CHAPTER 5

Fog in the Bottle Demonstration

In this chapter, fog in the bottle demonstration was described in more detail. The objective of this study is to study thermodynamics of a fog formation. A section 5.1 goes over theoretical aspects of this demonstration. A section 5.2 describes experimental setup and equipment. Then, a section 5.3 reports the experimental results and discussion. Finally, section 5.4-5.5 includes conclusions and an implementation to teaching. Full details are described in the following sections.

5.1 Theoretical aspects

The formation of fog in the bottle is an experiment which related to an adiabatic process. Air inside a closed bottle was increased in pressure by using an electrical mini air pump. When the pressure increase, the cork of the bottle was suddenly released. A sudden expansion of air in a bottle made a temperature decrease, which caused condensation of water vapor existent in the air. A fog or small water droplets inside the bottle were observed.

This process of fog formation cab be describes by an adiabatic irreversible process. A thermodynamic system is air inside a bottle. The amount of air molecules inside the bottle have to be assumed to be constant and to obey the ideal gas law. The volume inside the bottle is V_i and the gas is initially at pressure P_i and initial temperature T_i . In this experiment, an equation of state of the system is given by

$$PV = nRT \tag{15}$$

and the capacity ratio of an ideal gas (γ) is 1.4.

For an initial state, the number of moles in the bottle can be calculated by

$$n = \frac{P_i V_i}{RT_i} \tag{16}$$

After the stopper bursts out from the bottle, the system is expanded against the atmosphere pressure (P_0) and the work made by the system or the gas is [85]

$$\Delta w = -P_0 \Delta V \tag{17}$$

where $\Delta V = V_f - V_i$, indicating an expansion of the gas volume. The expansion is so fast that the system do not transfer heat to the environment, so it can be considered as the adiabatic process. The change of internal energy is given by

$$\Delta U = nc_V (T_f - T_i) \tag{18}$$

At the final temperature, the vapor pressure can be calculated from the Clausius–Clapeyron equation. The vapor pressure of water at temperature T is given by

$$P_V(T) = P_0 \, exp\left[-\frac{\Delta h_V}{R} \left(\frac{T_0 - T}{T_0 T} \right) \right] \tag{19}$$

where Δh_V = 40,500 J mol^{-1} is the molar enthalpy variation for the vaporization of water (Assumed to be constant), and T_0 = 373.15 is the boiling point of water at atmospheric pressure, P_0 = 1.013×10^5 Pa. At low temperatures, the vapor pressure is near zero, with agreement of the Clausius–Clapeyron equation, all water vapor condensates, forming a fog. This phenomenon is better observed with the bottle filled with a few drops of water. A fraction of second before the bottle stopper is bursted out, the initial temperature is $T_i = \frac{P_i V_i}{nR}$ .After bursting out of the stopper, the final temperature is $T_f = \frac{P_0 V_f}{nR}$, which is given by equation (15). As before, the final temperature (T_f') is determined when the gas is submitted to a reversible adiabatic expansion with the same final pressure (P_f) in the similar as the irreversible process. The final temperature (T_f') is given by

$$T_f{}' = T_i\left(\frac{P_i}{P_f}\right)^{\frac{1-\gamma}{\gamma}} \tag{20}$$

Furthermore, the final volume (V_f') is determined when the gas is submitted to a reversible adiabatic expansion with the same final pressure (P_f) in the similar as the irreversible process. The final volume (V_f') is given by

$$V_f{}' = V_i\left(\frac{P_i}{P_f}\right)^{\frac{1}{\gamma}} \tag{21}$$

The work done by the reversible adiabatic process with the same final pressure (P_f) is given by

$$w_{Re} = \frac{P_f V_f - P_i V_i}{1-\gamma} \tag{22}$$

If the fog formation is considered to be a reversible adiabatic expansion from the initial state (P_i, V_i, T_i) to a final state $(P_f{}'', V_f, T_f{}'')$ the final temperature T_f'' and final pressure (P_f'') can be determined from following equations.

$$T_f{}'' = T_i\left(\frac{V_i}{V_f}\right)^{\gamma-1} \tag{23}$$

The final pressure (P_f'') can be determined from

$$P_f'' = P_i\left(\frac{V_i}{V_f}\right)^{\gamma} \tag{24}$$

The work done by the irreversible adiabatic process with the same final volume (V_f) is given by

$$w_{Irre} = P\Delta V \tag{25}$$

It is interesting to study this fog formation process from both reversible and irreversible adiabatic processes because students do not quite grapse a concept of an irreversible process, especially an adiabatic one. Therefore in this experiment, students will have an opportunity to observe and calculate real data for state variables, and then discuss about the irreversible adiabatic process.

5.2 Experimental design

In this experiment, the apparatus and supplies are shown in Figure 5.1.

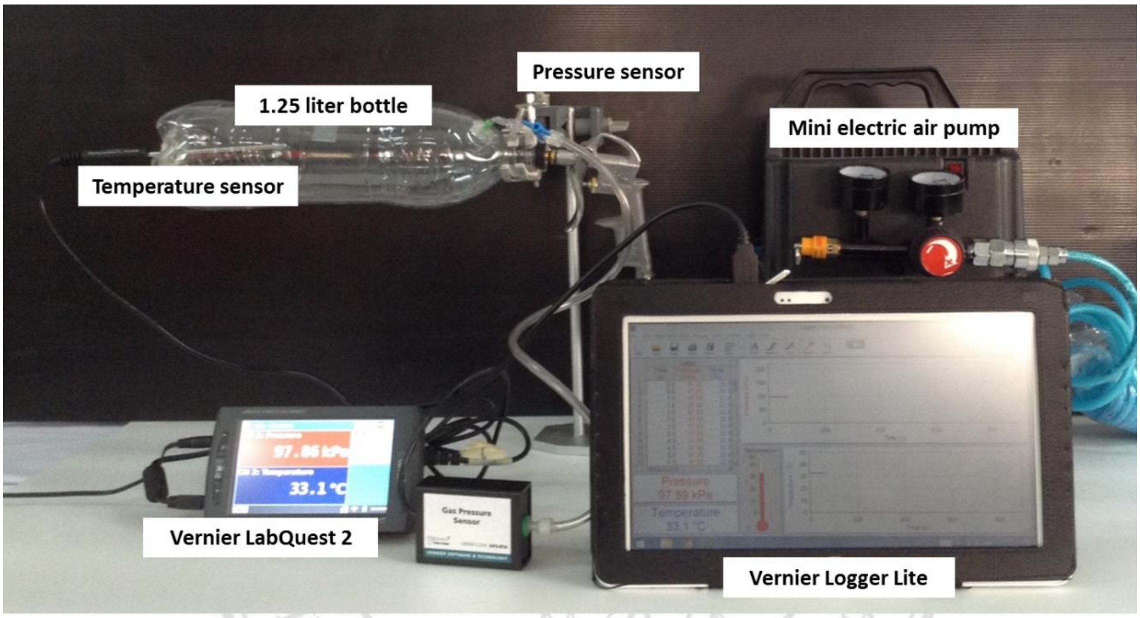

Figure 5.1 The apparatus of the fog formation experiment.

The equipment of the experiment consist of the 1.25 liter bottle with hole allows the connection of temperature sensor, the stopper with junction allows the connection of pressure sensor, the Vernier LabQuest interface, the electrical mini air pump, and the IR- camera. For the experimental setup, an electrical mini air pump was operated. The pressure is increased inside a bottle with a horizontal entrance and with the stopper firmly attached to its mouth. The junction allows the connection of a temperature sensor and pressure sensor with the Vernier LabQuest interface. In this experiment, when the pressure was high enough, the stopper of the bottle was bursted out. The fog inside the bottle is observed. The whole process takes only a few seconds as shown in the Figure 5.2.

Figure 5.2 The fog formation inside the bottle.

Temperature and pressure inside the bottle were collected from the Vernier LabQuest interface. In addition, the IR-camera was used to record the temperature changing during the fog formation in the bottle. After the experiment finished, the temperature and pressure were used to calculate the final state of gas and work done by the gas in the bottle.

5.3 Experimental results and discussion

In this experiment, when the pressure inside the bottle reached 250 kPa, the stopper was suddenly exploded. The pressure and temperature in the bottle were collected by the sensor probes for final pressure (P_f) and final temperature (T_f). In this experiment, the ambient temperature was 25.5^{O}C. The equation (21) was used to calculate the final volume (V_f'). The experiment was repeated for 5 times and average data was shown in the Table 5.1.

Table 5.1 Data of state variables during the irreversible adiabatic process

State variables	Initial state	Final state	Changing
Pressure (kPa)	216.87	96.76	Decrease
Volume (m^3)	1.25×10^{-3}	2.22×10^{-3}	Increase
Temperature (K)	302.05	300.89	Decrease

The pressure and temperature were collected by Vernier LabQuest 2 interface for every second. The data of pressure and temperature as functions of time was shown in Figure 5.3.

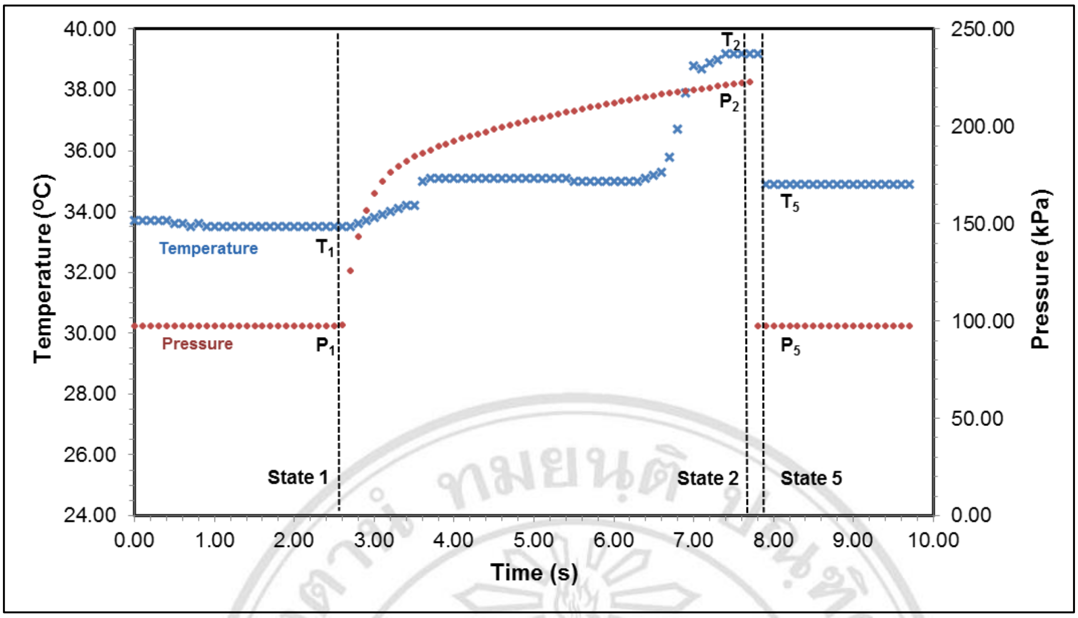

Figure 5.3 The measured temperature and pressure with operated time.

Furthermore, the photos from IR-camera are shown in the Figure 5.4(a), Figure 5.4(b), Figure 5.4 (c), and Figure 5.4 (d) with the ambient temperature at 30.0^{O}C. It presented that the temperature before the operation as shown in the Figure 5.4 (a). Temperature of air inside the bottle increased when operating the electrical mini air pump, as shown in the Figure 5.4 (b) and Figure 5.4 (c). Then, the stopper of the bottle was suddenly released, the temperature decreased as shown in the Figure 5.4 (d). The temperature of gas inside the bottle was changing

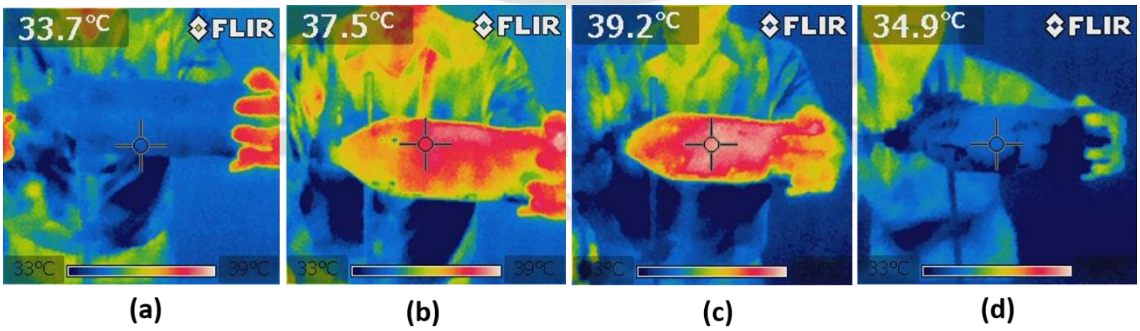

Figure 5.4 The photos from IR-camera (a) before the operation, (b) and (c) during the operation, and (d) after the operation

The number of mole, the work done by the gas in the bottle, and the vapor pressure inside the bottle were calculated by using equation (16), (17), and (19), respectively. The data was collect for 5 time as shown in the Table 5.2.

Table 5.2 Calculated values of number of mole, work done and vapor pressure of the system undergoing the irreversible adiabatic process

No.	Number of mole: n	Work: Δw (J)	Vapor pressure: P_V (bar)
1	0.105	-89.38	0.042
2	0.112	-100.21	0.044
3	0.112	-100.27	0.046
4	0.101	-83.36	0.044
5	0.111	-98.51	0.044

In addition, the state variables of the system were determined when considering the process as the reversible adiabatic process between the same initial states and final states which one of the state variables is the same as the irreversible process. The final temperature, the final volume, and the work done by the adiabatic reversible process with the same final pressure were calculated by using equation (20), (21), and (22) respectively. The result for each experiment was shown in the Table 5.3.

Table 5.3 Final state variables and work done by the system for both adiabatic irreversible and reversible process with the same final pressure

No.	Adiabatic irreversible process				Adiabatic reversible process			
	P_f (kPa)	V_f (cm^3)	T_f (K)	w_{Irre} (J)	P_f (kPa)	V_f' (cm^3)	T_f' (K)	w_{Re} (J)
1	96.63	2175.00	300.15	-89.38	96.63	2174.06	241.71	-130.53
2	96.59	2287.50	301.05	-100.21	96.59	2284.96	237.37	-150.80
3	96.65	2287.50	301.75	-100.27	96.65	2284.09	237.96	-150.73
4	96.65	2112.50	300.65	-83.36	96.65	2111.61	244.32	-119.94
5	97.29	2262.50	300.85	-98.51	97.29	2258.32	238.02	-146.85

For the same final volume of the adiabatic reversible process, the equation (23), (24), and (25) were used to calculate the final temperature, the final pressure, and the work done by the adiabatic reversible process with the same final volume. The final state variables for both reversible and irreversible adiabatic process were compared in the Table 5.4.

Table 5.4 Final state variables and work done by the system for both adiabatic irreversible and reversible process with the same final volume

No.	Adiabatic irreversible process				Adiabatic reversible process			
	P_f (kPa)	V_f (cm^3)	T_f (K)	w_{Irre} (J)	P_f'' (kPa)	V_f (cm^3)	T_f'' (K)	w_{Re} (J)
1	96.63	2175.00	300.15	-89.38	96.60	2175.00	241.78	-130.36
2	96.59	2287.50	301.05	-100.21	96.47	2287.50	237.35	-150.86
3	96.65	2287.50	301.75	-100.27	96.48	2287.50	237.90	-150.87
4	96.65	2112.50	300.65	-83.36	96.48	2112.50	244.54	-119.49
5	97.29	2262.50	300.85	-98.51	97.07	2262.50	237.92	-147.07

The process is an irreversible adiabatic expansion so, the relation between temperature and pressure is given

$$T_f\left(C_V + R\right) = T_i\left(C_V + \frac{P_f}{P_i}R\right) \tag{26}$$

From the result, the final pressure $\left(P_f\right)$ is lower than the initial pressure $\left(P_i\right)$, so the final temperature $\left(T_f\right)$ is lower than the initial temperature $\left(T_i\right)$ too. While, the reversible adiabatic expansion the final volume $\left(V_f\right)$ is higher than the initial volume $\left(V_i\right)$ and the gas cools during the process, so the final temperature $\left(T_f''\right)$ is lower than the initial temperature $\left(T_i\right)$ as given by the equation (23). The reversible adiabatic process is in the quasi-static equilibrium, the initial and final states are in the equilibrium with each other. The gas expands a little bit before reaching very fast to the new equilibrium state. While, during the irreversible adiabatic process, the initial and final states are not in the equilibrium with each other. The gas expand very rapidly to the new equilibrium but it is different from the summation of the changing in the quasi-static equilibrium.

The work done on the reversible adiabatic process was higher in absolute value than on the irreversible adiabatic process.

5.4 Conclusion

In this experiment, it presents the visual adiabatic irreversible process and it can be measure and calculate the state variable of the process. It focused on temperature changing and pressure changing which are decreased. This result is quite concern with the second law of thermodynamics for state functions. It related two principles that generate the second law of thermodynamics. The detail is described in the following subsection.

5.4.1 The Caratheodory principle

A Caratheodory principle is formulated by Christian Caratheodory in 1908 as the formulation of the second law of thermodynamics. It was not based on the empirical data and express as a theorem in pure mathematics [86]. The Caratheodory is: In the neighborhood of any state A of an object there are other states B that cannot be reached from state A in reversible adiabatic process [87]. For the second law of thermodynamics, the entropy change of irreversible process for isolated system is greater than zero. The initial state cannot be reach to any final state to the left of the reversible adiabatic process. Therefore, the irreversible adiabatic process can be exist between the same initial state and final state must be lie to the right of the reversible adiabatic process. For this result, in P-V diagram, any adiabatic irreversible process can only reach the final state to the right of the line of the reversible process which obey a principle of Caratheodory.

5.4.2 The Le Chatelier principle

A Le Chatelier principle is devised by Henry Louis Le Chatelier in 1885. The Le Chatelier principle is: If the external conditions of a thermo dynamical system are altered, the equilibrium of the system will tend to move in such a direction as to oppose the change in the external conditions [88]. For the isothermal process the pressure decreases in inverse proportion to volume (V). In adiabatic expansion, the pressure decreases in inverse proportion to V^{γ} more rapidly for $\gamma > 1$. If these processes are presented graphically in P-V diagram, the slope of the adiabatic line is smaller than the slope of the isothermal line at the same point. For this result, it obey the Le Chatelier principle.

5.5 Implementation for teaching

This experiment demonstrates the adiabatic irreversible process with a measureable state variables. For thermodynamics teaching, the state variables are the important factors to indicate the characteristic of thermodynamics process, the value of state variable were collected in real time for the setup of this experiment. Whereas, if there is a lack of a pressure sensor and a temperature sensor to collect the data, only the fog formation can be used to demonstrate the adiabatic irreversible process and it can present the temperature changing by touching the bottle. This experiment is a great catalyst for starting a classroom discussion and instruction about the irreversible adiabatic process and a concept of entropy.