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**A REVIEW ON SOLUBILITY MEASUREMENT IN SUPERCRITICAL  
CONDITION**

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**ABSTRACT**

Supercritical fluid technology (SFT) has been applied in many areas such as petroleum and coal, environmental, material processing, pharmaceutical and food sectors due to its outstanding features. As global environmental issues are much concerned nowadays, SFT is a clean, sustainable and efficient technology to perform extraction, particle formation, purification and fractionation process while leaving no or less organic residues compared to conventional process. In order to apply SFT in processes, solubility data of interest compound in the supercritical fluid plays an important role. Fundamental knowledge of solubility also contributes in optimizing, designing and scaling up the mentioned processes. Although many researchers had done the solubility study for different compounds, yet there is still lacking of review that summarizes the experimental method used to measure solubility concisely. Therefore, this article is produced to review the solubility measurement method and discuss the advantages and disadvantages of each method as well as precautions needed when dealing with various kinds of method.

**Keywords:** *Supercritical fluid technology, solubility, static, dynamic*

**INTRODUCTION**

Supercritical fluid technology has successfully attracted the interest of many researchers lately for replacing the conventional process which uses organic solvent as working fluid. The advantages of using supercritical fluid technology are energy saving, environmental friendly, better efficiency, easily controlled, suitable for heat-labile substance, easy separation of solvent from solute and no or lesser solvent residue left in extract. Thus, it is widely used in many areas including environmental management [1], material and chemical processing [2, 3], food [4-7] and pharmaceutical [5, 8] sectors.

Supercritical fluid technology utilizes the unique properties of supercritical fluid which is pressure dependent dissolving power to alter the process performance. Supercritical fluid offers exclusive behaviour that it possesses dual characteristic of fluid, which is gas and liquid. As for gas, it has low mass transfer resistance and therefore high diffusivity and penetrable; while for liquid, the higher density makes it able to dissolve materials. Besides, low surface tension and low viscosity make supercritical fluid a good solvent to be used over many processes [2].

Among all supercritical fluid available, carbon dioxide is a common fluid used mainly due to inexpensive, safe, available in high purity and its mild properties. Besides, carbon dioxide is a small size molecule with linear structure that offers quick diffusion compared to other solvents. Carbon dioxide as a lipophilic solvent is also able to solubilize nonpolar materials and mix homogeneously with many types of organic solvents. The critical temperature and pressure for carbon dioxide is 31.3 °C and 71.9 bars, these mild conditions and non-toxic behaviour of carbon dioxide have brought up benefits to many food and health related processes.

In order to apply supercritical fluid technology, fundamental knowledge of solubility is useful to control, design and initiate a more efficient and environmental friendly processes. Thus, there is increasing number of studies on the solubility of different compounds in supercritical fluid. Nevertheless, this information is not well summarised. Therefore, this review paper is to discuss the common experimental solubility measurement methods. Some analysis methods and popular correlations used are also remarked briefly in this paper.

## **SOLUBILITY MEASUREMENT METHODOLOGY**

The meaning of solubility in this paper is referred as a measurement of solute molar fraction or mass fraction in supercritical fluid. Some may define it as density of solute in a volume of supercritical fluid. Two main methods to obtain the solubility data are static and dynamic. Luque-Garcia and Luque de Castro included both methods in their extraction experiment and comparison was made [9].

In static method, solute is placed inside the equilibrium cell for a sufficient time to reach equilibrium phase with supercritical fluid. Shaking, recirculation [10], agitation and stirring are additional ways that make more efficient mass transfer between solute and supercritical fluid, thus reduce equilibrium time needed. The amount of solute solubilized is therefore determined by on-line or off-line analysis. Static method however can be subdivided into three categories – analytical, synthetic and gravimetric.

- In analytic method, the equilibrium cell volume is kept constant and solute placed in the cell will be let equilibrated with known amount of supercritical fluid. Then, small amount of equilibrium sample will be withdrawn and analysed. Schematic diagram of analytical method is shown in Fig. 1. Hybertson [11] employed this method to study solubility of interest compounds.
- In synthetic method, the equilibrium cell volume is not kept constant. A mixture of solute and supercritical fluid with known composition is prepared before charged into equilibrium cell. Then the working conditions are adjusted gradually by piston or liquid mercury to cause precipitation. The precipitation is detected visually through sapphire window. Then the composition of coexistence equilibrium phases is recalculated by iterative procedure on physical property such as composition, temperature or pressure which its first derivative undergoes a sharp change when phase transition happens. Through this method, no analysis of sample is required. This method is useful to study phase equilibrium [12], however initial known composition of mixture that will be charged into equilibrium cell is difficult to prepare. In addition, this method is suitable for system which subjects to low and normal pressure. This method application can be seen in Hezave's work [13].
- In gravimetric method, known amount of solute is kept in a small vial inside the high pressure equilibrium cell that contains supercritical fluid. Experiment is run such that solute is remained static in the small vial while the solubilized solute is diffused into the supercritical fluid. Over some time, equilibrium condition is reached and the vial is let to depressurize. The remaining amount of solute in the vial will be measured gravimetrically. The amount of solute solubilized is therefore the difference between final weight and initial weight of solute [14].

Static method is suitable for compound which is expensive because it requires only small amount of solute to be studied. Besides, its setup is simple and phase transition and inversion can be spotted visually. This is important for phase border and critical condition detection. However, static method is not cheap especially when mechanical system is included to aid mixing due to complex installation. It is also slower and not applicable to low solubility solute if compared to dynamic method, and more subject to error due to leakage from valve and fittings. Equilibrium of system may be easily affected when sample is withdrawn due to change in volume, causing precipitation of solute in valves and fittings [15]. It is also difficult to prevent changes in homogeneity and composition of solution when transport for analysis. For synthetic method, visual detection of phase transition may lead to inaccuracy. Many precautions have to be taken when using static method to ensure accurate equilibrium reading. For instance, all parts of apparatus are needed to vacuum so that no air is inside to contaminate. Since only small amount of solute is sampled, the sampling line has to be flushed with solvent and remained in condition similar to system to avoid precipitation.

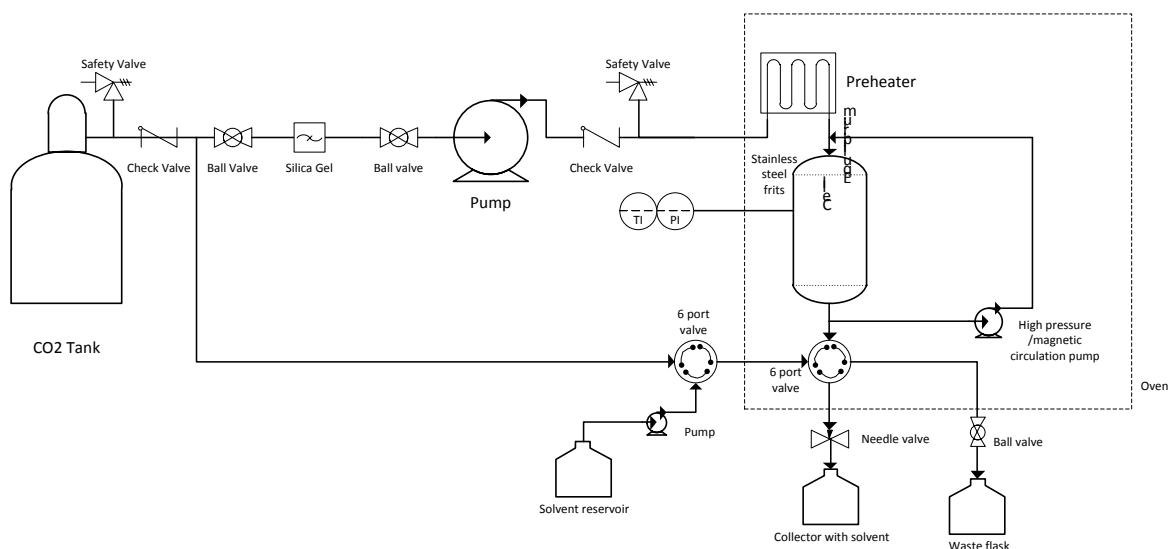


Fig. 1: Schematic diagram of static-analytic method coupled with recirculation loop.

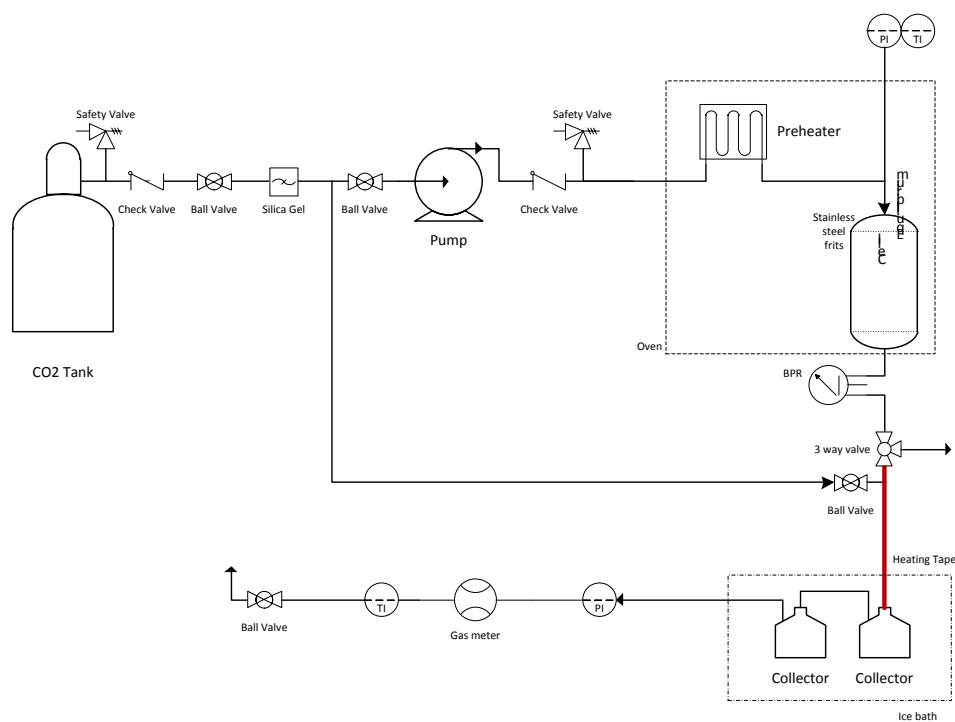


Fig. 2: Schematic diagram of dynamic method.

In dynamic method, the supercritical fluid that continuously pass through the equilibrium cell will leave the system after contact with the solute placed inside the equilibrium cell. Schematic diagram of dynamic method is shown in Fig. 2. The supercritical fluid is allowed to flow in the equilibrium system at low flow rate such that equilibrium condition is assumed to be achievable although adequate contact time may not be given. The outflow supercritical fluid is then extracted and analyzed to measure the solubility of solute. Mixing or recirculation can be incorporated to enhance mass transfer. Dynamic method is useful for unstable compound, reacting system [16] and compound with low solubility. In order to justify the assumption that equilibrium condition is reached, suitable flow rate is determined prior to experiment by trial and error method such that no increment of solubility is detected with variation of flow rate [17, 18]. In addition, length of equilibrium cell may be adjusted from time to time [17]. Dynamic method is relatively easier and faster process compared to static method which requires high skill to handle. In addition, large quantity of data can be processed and apparatus can be assembled easily. However, it requires more amount of solute than static method. Argument is also often raised that equilibrium condition may not achieve when supercritical fluid leaves the system, thus

increase the data error. Besides, phase transition cannot be detected by this method unless sapphire vessel is used, and this actually increases the risk of result error because saturation phase is affected. One should take care some precaution steps such as prevent condensation and clogging at the exit valve and fittings by coating the flow line with heating tape, prevent entrainment of solute from the equilibrium cell by flow of supercritical fluid. This can be done by installing frits and filter at the ends of cell. The amount of solute remained in equilibrium cell should be always checked so that no depletion is occurred. Many researchers [2, 19-23] employed this method for their solubility study due to its straight forward characteristic.

Of many types of method used in solubility measuring, there is no one best method as each serves different advantages and limitations as mentioned. Choosing the right method is dependent on amount and type of compound used, time, range of applicability, purpose of study, cost, and convenience. If a system contains multi component, then analytical method is a good option. However, it is applicable for system that is not near critical region. Synthetic method on the other hand is suitable for phase transition detection. Dynamic method is good to study compound with very low solubility, for example, drug.

## **RESULT ANALYSIS AND CORRELATION**

When solute of interest is solubilized in supercritical fluid after the static or dynamic solubilized method, the fluid is then needed to be analysed to obtain solubility data. Chromatography is a widely used technique, and lately it has been direct incorporated into the experiment system, therefore there is a new measurement method called supercritical fluid chromatography. It is actually a dynamic method comes with two solvent, and the result analysis is completed directly by chromatography after the exit of fluid upon depressurization [16].

Besides the supercritical fluid chromatography, analysis can be mainly divided into two categories, on-line and off-line, which is done after the static or dynamic solubilized method. On-line quantification measures the amount of solute solubilized instantaneously as it exits the reactor. However for off-line measurements, withdrawal and transfer of collected samples is required. In on-line analysis, sample is direct connected to measurement units such as spectrophotometry, refractometry or measure of substance's dielectric constant, continuous densitometry, chromatography and UV monitoring. While in off-line method, these measurement units can also be used for analysis, but sample is prior trapped in a solvent trap. Off-line analysis also involves gravimetric method that weighs the collected sample. On-line method can reduce the precipitation and condensation problem. Nevertheless, off-line method has no problem of response calibration and adjustment.

As the solubility data is obtained, correlation with mathematical model provides convenient extrapolation in different thermodynamic condition. Equation of state and semi empirical model are two types of model widely used in correlating data. Equation of state has theoretical background but parameter information is difficult to obtain, thus predictions and assumptions are needed when dealing with equation of state. Solution model, Peng Robinson equation of state, Soave Redlich Kwong equation of state and Lee Kesler Plocker equation of state are some thermodynamic theoretical correlations that widely used. As for semi empirical model, it is a model that agrees more to experiment condition rather than theories. Some examples of semi empirical models are Mendez Santiago Teja model, Bartle model and Adachi and Lu model.

## **CONCLUSIONS**

Supercritical fluid technology has many outstanding features that serve it as one promising and rapid developed technology. It has realized many clean processes and brings benefits to human beings and environment. Before applying this technology, fundamental knowledge of solubility is first needed so that processes can be optimized and scaled up. A general picture of solubility measurement methodology has been outlined in this paper, which includes static and dynamic method. When experiment is done, result will be analysed either by on-line or off-line quantification method. Then, suitable correlation model is chosen to fit data for extrapolation purpose.

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