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A novel educational laboratory experiment for constant-mass expansion of petroleum fluids

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ABSTRACT

This paper presents a new way to conduct an educational experiment for bubble-point determination of a hydrocarbon mixture. The visual fluid cell newly designed for educational purposes made it possible to teach bubble-point determination safely at low cost within a few hours for groups of students in a laboratory class. The educational experiment developed has been successfully implemented for three semesters at the authors' institution with positive responses from a vast majority of the students. It is hoped that this paper helps other interested instructors enhance students' learning experience in the subject of fluid properties.

Nomenclature

Roman Symbols

MW	molecular weight
P	pressure, kPa
P_{bubble}	bubble point pressure or saturation pressure, kPa
P_C	critical pressure, kPa
T	temperature, K
T_C	critical temperature, K

Greek Symbols

ω	acentric factor

Subscripts

C	at critical point
bubble	at the bubble point or saturation pressure

1. Introduction

Phase behavior is one of the most fundamental subjects required for petroleum engineers. For example, reliable estimation of the oil volume that can be produced from an oil reservoir requires accurately knowing volumetric behavior of the oil with varying pressure and temperature. Phase separation of oil into the vapor and liquid phases with decreasing reservoir pressure affects the production strategy as the vapor phase is much less viscous and dense than the oil phase in the reservoir. Furthermore, many methods of enhanced oil recovery use the effect of fluid composition on phase behavior as their key mechanisms.

Oil recovery processes often encounter a wide range of thermodynamic conditions. Therefore, it is common practice to characterize a reservoir fluid by using an equation of state (EOS) along with a limited amount of phase behavior data at relevant thermodynamic conditions. In particular, cubic EOSs are widely used because of their computational efficiency and reasonable accuracy in representation of hydrocarbon mixtures (Whitson and Brulé, 2000; Pedersen et al., 2015; Kumar and Okuno, 2016). Examples of such EOSs include the Peng-Robinson EOS (Peng and Robinson, 1976; Robinson and Peng, 1978), and the Soave-Redlich-Kwong EOS (Soave, 1972). These cubic EOSs have been implemented in commercial software, such as PVTSim Nova (Calsep 2018) and Winprop (Computer Modelling Group (CMG, 2016), and also used for educational purposes at universities.

Abbreviations: CME, constant mass expansion; EOS, equation of State; PR, Peng and Robinson; P–V, pressure-volume; PVT, pressure, volume, temperature.

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Cubic EOSs have two inherent parameters, the attraction and covolume parameters, for each component. These EOS parameters are usually calculated by using vapor pressure information, such as critical temperature (T_C), critical pressure (P_C), and acentric factor (ω), for each component (Kumar and Okuno, 2015). Mixing rules are then used to calculate the attraction and covolume parameters for a mixture based on the component-specific parameters and binary interaction parameters.

It is straightforward to calculate the attraction and covolume parameters for well-defined components, such as methane, pentane, decane, and carbon dioxide, because their vapor pressure curves are known. However, a reservoir oil also contains a large number of heavier components that are not identifiable, which are called "heavy fractions" (Pedersen et al., 2015). The heavy fractions are characterized by a small number of "pseudo components," for which the attraction and covolume parameters are adjusted to match experimental data through their T_C, P_C, and ω (or vapor pressure curves). This EOS-based characterization of the heavy fractions has to be done only indirectly by using experimental data of the hydrocarbon mixtures of interest. Then, the resulting set of T_C, P_C, and ω for each pseudo component gives a hypothetical vapor pressure curve.

It is important to understand what types of experimental data are effective in calibrating the EOS model for the reservoir oil of interest. The theoretical framework of cubic EOSs indicates two types of phase behavior: volumetric and compositional ones. An example of the former type is density, and that of the latter type is bubble point (or saturation point in general), representing the gas solubility in oil at a particular pressure and temperature.

The most widely used method of measuring bubble point and density data for a reservoir oil is constant mass expansion (CME) by using a pressure vessel equipped with a piston, a mixer, and a visual window in an oven. This pressure vessel is often called a PVT cell. In a CME experiment for oil, a single-phase liquid (oil) is placed in such a cell at the temperature of interest (e.g., oil reservoir temperature). An initial volume is recorded once the test fluid reaches equilibrium at the initial pressure and temperature. Then, the cell pressure is reduced in a stepwise manner by increasing the cell volume through adjusting the piston position. At each pressure step of CME, the cell volume and pressure are recorded after the fluid is mixed and reaches phase equilibrium.

A vapor phase starts appearing near the bubble point pressure. A first bubble can be observed through a visual window of the cell. However, such observation does not give a true bubble point since equilibrium phases are observed only at discrete pressure points, usually within a limited time for the phase behavior experiment. Several different methods have been proposed for determination of a bubble point from CME data (Potsch and Braeuer, 1996; Odi et al., 2012; Hosein and Mayrhoo, 2014; Hoang et al., 2017). The simplest way is to find an intersection of the trend lines constructed for the single- and two-phase segments of the pressure-volume (P–V) data.

CME also yields liquid density data at pressures above a bubble point, where single-phase volumes are recorded for different pressures for a given mass of the fluid. Below a bubble point, phase volumes (and volumetric fractions of phases) are recorded at each pressure point. Such volumetric fractions contain both volumetric and compositional information about the fluid of interest; that is, they depend on the phase molar volumes and the phase mole fractions, which in turn depend on the phase compositions.

As described above, CME gives the crucial information required for reliable characterization of the fluid by using an EOS. It is widely used likely because the method is simple, accurate, and reliably repeatable. To our knowledge, however, a CME experiment is not often taught through a hands-on lab experience in petroleum and chemical engineering programs at universities. This may be due to several different reasons related to safety, budget, and time. For example, commercial PVT cells are often too expensive and unavailable for educational use. Having one PVT cell system may be insufficient to teach a number of students registered for the program. A CME test for reservoir fluids usually takes several days to be completed. Since a CME test using a commercial PVT-cell system requires various pieces of high-pressure high-temperature equipment, basic safety training is not sufficient for undergraduate students to have a hands-on experience of CME tests in an educational laboratory.

Efforts have been made to teach the phase behavior experiment by developing software to simulate PVT experiments (Bouett et al., 1989). Such PVT-experiment software had been used for at least fifteen years by six different instructors at the authors' institution with a limited success in terms of students' learning experience. The instructors unanimously pointed out that software was not effective for the purpose of teaching the CME experiment. We then decided to develop a new educational laboratory experiment of bubble-point determination because it is crucial for students to learn how fluid data are obtained for petroleum engineering as described previously. It is simply more interesting to observe gas bubbles coming out of oil with decreasing pressure (and increasing volume) than clicking buttons following the instruction of PVT-experiment software in a computer room. Also, students can discuss various uncertainties associated with an experiment when they conducted a specific experimental method by themselves. The uncertainties associated with random and systematic errors are not included in many laboratory simulations (Feisel and Rosa, 2005) as is the case with the PVT-experiment software. As an applied science, engineering demands not only the development of analytical thinking and problem-solving skills, but also hands-on experience in face-to-face laboratories (Abdulwahed and Nagy, 2009).

In this paper, we present a new way to perform an educational laboratory experiment of CME. The main novelty lies in a simple visual cell newly designed for educational purposes, which made it possible to teach bubble-point determination safely at low cost within a few hours for groups of students in a laboratory class. The contents presented in this paper have been used for three semesters (112 students in total) so far at the authors' institution with positive responses from a vast majority of the students. We believe that the new educational laboratory experiment is practical and reproducible at other universities.

The main learning points of this experiment include.

To become familiar with CME tests to determine a bubble point of oil.

To observe an equilibration process using a visual fluid cell.

To learn how to interpret CME data and how to use them to calibrate an EOS.

To think about sources of experimental uncertainties associated with CME tests.

To become familiar with auxiliary equipment, such as a pump, a pressure gauge, a stirring plate and stirrer, and a cathetometer.

The pedagogy of our educational laboratory is based on the Experiential Learning Theory (ELT) of David Kolb (Kolb and Kolb, 2005; Kolb, 2015). This approach conceives learning as a process that comprises four stages for knowledge construction: (1) Concrete experience, (2) Reflective observation, (3) Abstract conceptualization, and (4) Active experimentation. Optimal learning occurs when an individual passes through the four stages in a balanced way (Abdulwahed and Nagy, 2009).

In this educational experiment, abstract conceptualization occurs when students are exposed in class to the theory of petroleum fluid characterization, EOS, and CME. Then, students go through the stages of concrete experience and active experimentation when they do the CME test. The use of equipment, the technical discussion, and the observation of the hydrocarbon-mixture phase behavior allow students to be in the reflective phase. To complete

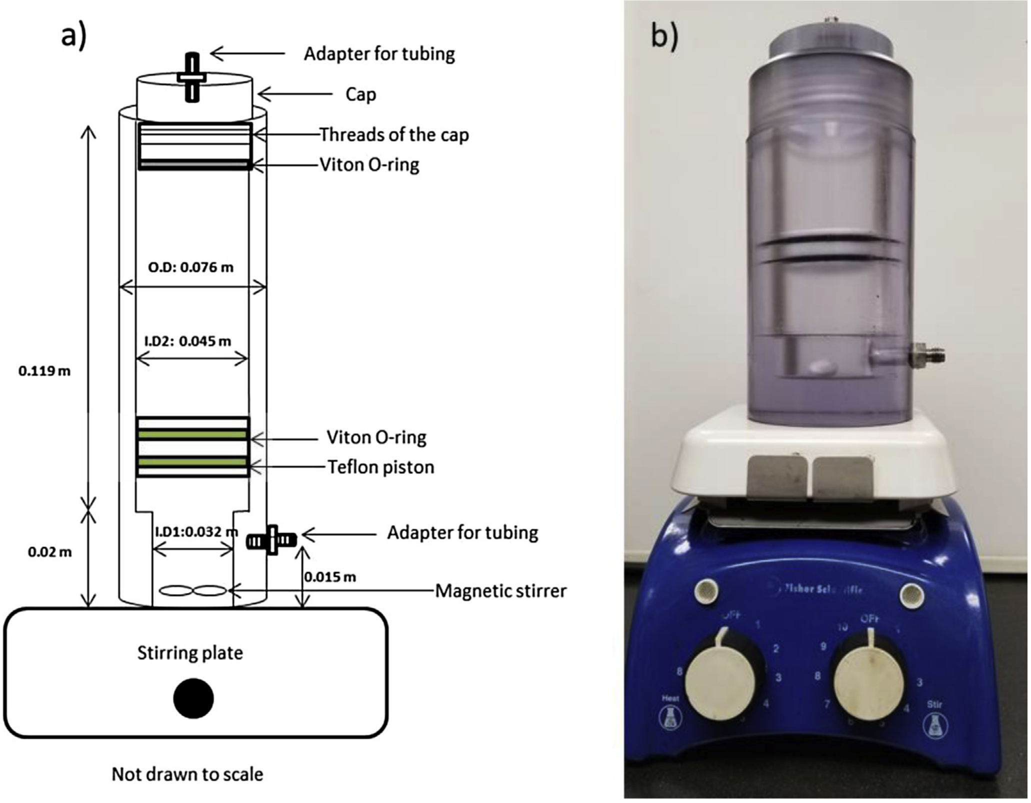

Fig. 1. The new fluid cell made of unfilled polycarbonate placed on a stirring plate.

the learning cycle and return to the abstract conceptualization phase, students write the report of the lab session and apply the theory taught in class to solve questions related to the experiment.

In what follows, Section 2 describes the design of the new visual fluid cell, the selection of a test fluid, and the experimental setup used. Section 3 gives the preparation of the visual cell, safety requirements, and the procedure of CME. Section 4 explains the current implementation of the laboratory experiment in the course “Properties of Petroleum Fluids” in the authors’ department at the University of Texas at Austin.

2. Experimental setup

This section presents a newly designed visual fluid cell that is easily made by a machine shop. Then, the set up for CME using the visual cell is explained, including the fluid used and other related pieces of equipment.

2.1. New visual fluid cell and other pieces of equipment

A normal PVT cell is a pressure vessel equipped with a visual window, a piston, and a stirrer (magnetic or mechanical). Commercially-available PVT cells are costly as they are designed for fluids at a wide range of reservoir conditions (e.g., up to 68 MPa and 423 K). The new fluid cell developed is inexpensive and easy to build and assemble in a machine shop. It allows chemical and petroleum engineering students to conduct CME and observe equilibration of petroleum fluids at room temperature.

Fig. 1a shows a schematic of the new fluid cell. This cell is a transparent cylindrical vessel made of unfilled polycarbonate, which is a thermoplastic of high molecular weight. As shown in Fig. 1a, the cell has two chambers with different inner diameters. The upper chamber has an outer diameter of 0.076 m and an inner diameter of 0.045 m. This chamber accommodates a piston that separates the test fluid and the hydraulic fluid, which can be simply deionized water. The piston is made of Teflon and uses two Viton O-rings to prevent the mixing of water and the test fluid.

The lower chamber has an inner diameter of 0.032 m and the wall thickness is 0.022 m. This chamber receives the test fluid through an adapter attached to a threaded hole made in the wall. The lower chamber contains a magnetic stirrer required to run the experiment. The cap of the cell is also made of polycarbonate. It has threads and a Viton O-ring to seal the cell. An adapter is also attached in the cap through a threaded hole to inject the hydraulic fluid. The cell is placed on a stirring plate. Fig. 1b is a photo of the visual fluid cell built at the machine shop of the authors’ department at the University of Texas at Austin. This educational fluid cell can operate at pressures up to 3447 kPa at room temperature (288–298 K).

Fig. 2a shows the entire experimental setup for the CME experiment as implemented. It consists of a pump, a pressure gauge, the visual fluid cell, a piston with O-rings, a magnetic stirrer, a stirring plate, a temperature sensor, an aluminum protective frame, and a cathetometer. Fig. 2b shows a picture of the experimental setup assembled.

The pump is a Teledyne Isco model (100 DX) that controls the pressure of the fluid cell by deionized water. The stirring plate is a Fisher Scientific ceramic top plate. The cathetometer is an E5160 model of Eberbach Corporation. The telescope magnification is 20X at 30 cm to 8X at infinity. The digital system of the cathetometer has a resolution of 10^{-5} m with an accuracy of $\pm\ [2 \times 10^{-5} + 5 \times 10^{-5}\ L\,(\mathrm{m})]$. The experimental setup as shown in Fig. 2 also needs the following: two 3-way valves, a 2-way valve, two adapters (male 1/8″ NPT – male 1/8″), an adapter (female1/4″ NPT - male 1/8″), a tee connector, two 1/8″ connectors with plugs, 1/8″ high-pressure tubing (I.D. 0.052″), 1/8″ connectors and ferrules, and three Viton O-rings (#141).

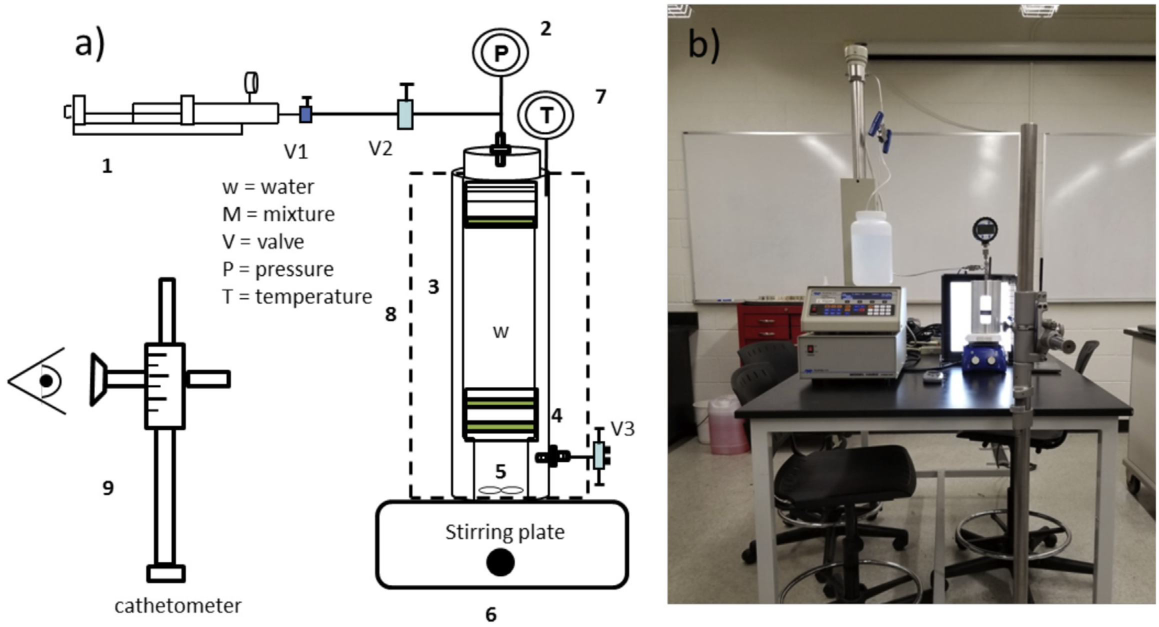

Fig. 2. The setup used for the CME experiment: (1) pump, (2) fluid-cell pressure gauge, (3) fluid cell, (4) piston, (5) magnetic stirrer, (6) stirring plate, (7) temperature sensor, (8) aluminum protective frame, and (9) cathetometer. w, M, V, P and T stand for water, mixture, valve, pressure, and temperature, respectively.

Table 1
Composition of the hydrocarbon mixture used.

Component	Mole fraction
Ethane	0.439
n-Butane	0.110
n-Decane	0.451

2.2. *Verification of the experimental setup*

The new set up was verified by measuring vapor pressures of propane at room temperature. The propane sample was provided by Matheson with a reported purity of 99.993 mol%. The saturation pressure obtained with the new set up was 972 kPa at an average temperature of 297 K and the reported NIST value is 928 kPa at 297 K for pure propane. The temperature of the fluid cell was measured with a traceable Kangaroo^{TM} thermometer. The accuracy of this thermometer is ± 1 °C. The fluid pressure in the fluid cell was measured by an Omega digital pressure gauge with an accuracy of ± 17 kPa.

2.3. *Selection of test fluid*

Several hydrocarbon mixtures were tested during the design process and a mixture of ethane, n-butane and n-decane was chosen for the educational laboratory. Table 1 shows the composition of this hydrocarbon mixture. Use of three components gives a sufficient flexibility in adjusting the bubble point, and it is simple to prepare. The mixture can be prepared in a university fluid laboratory or purchased from an industrial gases company. Bubble points for this mixture were obtained between 1275 and 1534 kPa at room temperature (288–298 K) using the current set up as also calculated by the PR EOS.

The test fluid should be selected so that students can obtain a sufficient number of data points above and below a bubble point for a given pressure limit, which is 3447 kPa with the new fluid cell. It is reasonable to select a test fluid with its bubble point in the range of 552–2758 kPa at room temperature. Note also that it is not necessary to achieve research-quality accuracy in educational laboratory experiments.

3. Experimental procedure

3.1. *Preparation*

The experiment may be prepared by a laboratory technician and a teaching assistant (TA), two or three days prior to the experiment. Fig. 3 shows a schematic of the setup consisting of pumps, a pressure gauge, the visual fluid cell, a piston with O-rings, a magnetic stirrer, a stirring plate, an accumulator, and an aluminum protective frame. This preparation procedure assumes that the mixture (Section 2.3) is prepared in the accumulator prior to the injection. The mixture must be a single-phase liquid at the injection pressure when it is injected into the visual fluid cell. The preparation of the experiment takes three hours at most. Once the hydrocarbon mixture is prepared inside the cell, it can be used for multiple lab sessions for CME during the semester.

The procedure is as follows:

Conditioning of the PVT cell

1) Assemble the experimental setup according to the Fig. 3,
2) Close all valves,
3) Disconnect the tubing between valves V1 and V2, then evacuate the hydraulic-fluid side of the fluid cell and the pressure gauge by a vacuum pump connected to V2 for 10 min,
4) Connect the line between V1 and V2,
5) Activate the pump 1a with the constant pressure mode at 689 kPa and open V1,
6) Purge the tubing by loosening the connector in V1 and then tighten it. Wait for stabilization of pressure (689 kPa),
7) Open V2. The piston in the visual fluid cell will reach the base of the upper chamber. Wait for stabilization of pressure (689 kPa),
8) Increase the pressure at Pump 1a to 2758 kPa by increments of 345 kPa,

Preparation of the hydrocarbon mixture before injection

9) Activate pump 1b in the constant pressure mode at the initial pressure, which is equal to the pressure inside the accumulator (2620 kPa). Then, open V6,
10) Purge the tubing in V5. Loosen the connector and then tighten it. Wait for stabilization of pressure (initial pressure inside the accumulator),

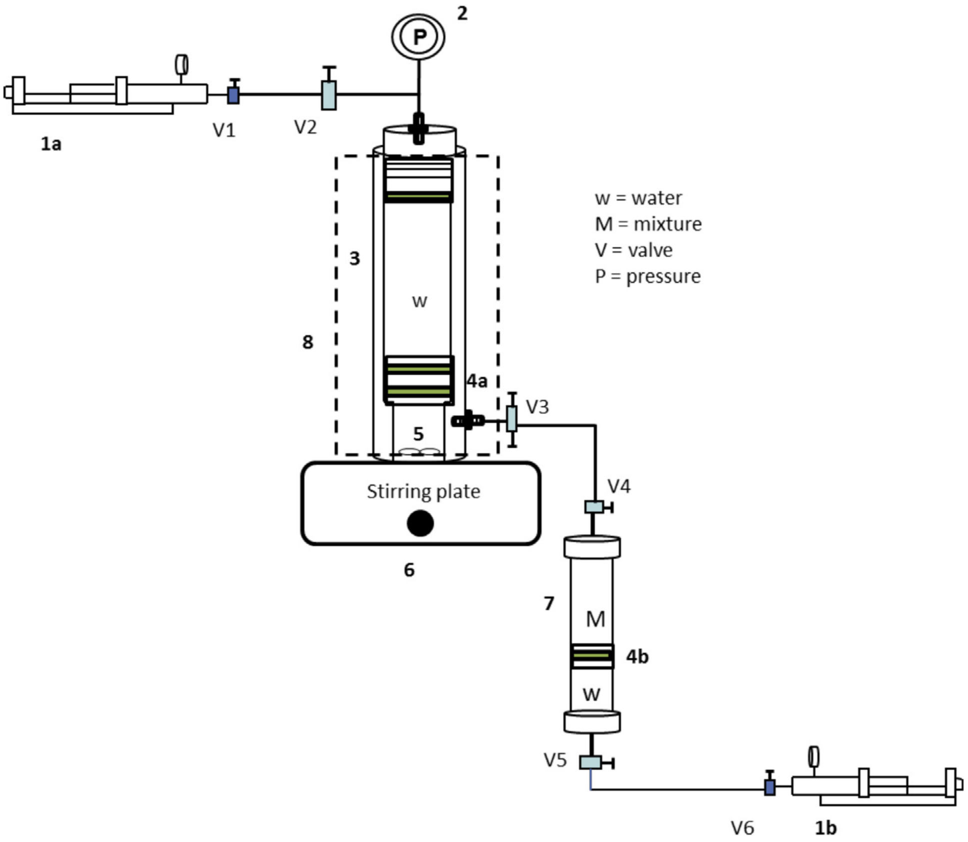

Fig. 3. The setup to inject the mixture into the visual fluid cell: (1) pumps, (2) fluid pressure gauge, (3) visual fluid cell, (4) piston, (5) magnetic stirrer, (6) stirring plate, (7) accumulator, and (8) Aluminum protective frame. w, M, V, and P stand for water, mixture, valve and pressure, respectively.

11) Open valve V5. The pump pressure and accumulator pressure should be similar to each other,
12) Connect a vacuum pump in V3 (which can be a 3-way valve or 3-way/2-stem valve) to evacuate the sample side of the visual fluid cell and the tubing between V3 and V4,
13) Open V3 and evacuate for 10 min,
14) Close V3 (stem of the vacuum pump) and disconnect the vacuum pump.
15) Open V4. Wait for stabilization of the pressure of pump 1b,
16) Purge the tubing in V3 carefully. Loosen the connector and then tighten it. Wait for stabilization of pressure (the initial pressure inside the accumulator, 2620 kPa).

Injection of hydrocarbon mixture into the PVT cell

17) Make sure that the volume read by the pump controller (pump 1b) is constant (this ensures that there is not vapor phase inside the tubing),
18) Record the volume, Volume 1, given by the pump controller,
19) Open valve V3. Pump 1b will automatically inject water to keep the pressure in the accumulator. Wait for stabilization of the pump. Turn on the stirring plate,
20) When only a liquid phase is observed at 2620 kPa in the visual fluid cell, turn off the stirring plate,
21) Record the volume, Volume 2, given by the pump controller,
22) Calculate the volume injected (Volume 2 – Volume 1) by the pump to fill out the lower chamber of the fluid cell. This must be closed to 1.583×10^{-5} m^3 (15.83 ml),
23) When the pressure is steady at both pumps, switch the pump 1b to the constant flow rate mode and set 2.778×10^{-9} m^3/s (10 cm^3/h),
24) The piston will start moving as soon as the pressure at pump 1b becomes higher than that at pump 1a (2758 kPa). Inject the mixture until a total injection volume becomes 5.0×10^{-5} m^3 (50 ml), including the volume injected previously,
25) Stop pump 1b,
26) Record the volume injected,
27) Close valves V4 and V3,
28) Disconnect the tubings between valves V3 and V4, the accumulator, and pump 1b,
29) Turn on the stirring plate for 1 h to homogenize the mixture,
30) Turn off the stirring plate. Rest the fluid for one hour. The setup is ready for the constant mass expansion experiment.

3.2. Safety requirements

Besides ordinary safety rules in a laboratory for undergraduate students, the experiment involves the following safety requirements: (a) the laboratory technician and TA must set the limit pressure of the pump as 3447 kPa, (b) TA must teach students how to operate the pump, (c) students and TA must wear safety glasses at all times, (d) plug the valve of the visual fluid cell (V3 in Fig. 3) just in case the valve is accidentally opened.

3.3. Procedure during the lab session

After the preparation given in Section 3.1, the experimental setup for the CME experiment is as shown in Fig. 2. The pump volume must match the actual sample volume in the fluid cell. This adjustment should be also completed by the TA before the lab session. Table 2 is provided to inform students of the pump pressures (column 1), mixing time (column 2), and wait time (column 3). Then, students will measure cell pressure, pump volume, cathetometer height, and temperature at each pump pressure.

Table 2
Template for CME experimental data. The results showed in this table were collected by one of the students for the hydrocarbon mixture given in Table 1.

Pumppressure	Mixingtime	Wait time	Cellpressure	Cellabsolute pressure	Pumpvolume	Cathetometerheight	Temperature
[kPa]	[min]	[min]	[kPa]	[kPa]	[cm^3]	[cm]	[K]
2275	2	5	2289	2390	48.36	74.3	295.8
2066	2	5	2080	2182	48.45	74.3	295.7
1791	2	5	1805	1906	48.58	74.3	296.4
1703	2	5	1718	1819	48.63	74.3	296.8
1586	2	5	1601	1702	48.66	74.3	296.7
1516	2	10	1531	1632	48.69	74.3	296.4
1442	2	10	1456	1558	48.72	74.3	296.5
1404	2	15	1419	1520	48.73	74.3	296.5
1370	2	15	1384	1486	48.78	74.3	296.4
1333	2	15	1347	1449	49.22	74.4	296.4
1299	2	15	1314	1415	51.75	74.5	296.6
1264	2	15	1278	1380	60.57	75.0	296.3
1228	2	15	1242	1344	68.62	75.6	296.4

The procedure that students follow is described below:

1) See through the cathetometer scope and adjust the reference line to the lower edge of the piston,
2) Set the pressure required in the fluid cell (see column 1 of Table 2).
3) Turn on the magnetic mixer for two minutes (see column 2 of Table 2)
4) Turn off the magnetic mixer.
5) Wait for equilibrium of the mixture (see the wait time in column 3 of Table 2).
6) Record the pressure of the fluid cell (column 4 of Table 2), the volume of the mixture (column 6 of Table 2), the new level of the cathetometer (column 7 of Table 2) and the temperature of the cell (the last column of Table 2).
7) Repeat steps 2 through 6 for all pump pressures.
8) Take a photo upon appearance of a first gas bubble in the mixture. Record this pressure.
9) Record a two-minute video (say, using a cell phone) when the mixer is turned on at the last pressure step.

In this paper, the procedure to carry out a CME experiment assumed use of the mixture of ethane, n-butane and n-Decane given in Table 1. The depressurization program shown in column 1 of Table 2 was found to be optimal for this particular mixture. It takes approximately two hours and forty minutes to complete the experiment with students.

4. Discussion

This laboratory session was implemented for the course on “Properties of Petroleum Fluids” offered to undergraduate students in petroleum engineering at the authors’ institution. This educational experiment was performed by 22 students (divided into 6 groups) in the Fall of 2017, by 76 students (divided into 11 groups) in the Spring of 2018, and 14 students (divided into 4 groups) in the Fall of 2018.

One week before the lab session, the instructor provided students with the reading material for the experiment, with which they became familiar with the objectives, the procedure, the equipment, and the safety rules. The session began by teaching how to use the pump, the stirring plate, and the cathetometer. All students carried out the procedure of the CME experiment (Section 3.3) and measured a pressure-volume relationship. All students took pictures of a first gas bubble, and a two-minute video of the nucleation of a vapor phase while mixing the fluid by a magnetic stirrer.

TAs led discussion among students while the equilibrium was being reached at each pressure step. TAs asked students various questions; e.g., the effect of stirring on the bubble point measurement was discussed so that students could realize the importance of mixing when it facilitated the equilibration of the vapor and liquid phases.

As part of the experimental results, all students completed columns 4–8 of Table 2. They were asked to plot the measured volumes of the fluid (column 6 of Table 2) at all specified pressures (column 5 of Table 2). This plot showed two groups of discrete data points: one in the single-phase region, and the other in the two-phase region. To determine a bubble-point pressure, students drew a straight line for each segment and found an intersection of the two straight lines in the pressure-volume plot. The intersection gives a bubble point based on their experimental data.

Table 2 gives a sample set of experimental results obtained by one of the students. Fig. 4 shows the P–V diagram based on the student’s data. The intersection of the two straight lines shown in Fig. 4 gave a bubble point of 1441 kPa.

Discussion points in their lab reports included the following:

1 “Describe your observation of the CME experiment, in particular, the nucleation of a vapor phase with decreasing pressure.”
2 “Give several potential sources of error in this CME experiment. Remember that thermodynamic properties are to be evaluated at an equilibrium state, and that phase behavior depends on temperature, pressure, and composition.”

For question 1, students summarized their observation of gas bubbles appearing from the liquid phase and the evolution of a vapor phase. Also, they discussed the effect of mixing (by a magnetic stirrer) on the equilibration process at a given pressure. For question 2, students listed various potential sources of error as follows:

- *Equilibration time*: Pressure and volume may be recorded in a non-equilibrium state.
- *Temperature of the system*: temperature can vary during the experiment since the experimental temperature is not precisely controlled.
- *Cleaning of the PVT cell*: any impurities can affect phase behavior of the mixture.
- *Leakages*: Leakage can disturb the thermodynamic conditions of the experiment.
- *Equipment calibration*: a systematic error occurs, for example, if the pressure and temperature gauges used are not calibrated properly.

The experimental data (i.e., a bubble point and fluid volumes at different pressures at room temperature) can be compared with calculation results from a cubic EOS. Such comparisons can be a

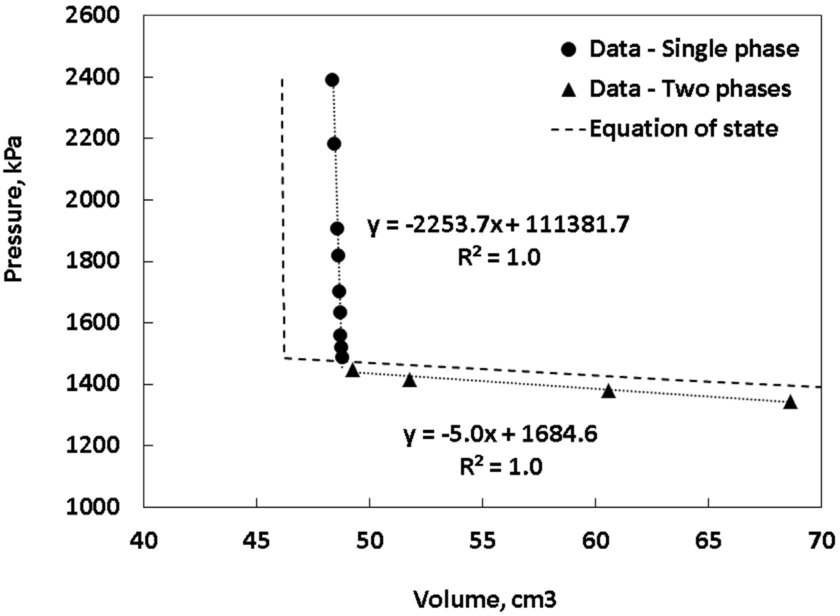

Fig. 4. A pressure-volume diagram of the ethane/n-butane/n-decane mixture (Table 1 and 3) at 296 K (average room temperature). The circles and triangles represent the data in the single-phase region and two-phase region, respectively. Equations and dashed lines represent the fitted straight lines in both regions. This figure also shows the comparison of the experimental data with the PR EOS.

Table 3
Fluid properties and parameters of the hydrocarbon mixture for the CME experiment. The Peng-Robinson EOS was used. Binary interaction parameters were all set to zero.

Component	MW(g/mol)	Tc(K)	Pc(kPa)	ω	Volume shift parameter (cm^3/mol)
Ethane	30.070	305	4883	0.098	−5.790
n-Butane	58.124	425	3800	0.193	−6.490
n-Decane	142.285	618	2108	0.490	16.140

good introductory material on fluid characterization. For example, students were asked to do the following calculations:

3 "Suppose that the measured bubble point (P_{bubble}) is a true value. Using the PR EOS, calculate a bubble point of this ternary mixture at the average temperature during the CME test. Use the values shown in Table 3 for the Peng-Robinson EOS with volume shift."
4 "Report the deviation of the calculated P_{bubble} from the measured P_{bubble}. Also, report the deviation between the measured P_{bubble} and the pressure at which you observed a first bubble (from Step 8 in the CME procedure)."
5 "Use the PR EOS model created (in question 3) to calculate volumes of the mixture at all specified pressures in your experiment. Use the average temperature during the experiment for the calculation. Compare the calculated volumes with the measured volumes in the same P–V diagram."

For these questions, the students can learn to use commercial PVT software, such as PVTsim Nova (Calculation of Separation Processes (CALSEP, 2018). For example, Fig. 4 compares the calculated volumes using the PR EOS with the measured data. We also asked students to study the impact of binary interaction parameters on the calculated bubble point, and that of volume shift on the calculated volumes. For example, students used default values of binary interactions parameters in PVTSim, instead of those listed in Table 3. The results were compared with those obtained for questions 3–5. Then, students calibrated the PR EOS model with the measured bubble point using binary interaction parameters as needed. Depending on the theory part of teaching material, it is possible to expand the EOS-related questions in various ways.

5. Summary and students' survey

This paper presented a novel way of teaching hydrocarbon phase behavior through CME experiment by using a simple fluid cell that was uniquely designed for educational purposes. The developed teaching material covers the concept of CME, bubble-point determination, the equilibration process, and use of an EOS model and its parameters for multicomponent fluids. This educational laboratory was successfully implemented for three semesters. We have made 6 units of the experiment setup and continue to improve the teaching content through the coming semesters.

For the past three semesters, we conducted students' survey on the effectiveness of this laboratory. They indicated that the experiment was useful in their knowledge construction stages of concrete experience, active experimentation, and reflective observation. In particular, the laboratory experiment was implemented with detailed explanation and discussion regarding various factors affecting multicomponent phase behavior and its experimental study, such as mixing, contamination, and leakage. The evaluations showed that 95% of the students (on average for three academic semesters) indicated the usefulness of this lab session to understand phase behavior of hydrocarbon mixtures.

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