2013 Problem 10 : Water Rise

the rising water after covering a burning candle

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Abstract

The phenomenon of water rising after covering a burning candle mainly involves the combustion of candle and the contraction of trapped heat air. The theoretical and experimental rise ratio that combustion can contribute was obtained. Experimentally, the candle was ignited by a wire to maintain a closed system. Both experimental and theoretical values were lower than the reference rise ratio. The effect of trapping heated air was also considered. The hot air replaces part of the cold air due to convection and contracts after the candle extinguishes. The replacing phenomenon was validated through observations. The light bulb was used to imitate the thermal effect of a candle. Result showed that thermal effect contributes most of the rise ratio. Different numbers of candle representing different heating conditions was considered in the experiment. The temperature distribution of them was measured. More candles resulted in a larger high temperature area and led to higher rise ratio. This confirmed the importance of thermal effect. The rising process could be divided into three regimes, which the second and third regime is the most significant and caused by decreasing temperature. The match between the rising rate and temperature decreasing rate confirms our theory.

Keywords

thermal expansion/contraction, combustion, Introduction

Introduction

The phenomenon of water rising after covering a beaker on a candle lit with water surrounding it had been noticed back in 3rd century BC. Several explanations have since been proposed but proven incorrect in literature. (Vera, Rivera & Núñez, 2011) One of the major controversies is over the role of chemical reaction in this phenomenon. An intuitive but incorrect explanation is that, the rise ratio of the water represents the oxygen content in the atmosphere, which is 21%. Secondly, the effect of "hot air trapping" or bubbling is also regarded as a possible reason. We have investigated both effects to clarify the reasons behind water rising with experiments.

Experiment

1. Amount of rising water

We started with the typical setup of this phenomenon: a vertically standing candle in water was lit then covered with a graduated cylinder (diameter:6.0cm).(Fig 1) Since the combustion and heating of air might be important, the time interval between lighting candle and covering the beaker was strictly controlled within 15 seconds. The beaker was vertically inserted to the same depth each time. We measured the rising height of water after the temperature returned to room temperature. As for the result, we defined the rise ratio, which was the proportion between the rising water volume and the initial air volume. (Fig 2) Note that in this case, the volume of the candle covered was subtracted from the initial volume for standardization under different candle conditions in further experiments. We approximated the cylinder and the candle as columns and calculated the volume by the height we measured. The final rise ratio was 16.0±0.4%. This would be the reference rise ratio for a "typical" candle-beaker experiment in this research.

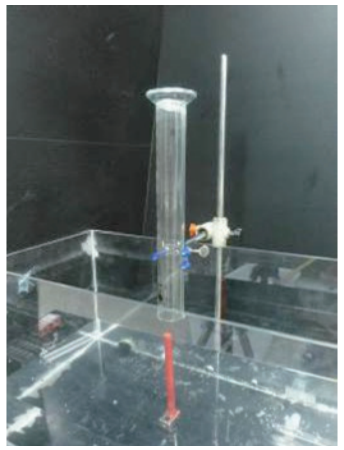

Figure 1: The setup for a typical candle-beaker experiment

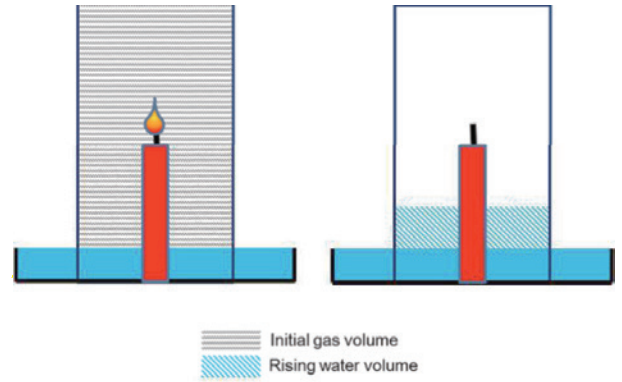

Figure 2: Illustration of rising ratio (=Rising water volume/Initial gas volume)

2. Reason for water rising

a. Chemistry perspective: Combustion

i. Theoretical maximum rise ratio

Considering the following chemical reaction:

$$C_mH_{2m+2} + \frac{3m+1}{2}O_2 \rightarrow mCO_2 + (m+1)O_2$$

The "m" represents the number of carbon. Obviously, the possible volume change is caused by the changing gas mole number. Since we are considering the max rise ratio, we apply the following assumptions: 1. All oxygen is consumed. 2. All the vapor is condensed after combustion. We can obtain the gas mole number changed from

3m+1/2 to m. Note that the candle isn't a simple organic compound but a mixture of paraffin with 22 to 28 carbons. (Birk & Lawson, 1999) With the high carbon number, the change in mole number is about 2/3 times. Then, we consider the ideal gas formula

PV = nRT

The increased height was less than 5cm, and thus the change of gas pressure in the beaker should have been less than 0.5% of 1atm, which was negligible. Also we measured the rise ratio when it returned to room temperature, which indicated the temperature remained constant. We obtained

$$V = \frac{nRT}{P} \propto n$$

So the gas volume after combustion was 2/3 of initial gas volume, which meant that the other 1/3 of volume was replaced by water. In light of the fact that oxygen takes up approximately 21% of the volume of air, the theoretical maximum rise ratio should be approximately 21%×1/3=7%.

ii. Isolating chemical reaction: Closed system

We have obtained the maximum rise ratio theoretically. We have also proposed an experimental approach. To accurately validate the theory, the experiment has to focus on chemical reaction itself. In other words, it should be a "closed system", in which the cylinder is first covered and then the candles lit. There would be no "pre-heated air" in this experiment. Similar experiment had been done earlier. (Vera, Rivera & Núñez, 2011) An igniting wire was connected to the cylinder and was twined around the wick. (Fig 3)The cylinder was covered first then the DC power supply was turned on. The final rise ratio was 1.3±0.8%. Note that during the process of igniting (i.e. the air was heated by the wire itself), the air did expand but did not escape from the cylinder.

Fig was

iii. Comparison

Experimental rise ratio due to chemical reaction (1.3%) vs. theoretical maximum rise ratio (7%): Obviously, the experimental result was much lower. Given the assumption that 100% oxygen was consumed, we validated it by reigniting the candle again. We found that the candle was actually able to reignite, which indicated there was still some oxygen left in the cylinder. A Gas Chromatograph analysis suggests that burning a piece of paper in a closed system only consumes about 56% of the oxygen.(Vitz, 2000)Though the component of candle and paper are different, we could still conclude that close system combustion only consumes part of the oxygen content. The reason of candle extinguishing may have been caused by low local concentration of oxygen but not necessarily the full consumption of oxygen. Theoretical maximum rise ratio (7%) vs. typical candle-beaker experiment rising

ratio (16.0%): This clearly shows that even if we take the full effect of reaction into account, we still can't explain the whole phenomenon. There should be another reason thathave causedthe water to rise.

b. Physics perspective: Thermal expansion/contraction

The hypothesis considering the thermal expansion/contraction is as the followed: during the process of covering, the convection flow caused by the candle continuously blew heated air into the cylinder. The heated air replaced the initial cool air in the cylinder. When the cylinder touched water, the heated air was trapped. After the candle extinguished and the air cooled down, the heated air contracted and the water rose. The following experiments would validate this hypothesis.

i. Convection: Does the heated air actually replace cool air?

The premise of this hypothesis is that replacing did take place. To validate it, we filled the cylinder with smoke and covered the burning candle. As the cylinder got close to the candle, smoke was blown out by convection. When the cylinder reached water surface, approximately 15~20% air closest to the candle was replaced.

ii. Isolating thermal effect

Similar to part a, we've conducted an experiment isolating the thermal effect itself. To exclude the reaction from the system, we replaced the candle with a 50W light bulb.(Fig 4) The same process used in the typical experiment was applied to both candle and light bulb. The result and the comparison between both were listed in Table 1. We observed a 8.4±0.6% rise ratio for the light bulb, which was lessthan 16.0% for the candle. We believe the difference was caused by the following two reasons: temperature and convection. As the table shows, the temperature at the closest point is significantly different. Also, the combustion of candle may have resulted in stronger convection flow due to the demand of oxygen, whereas the light bulb only led to convection caused by temperature distribution. Though there is a difference between the rise ratio of candle and light bulb, the result certifies the important role of thermal expansion/contraction in this phenomenon.

Figure 4: The "fake" candle: candlereplaced by a light bulb

	Candle	Light bulb
Rise Ratio	16.0::t0.4 %	8.4::t0.6%
Temperature (Closest point)	1000~1200(K)	400~600(K)

Table 1. Comparison between candle and light bulb

iii.Different heating condition:

After confirming the replacement and heat expansion in this phenomenon, we tried to vary the heating conditions by adding candles. Before covering the candles, we measured the temperature distribution of single candle and two candles. The setup is shown in (Fig 5). Note that even slight air flow could significantly fluctuate the fire and influence the measured temperature, so we adopted a wind proof cover. The K type thermocouple was used to measure the temperature. We measured in two axes. There was no significant difference on the vertical axis (Fig 6). But with two candles burning, the temperature distribution on the horizontal axis showed a clear difference (Fig 7). The high temperature part distributed about 1cm wider. Considering our hypothesis, it may have resulted in more heated air trapped and thus a higher rise ratio. We have measured the rise ratio when different numbers of candles were included. due to the limitation of the diameter of the cylinder , We could not use more than 4 candles. We observed that more candles resulted in higher rise ratio. (Fig 8)

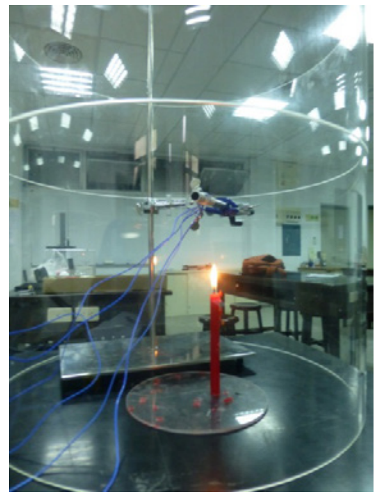

Figure 5: The setup of measuring temperature distribution of candles.

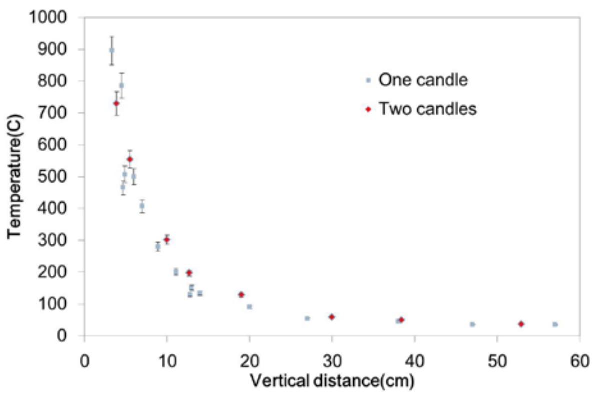

Figure 6: The temperature distribution on the vertical axis

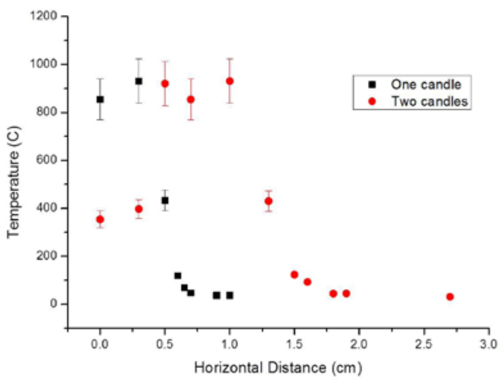

Figure 7: The temperature distribution on the horizontal axis.

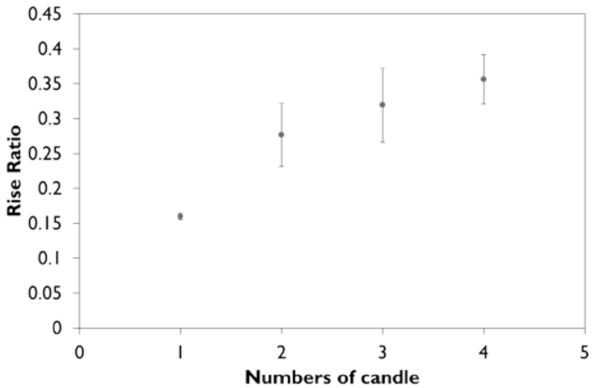

Figure 8: The rise ratio of different numbers of candles.

Mechanism of rising water

Besides the rise ratio of the water, we also observed the process of water rising. We divided the rising process into three time-dependent phases: 1. Combustion (with cylinder covering): the water barely rose 2. The moment after the candle extinguished: the water rose abruptly and dramatically 3. Cooling: The water slowly rose as temperature returned to room temperature. The reasons for water rising in the first phase was chemical reaction, and the second and third phase contraction of the heated air. The temperature in the cylinder and the rise ratio of the water were measured simultaneously. (Fig 9) The rising rate of water and the decrease rate of temperature are closely related, matching the second and third phase.

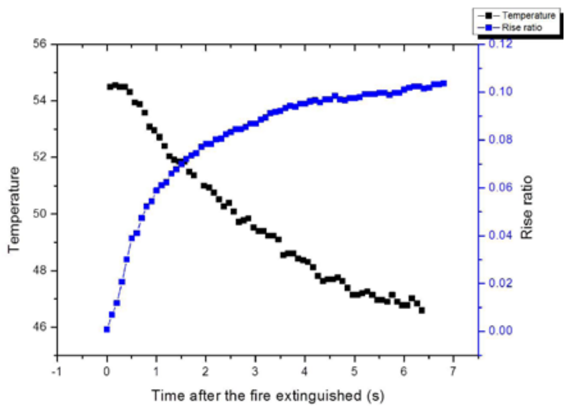

Figure 9: The relationship between rise ratio and temperature (time-dependent). Conclusion

The phenomenon water rising can be attributed to a reduced number of gas moles caused by combustion and contraction of trapped heated air. . Through separating these two effects in experiments, we have concluded that the rise ratio is mainly a result of heated air contraction. Furthermore, by dividing the water rising process into three phases, we could see the most significant rise happened in the second phase, a result of a sudden decrease in temperature after the candle extinguished.

Conclusion

The phenomenon water rising can be attributed to a reduced number of gas moles caused by combustion and contraction of trapped heated air.. Through separating these two effects in experiments, we have concluded that the rise ratio is mainly a result of heated air contraction. Furthermore, by dividing the water rising process into three phases, we could see the most significant rise happened in the second phase, a result of a sudden decrease in temperature after the candle extinguished.

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