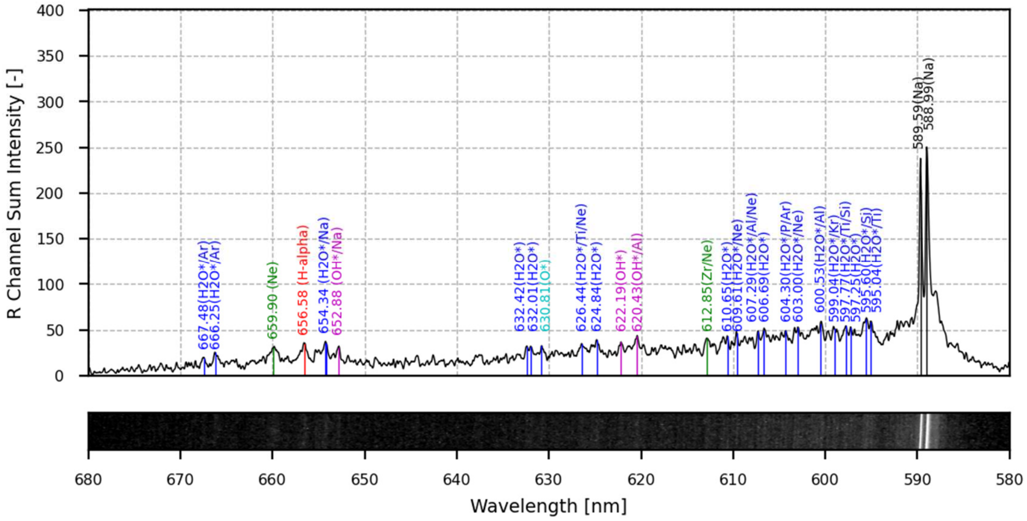

Figure 5. Hydrogen diffusion flame spectrum plot ("*" indicates that the molecule is in an excited state).

Table 2. Hydrogen emission lines in the range from 650 nm to 670 nm from HITRAN [9].

HITRAN (Vacuum) (nm)	HITRAN (Air) (nm)
656.71	656.53
658.70	658.52
661.69	661.51

The emission line at 656.58 nm in the experiment matches the wavelength of the hydrogen emission line at 656.53 nm (in air) provided by HITRAN. According to the database, the intensity of this emission line is highest among the three lines. The intensity of emission lines at 658.52 nm (in air) and 661.51 nm (in air) provided by HITRAN are 10 times lower than the emission line at 656.53 nm (in air) [9]. H radicals are abundant during combustion and those excited H radicals may emit $H-\alpha$ light when the electron falls back to the n = 2 energy level. Therefore, it is highly likely for $H-\alpha$ to exist in a hydrogen flame. In addition, the intensities of the other two emission lines are relatively low; hence, there is no obvious emission line in the spectrum.

In addition, as shown in Table 3, the NIST database gives the emission lines of a hydrogen atom in the range from 650 nm to 670 nm.

Table 3. Hydrogen atom emission lines between 650 nm and 670 nm from NIST [12,13].

Wavelength in Air (nm)	Transition
656.271	$2P_{1/2}-3D_{3/2}$
656.272	$2P_{1/2}-3S_{1/2}$
656.285	$2P_{1/2}-3D_{3/2}$

The values of hydrogen emission lines given by HITRAN and NIST have a minor difference, which might be caused by different data collection methods. The HITRAN database is a mixture of experimental and calculated results, while NIST mainly focuses on the theoretical calculation and observation from the solar corona. It is considered that the experimental results are usually more accurate, but the results given by the calculation are more complete. Therefore, these two lines might not be recorded in the NIST database.

The cause of the other three emission lines has not yet been explained by any research. However, after comparing the data in the HITRAN database and NIST database in detail, it was found that the emission lines match some relevant elements.

In the mechanism of hydrogen–air combustion, H, H_2, O, O_2, OH, N_2, HO_2, H_2O, and H_2O_2 are involved. In the wavelength range from 590 nm to 620 nm, the main source of emission lines is H_2O. All the 13 emission lines (595.04 nm, 595.60 nm, 597.25 nm, 597.77 nm, 599.04 nm, 600.53 nm, 603.00 nm, 604.30 nm, 606.69 nm, 607.29 nm, 690.61 nm, 610.65 nm, and 612.85 nm) might be caused by the emission of water vapour. Also, in the wavelength range from 620 nm to 635 nm, there are 4 out of 7 emission lines that might also mainly be caused by H_2O, which are at 624.79 nm, 626.463 nm, 632.00 nm, and 632.38 nm. Besides H_2O, OH and O_2 have strong emission lines at 620.27 nm, 620.28 nm, 622.17 nm, 622.19 nm, and 630.66 nm. There are two relative intense emission lines in the range from 660 nm to 700 nm. H_2O might be one of the possible contributors to red-colour emission as well. In addition to the species that participated in the combustion process, elements from the impurities and the atmosphere could also be involved in the reaction. By comparing with the NIST database, the possible elements that contribute to the spectrum were picked up and analysed. There are two main possible impurity sources, the cast-iron-made burner and the 304 stainless steel-made nozzle. Hence, the elements contained in this equipment and atmosphere were considered to contribute to the experimental emission lines. These elements include titanium, silicon, neon, aluminium, phosphorus, argon, and zirconium.

In addition, the air or oxygen co-flows were applied to the hydrogen–air diffusion flame. The spectra of these flames are presented in Figure 6. In the wavelength range from 590 nm to 620 nm, there are eight emission lines that appear in all the flames. They are at around 595.5 nm, 600.4 nm, 603.2 nm, 604.5 nm, 606.5 nm, 609.5 nm, 610.8 nm, and 612.5 nm. These emission lines are contributed mainly by H_2O. There are also some lines that only appear in certain co-flow conditions. For example, the lines at 591.2 nm, 598.6 nm, and 617.5 nm exist in both the air and oxygen co-flow flames but not in the non-co-flow flame. On the other hand, there are some emission lines that only appear in the hydrogen diffusion flame and not in flames with co-flows. They are 595.6 nm, 599.0 nm, and 607.3 nm. In addition, the emission line at 608.8 nm only exists in the hydrogen flame with 6.5 L/min air co-flow. Also, the lines at approximately 596.8 nm, 613.9 nm, and 615.7 nm only appear in the spectra of hydrogen flames with oxygen co-flow and 13 L/min air co-flow.

In the wavelength range from 620 nm to 650 nm, there are four emission lines present in all the hydrogen flame spectra. They are at about 620.3 nm, 624.6 nm, 630.5 nm, and 631.6 nm. In addition, there are three emission lines that only appear in the hydrogen diffusion flame and flames with air co-flow. Their wavelengths are 622.2 nm, 626.4 nm, and 632.4 nm. Furthermore, two emission lines exist in the air co-flow flames only, which are at around 637.5 nm and 644.6 nm.

In the 660 nm to 700 nm band, the number and intensity of emission lines are lower than those of the other bands discussed earlier. The line at approximately 666.2 nm appears in all the five testing flames, and the line at 667.5 nm only exists in the flame without co-flow and the flame with 6.5 L/min air co-flow.

To better compare the emission lines of hydrogen diffusion flame under different co-flow conditions, they are listed in Table 4.

Under the air co-flow conditions, these different lines are mainly contributed by H_2O. The addition of air co-flow means better hydrogen and air mixing, which leads to a higher local flame temperature. Moreover, an increase in the flow rate of the air co-flow also increases the possibility of collisions of the atoms. Hence, it is more likely for these atoms to be excited due to the effect of collisions at a higher flow rate. Therefore, in the case of 13 L/min air co-flow, the emission line intensities of OH, O, and $H-\alpha$ are higher. Moreover, the temperature of the oxygen co-flowed flame would be higher than the flame with air co-flow. Hence, the intensities of OH emission lines might become more apparent in the spectra due to the higher local flame temperature, and more elements in the equipment materials or the atmosphere will be excited, resulting in the appearance of emission lines.

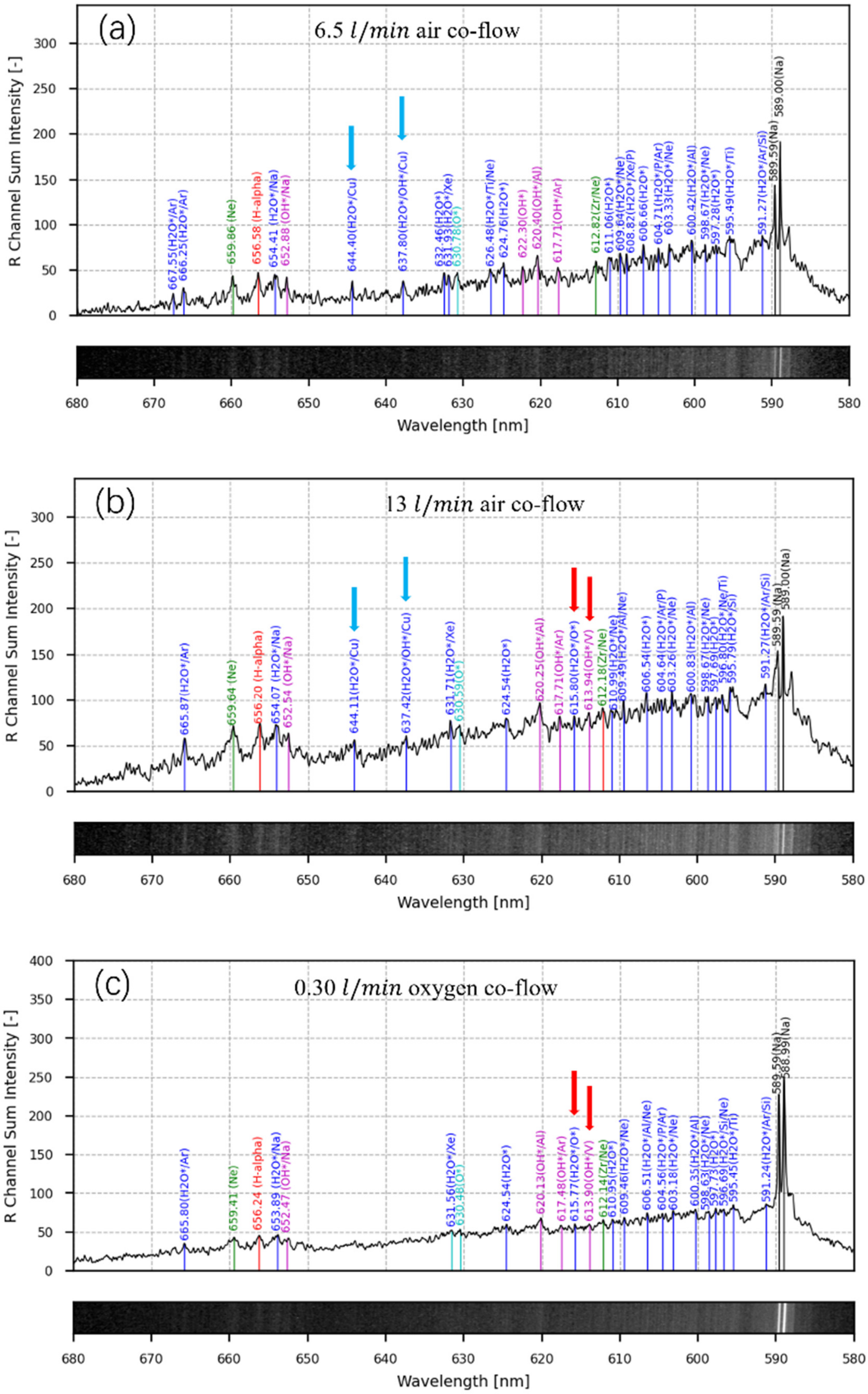

Figure 6. *Cont.*

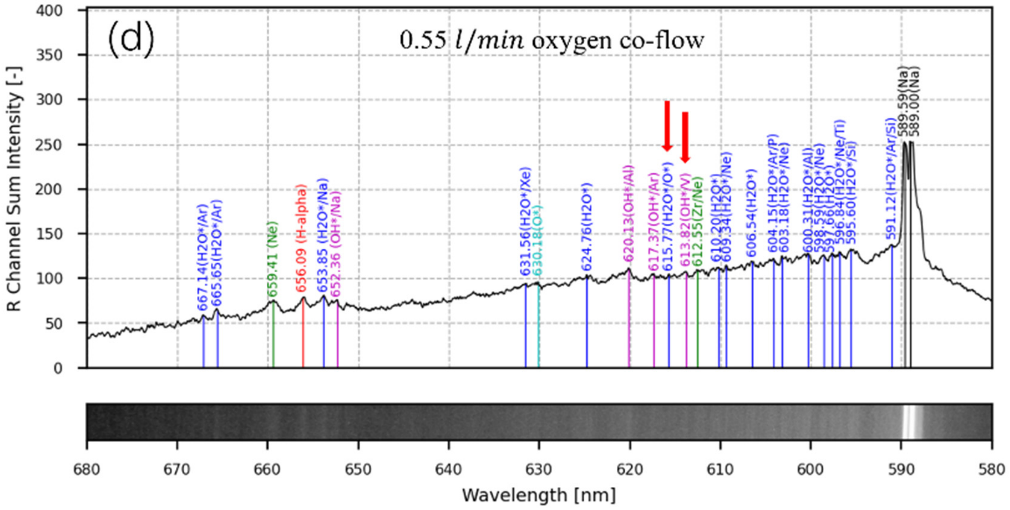

Figure 6. Spectrum plot of hydrogen–air diffusion flames with 3 L/min hydrogen flow rates and (**a**) 6.5 L/min air co-flow; (**b**) 13.0 L/min air co-flow; (**c**) 0.30 L/min oxygen co-flow; and (**d**) 0.55 L/min oxygen co-flow. The red arrows indicated the emission lines only appear in the spectra of hydrogen flames with oxygen co-flow and 13.0 L/min air co-flow, while the blue arrows indicated the emission lines only appear in the spectra of hydrogen flames with air co-flow.

The most interesting wavelength range is between 650 nm and 660 nm, which is the range that might have $H - \alpha$. All the flames have the same emission lines in this range. They are at about 652.6 nm, 654.0 nm, 656.4 nm, and 659.7 nm. The 652.6 nm emission line might be due to OH and Na. The one at 654.0 nm might be because of H_2O and Na, and the line at 659.7 nm would be due to Ne. It is worth noting that the line at 656.4 nm matches the emission line of $H - \alpha$. This emission line is present in all the hydrogen–air diffusion flames. Therefore, it is highly possible that $H - \alpha$ contributed to the reddish flame colour of the hydrogen diffusion flame.

Furthermore, the integration of H_2O, OH, O, and $H - \alpha$ emission lines in the experiments is listed in Table 5.

Table 4. List of emission lines of hydrogen diffusion flame under different co-flow conditions in the range from 580 nm to 680 nm.

Co-Flow Conditions					Elements/Species
None	6.5 L/min air	13 L/min air	0.30 L/min O_2	0.55 L/min O_2	
/	591.27	591.27	591.24	591.12	H_2O/Ar/Si
595.04	/	/	/	/	H_2O/Ti
595.60	595.49	595.79	595.45	595.60	H_2O/Si
/	/	596.80	596.69	596.84	H_2O/Ne/Ti
597.25	597.28	/	/	/	H_2O
597.77	/	597.69	597.73	597.84	H_2O/Ti/Si
/	598.67	598.67	598.63	598.59	H_2O/Ne
599.04	/	/	/	/	H_2O/Kr
600.53	600.42	600.83	600.35	600.31	H_2O/Al
603.00	603.33	603.26	603.18	603.18	H_2O/Ne
604.30	604.71	604.64	604.56	604.15	H_2O/P/Ar
606.69	606.66	606.54	606.51	606.54	H_2O
607.29	/	/	/	/	H_2O/Al/Ne
/	608.82	/	/	/	H_2O/Xe/P
609.61	609.64	609.49	609.46	609.34	H_2O/Ne
610.65	611.06	610.99	610.95	610.20	H_2O
612.85	612.82	612.18	612.14	612.55	Zr/Ne
/	/	613.94	613.90	613.82	OH/V
/	/	615.80	615.77	615.77	H_2O/O

Table 4. *Cont.*

Co-Flow Conditions					**Elements/Species**
/	617.71	617.71	617.48	617.37	OH/Ar
620.43	620.40	620.25	620.13	620.13	OH/Al
622.19	622.30	/	/	/	OH
624.84	624.76	624.54	624.54	624.76	H_2O
626.45	626.48	/	/	/	H_2O/Ti/Ne
630.81	630.78	630.59	630.48	630.18	H_2O
632.01	631.93	631.71	631.56	631.56	H_2O/Xe
632.42	632.46	/	/	/	H_2O
/	637.80	637.42	/	/	H_2O/OH/Cu
/	644.40	644.11	/	/	H_2O/Cu
652.88	652.88	652.54	652.47	652.36	OH/Na
654.34	654.41	654.07	653.89	653.85	H_2O/Na
656.58	656.58	656.20	656.24	656.09	$H-\alpha$
659.90	659.86	659.64	659.41	659.41	Ne
666.25	666.25	665.84	665.80	665.65	H_2O/Ar
667.48	667.55	/	/	667.14	H_2O/Ar

Table 5. Integration of H_2O, OH, O, and $H-\alpha$ emission lines in the hydrogen diffusion flames with different co-flow conditions in the wavelength range from 580 nm to 680 nm.

	Co-Flow Conditions				
	Non-Co-Flow	**6.5 L/min Air**	**13 L/min Air**	**0.30 L/min O_2**	**0.55 L/minO_2**
H_2O	331.6	434.1	639.4	649.7	1113.1
OH	72.3	138.9	274.5	191.8	395.4
O	15.8	37.8	80.6	68.3	138.7
$H-\alpha$	44.7	53.9	91.3	70.0	126.7

4. Conclusions

The spectrum and the filtered photography of the hydrogen flame highlighted that H_2O, OH, O, and $H-\alpha$ contribute 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, which is handy as a calibration source.

In general, the spectra of hydrogen–air diffusion flames with co-flows are similar to the hydrogen flame spectrum without a co-flow. The sodium doublet lines at 588.59 nm and 580.00 nm are present in all co-flow conditions. By comparing with data in the HITRAN and NIST databases, in the red-light band, most of the emission lines are caused by the final product H_2O, intermediate product OH, and pollutants from the equipment and atmosphere. In the wavelength range from 580 nm to 700 nm, there are many products or pollutants that produce emission lines, resulting in the red flame of hydrogen. The four emission lines ranging from 650 nm to 660 nm are identified in this study. The spectrum line at 652.88 nm might be OH or the sodium emission line. The line at 654.34 nm might be H_2O or a sodium emission line. The line at 659.90 nm might be the emission line of nickel, which may come from the stainless steel of the burner nozzle. The current hydrogen–air combustion mechanism does not consider any excited species, so the excited species should be investigated in the future because the emission band at 656.58 nm is highly likely to be $H-\alpha$. Although the colour of the hydrogen diffusion flame is a complex combination, $H-\alpha$ emission is highly likely to play a non-negligible role in the faint reddish colour of a diffusion hydrogen flame. It also indicates that hydrogen atoms are very likely to be excited in the combustion process. Therefore, the mechanism could be improved with further study on the topic of excited hydrogen atoms.

The observation of $H-\alpha$ emission provides the possibility for a new diagnostic method in terms of the combustion of hydrogen-containing gaseous fuel. The intensity of the emission lines produced by $H-\alpha$ in a hydrogen-containing fuel flame can be used for diagnostics and monitoring purposes. Besides the $H-\alpha$ line, other emission lines in the red zone are identified and discussed, which fills the research gap in the hydrogen diffusion flame spectrum.

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