

# DESIGN AND OPTIMIZATION OF CONDITIONS FOR PROCESSING WITH SUBCRITICAL WATER

J. W. KING\*<sup>1</sup>, E.C. CLAUSEN<sup>1</sup>, L. DUAN<sup>1</sup>, D.J. CARRIER<sup>2</sup>, and J.M. del VALLE<sup>3</sup>

<sup>1</sup>University of Arkansas, Department of Chemical Engineering, Fayetteville, AR 72701, USA

<sup>2</sup>University of Arkansas, Department of Biological & Agricultural Engineering, Fayetteville, AR

<sup>3</sup>Pontificia Universidad Catolica de Chile, Chemical & Bioprocess Engineering Department

Extraction Laboratory of Biological Material, (LEMaB), Santiago, Chile

jwking1@uark.edu, Fax: 001-479-575-5979

## ABSTRACT

The use of hot compressed water in both its sub- and super-critical regions embraces a range of reduced temperatures ( $T_r$ ) and pressures ( $P_r$ ) depending on the unit processing result that is desired. Solute solubility enhancements in sub-critical water can be estimated a priori by several empirical cubic equations correlating solute solubility with temperature. These include the well known Clifford relationship which predicts solubility enhancements of  $10^2 - 10^6$  or greater depending on the properties of solute moieties being extracted in sub-critical water. We have also utilized solution thermodynamic data such as solute solubility data, Henry Law constants, and partition coefficients in aqueous media at ambient conditions to predict the increase in solubility under sub-critical water conditions. The recent compendium of aqueous solubility data of Yalkowsky and He at ambient conditions can be used with the above relationship and other predictive equations. Fundamental mass transfer data; such solute diffusivities, mass transfer coefficients, and fluid linear velocity should be optimized to achieve high solute flux rates in the case of sub-critical water extraction (SWE). Solute diffusion in sub- $H_2O$  increases over ten-fold relative to ambient diffusivities and similarly,  $k_{pi}$ , the overall mass transfer coefficient increases with temperature in the sub- $H_2O$  region. Experimental data show that an accurate mass balance of all of the components in sub-critical water process requires differential equations formulated to account for the extraction of the target solutes - as well as their conversion (degradation) - as a function of temperature and processing time. Preliminary evidence from degradation rate constants suggests that components in the sample matrix synergistically-interact to reduce loss of the sub-critical water-extracted solutes due to thermally-induced degradation. From a practical perspective, the simultaneous occurrence of both extraction and reaction modes during sub-critical water processing predicts that there is an optimal extraction time to achieve SWE and minimize degradation of the target solutes, unless conversion to another end product is desired. Experiments in the sub- $H_2O$  processing of milk thistle verify this as well as the importance of conducting extractions at the lowest temperature possible and/or optimizing the sub- $H_2O$  velocity through the processing vessel to avoid solute degradation. Hence in the case of SWE, the suppression of the rate constant for solute degradation,  $k_d$ , is opposite for the case of sub-critical water reaction (SWR), where  $k_d$  is optimized or regulated to give a desired product composition.

## INTRODUCTION

To achieve effective processing objectives with pressurized water requires that both thermodynamic and kinetic (mass transfer) parameters be optimized. Operating above the boiling point (bp) of water under modest compression pressure can affect increases  $10^1$ - $10^3$  in the mole fraction of individual solutes relative to their solubility at 20 – 50°C. Although changes in the dielectric constant ( $\epsilon$ ) are often cited to justify this increase in solute solubility, loss in hydrogen-bonding capacity, polarizability, and cohesive energy density more closely reflect the molecular-level changes occurring in water as its temperature is increased above the bp. In this regard, the use of the Hildebrand solubility parameter ( $\delta$ ) concept semi-quantitatively explains the relative solubility propensity of solutes or reactants in sub-critical water as a function of temperature and solute molecular structure. Solubility parameters for water vary from  $23.5 \text{ cal}^{1/2}/\text{cc}^{3/2}$  at ambient conditions to approximately  $7 \text{ cal}^{1/2}/\text{cc}^{3/2}$  at its critical point.

Mass transfer for solutes in sub-critical fluids is also temperature-dependent and can exert a significant influence on extractions or reactions conducted in this medium. A typical diffusion coefficient for a solute in water at 100°C is of the order of  $10^{-6} \text{ cm}^2/\text{sec}$ , and this increases above the boiling point of water. Optimization of the fluid superficial velocity through the extractor/reactor vessel is critical in terms of affecting rapid mass transfer and minimizing degradation of labile solutes when using sub-critical water. Proper adjustment of the fluid velocity and extraction pressure/temperature in the case of sub-critical water extraction is crucial to minimizing solute degradation or inducing reaction conditions for producing a targeted product having desired attributes, e.g., production of flavour precursors.

Integrated processing schemes using both sub- and supercritical fluids are becoming more prevalent in the literature and soon will see actual industrial implementation [1-3]. Such processes will involve both the use of SC-CO<sub>2</sub> and water in its sub- and supercritical fluid state [4-5]. The interaction between solutes (reactants) and sub-critical water is more poorly understood, since as shown in Figures 1a and 1b, the range of processing conditions covers quite a large regime of pressure and temperature.

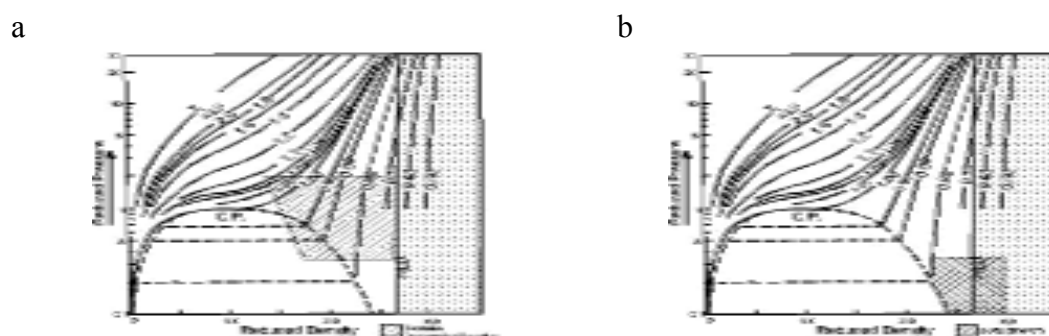


Fig.1. Reduced state conditions for bio-based reactions (a) and extraction of natural products (b) with sub-critical water.

## MATERIALS AND METHODS

### Apparatus and procedures

The reported experimental data for the extraction of silymarin flavonolignans (Figure 2) from milk thistle seeds is reported in thesis of Duan [6]. Seeds obtained from Frontier Herbs (Norway, IA) were extracted both dynamically and in a batch apparatus using Milli-Q purified water. Taxifolin and silymarin and silybinin as well as silychristin and silydinin were obtained from Extrasynthese (Lyon, France), Sigma Chemical (St. Louis, MO), and Phytolab, Hamburg, Germany), respectively. Their structures are shown below.

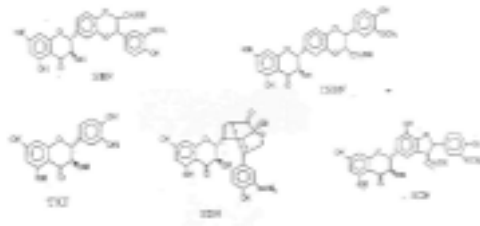


Fig. 2. Structures of silymarin flavonolignans in milk thistle (SBN = Silybinin A; ISBM = Isosilybinin or Silybinin B; TXF = Taxifolin; SDN = Silydanin; SCN = Silychristin).

For the reported studies, a high pressure stirred reactor vessel from Parr Instruments (Moline, IL) was utilized and pressure applied via  $N_2$  and a gas inlet tube. Samples were drawn off using a take a tube immersed to the bottom of pressurized vessel. Analysis of the silymarin flavonolignans was done by HPLC as described by Duan [6]. Several conventional extraction methods were used to determine the initial content of the silymarin flavonolignans, including Soxhlet extraction of the ground seeds. Further experimental protocol and be found in the thesis of Duan [6].

### Calculations

Solubility parameter calculations for water as a function of temperature and pressure were done using the equation of Giddings, et al. [7] and the reduced state correlations provided by Lydersen, Greenkorn, and Hougen [8]. Solute solubility parameters were computed using the group contribution method of Fedors [9] or taken from the Barton compendium [10]. Three methods were used to estimate binary diffusion coefficients. These included the method of Wilke and Chang, the correlation of Hayduk and Minhas, and Nakanishi's method as noted in Reid, et al. [11]. Such correlations can be separated into a term that is temperature dependent (which also includes the fluid's viscosity) and one that is solute-dependent and independent of temperature. Using such an approach, it is possible to correlate the calculated diffusion coefficient data from a reference value at 25°C and atmospheric pressure with temperature, which allows a predictive correlation between a solute's diffusion coefficient in water and temperature to be established. Solute molar volume data were calculated by using the well known method of LeBas [11].

Viscosity data for water were taken from the literature and as a function of temperature and appropriate values interpolated over a range of temperatures (10 – 100°C, 120 – 180°C). Then the method of Lucas was then used to test the effect of pressure on the viscosity of water up to 20 atm. – the results indicating that pressure has a negligible effect on the binary diffusion coefficients.

## RESULTS AND DISCUSSION

The solubility parameter for water as a function of temperature is shown in Figure 3. The calculated value at room temperature using the approach discussed in the last section is consistent with reported values [10]. There is a monotonic decrease from 50 to 250°C in which water's cohesive energy density matches that of very polar organic solvents and solutes. For example, the solubility parameters of polar solutes exhibiting high water solubility as a function of temperature, such as glucose, gallic acid, quercetin, and catechin, range in value from 16.7 – 22.4 cal<sup>1/2</sup>/cc<sup>3/2</sup>. Silybinin, a compound which we will discuss shortly, has a solubility parameter of 16.7 cal<sup>1/2</sup>/cc<sup>3/2</sup>, a value consistent with its extraction using hot compressed water. Water at 325°C experiences a rapid decrease in solubility parameter with temperature and at 325°C has a solubility parameter equivalent to that of naphthalene (10.8) – indeed at this temperature naphthalene is mutually miscible with water. At the critical point, water has a solubility equivalent to a hydrocarbon solvent such as hexane.

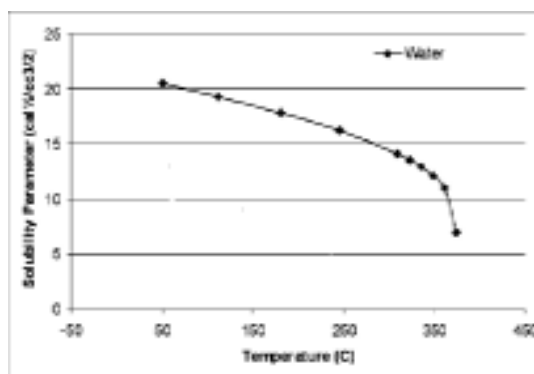


Fig 3. Solubility parameter of water as a function of temperature.

Diffusion coefficients ( $D_{AB}$ ) increase with temperature as is evident in Figure 4 below. Depending on the predictive equation used, this increase relative to their  $D_{AB}$  at 25°C indicates approximately a ten-fold increase, and in the case of values obtained utilizing the temperature dependence given in reference [11] (top curve), over a thirty-fold increase depending on the nature of the fluid/solvent system.

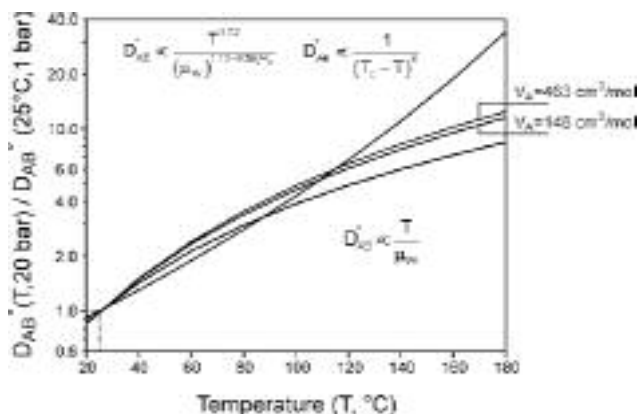


Fig. 4. Variation in the solute  $D_{AB}$  with temperature in water.

With respect to the extraction of natural products with sub-critical water, recent research on the silymarin flavonolignans provides a model system in which to study the effect of extraction parameters and their optimization. Based on HPLC analysis of samples taken during the extraction of the above moieties, thermodynamic distribution coefficients,  $m_i$ , have been calculated and are presented in Table 1. In going from an extraction temperature of 90, 100, and 120°C down in Table 1, it is apparent that the extraction of silychristin (SC), silydianin (SD), silybinin (SA), and silybinin (SB) all increase from milk thistle matrix at a mass ratio of water/grams of seed = 100. This is consistent with the increased solubility of organic compounds in water with an increase in temperature, and the recent data reported by Bai et al. [12] for silybin in aqueous solution.

Table 1. Distribution coefficients ( $m_i$ ) and degradation rate constants ( $K_{Di} \times 10^2 \text{ }^{-1} \text{ min}$ ) for silymarin flavonolignans milk thistle at 90, 100, 120°C.

$K_{Di}$	$K_{Di}$	$K_{Di}$	$K_{Di}$	$m_i$	$m_i$	$m_i$	$m_i$
SC	SD	SA	SB	SC	SD	SA	SB
0.43	0.57	0.42	0.55	0.0294	0.0333	0.0125	0.0147
0.53	0.78	0.76	0.75	0.0481	0.0477	0.0191	0.0225
0.81	1.17	1.20	1.23	0.0667	0.0714	0.0357	0.0526

Similarly, the variation in the degradation rate constant ( $K_{Di}$ ) for the above four compounds as a function of temperature over the same range also increases, indicating a susceptibility to thermal degradation of these compounds with increasing temperature. This would indicate that a successful extraction of these compounds with sub-critical water should be optimized with respect to operating temperature, time that the solute spends in the extraction vessel, and flow rate of the sub-critical water through the extraction vessel. Hence, from Figure 4 the increase in  $D_{AB}$  for silybinin would be to  $6.4 \times 10^{-6} \text{ cm/sec}^2$  or  $1.72 \times 10^{-6} \text{ cm/sec}^2$  depending on which equation is used to calculate the  $D_{AB}$  as a function of temperature. This increase in silybinin's  $D_{AB}$  suggests that extraction efficiency can be maintained while minimizing compound degradation as the extraction temperature is increased by increasing the flow rate of sub-critical water through the extraction vessel. Experiments to confirm this possibility are currently being conducted and will be reported at a later date.

Figure 5 shows the results a comparison of experimental with modeling data for the extraction (and reaction) of silydianin from milk thistle using sub-critical water at 100°C as a function of residence time in the vessel. The drop in SD concentration in the solid phase (milk thistle seeds) as a function of processing time indicates effective extraction over approximately 3 hours (180 min); approximately 92% SD can be extracted. However measurement of the liquid phase concentrations of SD in sub-critical water as a function of processing time indicates an increasing concentration up to about 75 minutes. After this period, SD concentration decreases with further processing time which is commensurate with compound degradation under these extraction conditions. Hence extraction times beyond 75 minutes maybe deleterious to the recovery of SD when using sub-critical water under the stated conditions. Note that at 75 minutes of processing time approximately 80% of the SD is

extracted. One possible option to facilitate increased extraction of the SD at 100° C while minimizing its degradation is by increasing the flow of sub-critical water through the extraction vessel.

The modeling curves shown in Figure 5 were calculated from the differential mass balance equations governing the concentrations of SD in the liquid and solid phases, respectively [6]. From Figure 5 it is apparent that the model equations represent the physical situation occurring in the extraction vessel fairly well. These differ slightly for the individual silymarin flavonolignans, mainly with respect to where the maximum concentration in the liquid phase occurs for each of the individual silymarin flavonolignans. More will be noted on this factor later in this section.

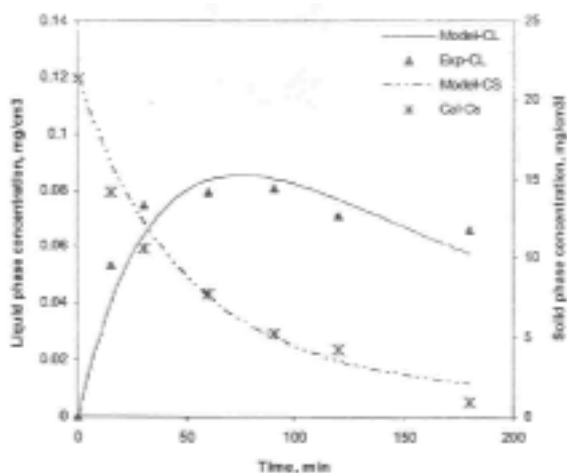


Fig. 5. A comparison of experimental and modeling data for silydianin extraction at 100°C.

Overall experimental mass transfer coefficients,  $k_{pi}$ , for the individual silymarin flavonolignans were also obtained from simulations on the model system, using MATLAB 6.5. An AARD criterion was applied to choose the acceptable values. The values for the individual silymarin flavonolignans are of the same order of magnitude, the  $k_{pi}$  of silybinin B always being larger than those for the other compounds. The  $k_{pi}$ 's for all of the silymarin flavonolignans increase with temperature, verifying the combined effects of enhanced solubility and increased diffusion of the solutes as temperature is increased. The experimental mass transfer coefficients were found to be consistently higher than the estimated  $k_{pi}$ 's. Estimated mass transfer coefficients are also within an order of magnitude for the individual silymarin flavonolignans and of similar magnitude to the experimental values. The Biot number in this case is much greater than unity (~200) indicating the dominance of internal mass transfer in the extraction process. This suggests perhaps an uneven distribution of the silymarin flavonolignans within the milk thistle matrix.

Additional modeling simulation studies were conducted at various experimental conditions for each of the silymarin flavonolignans. One set of results (110°C, 4 atm, 150 rpm, particle size 0.4 mm) is shown in Figure 6 below. Using the reported thermodynamic distribution coefficients and degradation rate constants for the silymarin flavonolignans under these conditions permits the rates of extraction and reaction (degradation) for each individual compound to be estimated. The pronounced apex for SD is a result of its higher concentration in the milk thistle seed – all of the silymarin flavonolignans have a maximum in their liquid

phase concentration curves with respect to time. These maxima all occur within approximately ten minutes of each other which is not surprising considering the similarity in their molecular structures. This fact also facilitates optimizing the processing conditions for the entire extraction.

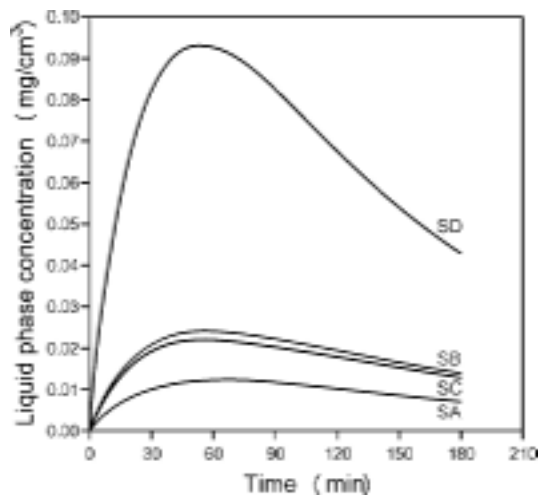


Fig. 6. Modeling results for extraction and degradation of milk thistle components.

Finally the effect of knowing the recovery of silymarin flavonolignan as a function of the amount of solvent relative to mass of seeds,  $F$ , being extracted is of some importance in terms of minimizing excess extraction solvent or time, and dilution of the recovered product. Simulation using the model equations and different values for  $F$  at the conditions noted yielded the curves shown in Figure 7 for  $F$  equal to 10, 50, 100, and 200, respectively. The modeling results indicate that by using a larger amount of sub-critical water with respect to seed mass, a higher recovery of the target solute is achieved, but at the expense of a lower concentration of the solute in water. This is important in terms of optimizing the trade off between the amount of solvent used and the dilution of the desired end-product, and the need to apply a post-extraction technique to concentrate the resultant extract.

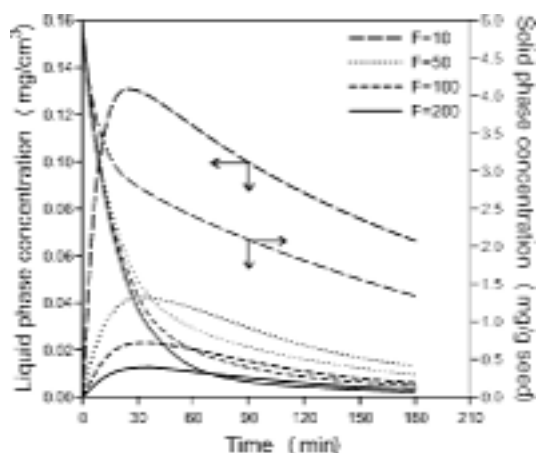


Fig. 7. Modeling results for the extraction of silybinin B with water at 120°C for various  $F$ .

## CONCLUSIONS

In this study key parameters such as solute solubility, diffusion coefficients, fluid solubility parameter, and mass transfer coefficients have been determined which should aid in the design of an optimal chemical process. Experimental data associated with the sub-critical water extraction of silymarin flavonolignans from milk thistle have been determined, modeled and the extraction or reaction process simulated, to yield an overall model applicable for the use of sub-critical water as a processing agent. The use of this approach should lead to more effective use of sub-critical water as a processing solvent and its integration into an environmentally-benign processing platform.

## REFERENCES:

- [1] KING, J., Coupled processing options for agricultural materials using supercritical carbon dioxide, A. Gopalan, C. Wai, and H. Jacobs (eds), *Supercritical Carbon Dioxide: Separations and Processes*, **2003**, American Chemical Society, Washington, DC, p. 104.
- [2] KING, J., Critical fluid technology for the processing of lipid-related natural products, *Compt. Rendus Chimie*, **2004**, 7, p. 647.
- [3] SETIANO, W., SMITH, R., IOMATA, H., ARAI, K., Processing of cashew nut (*Anacardium occidentale L.*) and cashew nut shell liquid with supercritical carbon dioxide and water, *Proceedings of the 6<sup>th</sup> International Symposium on Supercritical Fluids – Tome 1*, **2003**, Versailles, France, , p. 41.
- [4] DEL VALLE, J., ROGALINSKI, T., ZETZL, C., BRUNNER, G., Extraction of *boldo* (*peumus boldus M.*) leaves with supercritical CO<sub>2</sub> and hot pressurized water, *Food Res. Int.*, **2005**, 38, p. 203.
- [5] LANG, Q., WAI, C., Supercritical fluid extraction in herbal and natural product studies - a practical review. *Talanta*, **2001**, 53, p. 771.
- [6] DUAN, L., *Extraction of silymarins from milk thistle, silybum marianum, using hot water as solvent*, **2005**, Ph. D. Thesis, University of Arkansas.
- [7] GIDDINGS, J., MYERS, M., MACLAREN, M., KELLER, R., High pressure gas chromatography of non-volatile species, *Science*, **1968**, 162, p. 67.
- [8] LYDERSEN, A., GREENKORN, R., HOUGEN, O., *Generalized Thermodynamic Properties of Pure Fluids*, University of Wisconsin Engineering Experimental Station, Madison, WI, **1955**, Report No. 4.
- [9] FEDORS, R., A method for estimating both the solubility parameters and molar volumes of liquids, *Polym Eng. Sci.*, **1974**, 14, p. 147.
- [10] BARTON, A., *CRC Handbook of Solubility Parameters and Other Cohesional Parameters*, 1991, CRC Press, Boca Raton, FL.
- [11] REID, R., PRAUSNITZ, J., POLING, B., *The Properties of Gases and Liquids-4<sup>th</sup> Ed.*, **1987**, McGraw-Hill, New York., NY.
- [12] BAI, T. YAN, G., ZHANG, H., HU, J., Solubility of silybin in aqueous dextran solutions, *J. Chem. Eng. Data*, **2005**, 50, p. 1596.