

# Solubility and phase diagram investigation of the ternary system LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O at 323.15 K and 348.15 K

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## ABSTRACT

The solubility of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system along with its sub-binary systems LiCl–H<sub>2</sub>O and SrCl<sub>2</sub>–H<sub>2</sub>O at 323.15 K and 348.15 K has been measured via the Isothermal Dissolve Equilibrium (IDE) method. The gauged solubility for the LiCl–H<sub>2</sub>O and SrCl<sub>2</sub>–H<sub>2</sub>O binary systems is consistent with the result reported in literature. In view of the measured solubility and corresponding liquid–solid line results for the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 323.15 K, exist four equilibrium solid phases, i.e. LiCl·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O, SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O, and four corresponding independent crystallization regions for these solid phases, three invariant points E<sub>1</sub>, E<sub>2</sub>, E<sub>3</sub> for LiCl·H<sub>2</sub>O and SrCl<sub>2</sub>·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O, SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O, respectively. For the solubility of this ternary system at 348.15 K, there are only three equilibrium solid phases, i.e. LiCl·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O, accordingly two invariant points, E<sub>1</sub> for LiCl·H<sub>2</sub>O and SrCl<sub>2</sub>·H<sub>2</sub>O and E<sub>2</sub> for SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O. No existence of SrCl<sub>2</sub>·6H<sub>2</sub>O solid phase in this ternary system at 348.15 K. The comparison of the phase diagram at 323.15 K and 348.15 K indicates that, with the increase of temperature, the crystallization region of SrCl<sub>2</sub>·6H<sub>2</sub>O disappeared, however crystallization region of SrCl<sub>2</sub>·H<sub>2</sub>O became larger obviously.

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## 1. Introduction

Oil field brines in Nanyishan area of Qinghai-Tibet Plateau, China are connate waters found during deep rock penetration by the drill and rich in lithium, strontium, and calcium chloride [1]. The lithium and strontium concentrations of the brines could be up to 323.00 and 597.00 mg·L<sup>-1</sup> [2], separately. As sub-ternary systems of oil field brines, the solubility of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system, at relative wide temperature range, is of great importance for the extracting process of the lithium and strontium resources from oil field brines. The multi-temperature phase diagram can indicate the separation pathway of the pure LiCl or SrCl<sub>2</sub> hydrated salts. Furthermore, it is also a necessary guidance of the technological design of salt pans to extract valuable resources from Nanyishan oil field brine. The solubility of the binary LiCl–H<sub>2</sub>O [3] and SrCl<sub>2</sub>–H<sub>2</sub>O [4–6] systems at 323.15 K and 348.15 K and the ternary LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 273.15 K [7], 298.15 K [8,9], 308 K [10], 313 K [8] has been reported already. In our previous work [1], the thermodynamic properties of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system

at 298.15 K has been investigated, including the measurement of water activity with isopiestic method and solubility evaluation with Extended Pitzer model [11] and Pitzer-Simonson-Clegg (PSC) model [12–14].

Up to now, still no relevant research is launched in terms of the solubility of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at relative high temperature, such as 323.15 K and 348.15 K. In this work, employing the Isothermal Dissolve Equilibrium (IDE) method, the solubility of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at 323.15 K and 348.15 K is determined. The results indicate that the equilibrated solid phase at 323.15 K are LiCl·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O, SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O. However, when the temperature is up to 348.15 K, the crystallization region of SrCl<sub>2</sub>·6H<sub>2</sub>O disappeared, and relatively the crystallization region SrCl<sub>2</sub>·H<sub>2</sub>O became larger obviously, the solid phases are LiCl·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O.

## 2. Experimental sections

### 2.1. Materials

All chemical reagents used in the experiment are shown in Table 1, including the sources of compounds, purification method, final purity, etc. Further detailed information is given as follows.

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**Table 1**  
Chemical reagents used in the experiment.<sup>a</sup>

Reagents	CAS Reg. No.	Grade	Sources	Purification method	Final mass fraction purity	Impurity analysis method
Li <sub>2</sub> CO <sub>3</sub>	554-13-2	A. R.	Shanghai China-Lithium Industry Co., Ltd.	Recrystallization	0.9990	ICP
HCl	2647-01-0	G. R.	Beijing Chemical Works	—	0.9998	—
LiCl·H <sub>2</sub> O	16712-20-2	—	Prepared in this work	Recrystallization	0.9997	ICP
SrCl <sub>2</sub> ·6H <sub>2</sub> O	10025-70-4	G. R.	Shanghai McLean biochemical Technology Co., Ltd.	Recrystallization	0.9990	ICP
AgNO <sub>3</sub>	7761-88-8	A. R.	Sinopharm Chemical Reagent Co., Ltd.	—	0.9980	ICP
EDTA	139-33-3	A. R.	Tianjin Kermel Chemical Reagent Co., Ltd.	—	0.9900	—

<sup>a</sup> The final impurity of the chemical Reagents is determined in this work, and the purity basis is mass.**Table 2**  
Solubility data for LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at  $T = 323.15$  K and 0.1 MPa<sup>a</sup>.

No.	Solution composition					Wet solid composition			Solid phase <sup>b</sup>
	$m/\text{mol} \cdot \text{kg}^{-1}$		100w			100w			
	$m_{\text{LiCl}}$	$m_{\text{SrCl}_2}$	$w_{\text{LiCl}}$	$w_{\text{H}_2\text{O}}$	$w_{\text{SrCl}_2}$	$w_{\text{LiCl}}$	$w_{\text{H}_2\text{O}}$	$w_{\text{SrCl}_2}$	
1	22.07	0	48.34	51.66	0				L
2, E <sub>1a</sub>	20.08	0.08	45.68	53.68	0.65	26.41	32.82	40.77	L + Sr1
3, E <sub>1b</sub>	19.93	0.07	45.51	53.86	0.63	31.88	33.31	34.81	L + Sr1
4	18.97	0.07	44.28	55.08	0.64	30.57	41.29	28.14	Sr1
5, E <sub>2a</sub>	18.80	0.08	44.05	55.27	0.68	28.24	40.59	31.17	Sr1 + Sr2
6, E <sub>2b</sub>	18.80	0.08	44.03	55.25	0.72	27.26	40.61	32.13	Sr1 + Sr2
7	16.46	0.22	40.27	57.71	2.02	23.31	41.29	35.40	Sr2
8	12.71	0.56	33.11	61.47	5.42	17.26	40.84	41.90	Sr2
9	10.67	1.03	28.01	61.93	10.06	12.81	38.70	48.49	Sr2
10	9.22	1.40	24.24	62.04	13.72				Sr2
11	7.73	1.81	20.29	61.94	17.77				Sr2
12, E <sub>3a</sub>	5.29	2.50	13.84	61.68	24.48	8.27	50.07	41.66	Sr2 + Sr6
13, E <sub>3b</sub>	5.29	2.51	13.81	61.64	24.55	6.82	40.44	52.74	Sr2 + Sr6
14	4.33	2.83	11.23	61.25	27.52	5.62	50.51	43.87	Sr6
15	2.66	3.45	6.80	60.25	32.95	3.49	50.39	46.12	Sr6
16	1.37	4.01	3.42	59.02	37.56				Sr6
17	0	4.59	0	57.91	42.09				Sr6

<sup>a</sup>  $m$ , molality, moles per kilogram of solvent (pure water). The uncertainty of temperature and pressure are  $u(T) = 0.1$  K,  $u(p) = 0.1$ ; the relative standard uncertainty of molality and mass fraction are  $u_r(m) = 0.03$ ,  $u_r(w) = 0.03$ , respectively.<sup>b</sup> L = LiCl·H<sub>2</sub>O, Sr1 = SrCl<sub>2</sub>·H<sub>2</sub>O, Sr2 = SrCl<sub>2</sub>·2H<sub>2</sub>O, Sr6 = SrCl<sub>2</sub>·6H<sub>2</sub>O.**Table 3**  
Solubility data for LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at  $T = 348.15$  K and 0.1 MPa<sup>a</sup>.

No.	Solution composition					Wet solid composition			Solid phase
	$m/\text{mol} \cdot \text{kg}^{-1}$		100w			100w			
	$m_{\text{LiCl}}$	$m_{\text{SrCl}_2}$	$w_{\text{LiCl}}$	$w_{\text{H}_2\text{O}}$	$w_{\text{SrCl}_2}$	$w_{\text{LiCl}}$	$w_{\text{H}_2\text{O}}$	$w_{\text{SrCl}_2}$	
1	25.64	0	52.08	47.92	0				L
2, E <sub>1a</sub>	25.11	0.15	50.99	47.91	1.10	50.54	39.02	10.44	L + Sr1
3, E <sub>1b</sub>	24.63	0.15	50.48	48.35	1.17	37.74	33.24	29.02	L + Sr1
4	22.52	0.14	48.28	50.57	1.15	28.63	33.80	37.57	Sr1
5	19.25	0.22	44.10	54.03	1.87	22.55	32.67	44.78	Sr1
6	18.38	0.24	42.86	55.01	2.13				Sr1
7	14.62	0.53	36.37	58.67	4.96				Sr1
8	13.40	0.76	33.65	59.24	7.11				Sr1
9	12.36	0.93	31.34	59.83	8.83	13.38	36.56	50.06	Sr1
10, E <sub>2</sub>	12.29	0.94	31.19	59.88	8.93	17.18	38.7	44.12	Sr1 + Sr2
11	11.61	1.06	29.66	60.26	10.08				Sr2
12	10.83	1.24	27.72	60.4	11.88	11.26	37.83	50.91	Sr2
13	9.28	1.67	23.74	60.33	15.93	9.75	36.35	53.90	Sr2
14	6.30	2.74	15.68	58.76	25.56	7.28	37.05	55.67	Sr2
15	3.49	3.77	8.48	57.29	34.23	4.50	38.77	56.73	Sr2
16	1.21	4.98	2.78	54.34	42.88	1.48	33.94	64.58	Sr2
17	0	5.76	0	52.27	47.73				Sr2

<sup>b</sup> L = LiCl·H<sub>2</sub>O, Sr1 = SrCl<sub>2</sub>·H<sub>2</sub>O, Sr2 = SrCl<sub>2</sub>·2H<sub>2</sub>O.<sup>a</sup>  $m$ , molality, moles per kilogram of solvent (pure water). The uncertainty of temperature and pressure are  $u(T) = 0.1$  K,  $u(p) = 0.1$ ; the relative standard uncertainty of molality and mass fraction are  $u_r(m) = 0.03$ ,  $u_r(w) = 0.03$ , respectively.

Water purified by deionization followed by double distillation (once with trace KMnO<sub>4</sub>) with a conductance less than  $1.5 \times 10^{-4} \text{ S} \cdot \text{m}^{-1}$  was used for all sample purifications, preparations,

and dilutions in the experiment. LiCl·H<sub>2</sub>O was prepared by neutralizing Li<sub>2</sub>CO<sub>3</sub> (Shanghai China-Lithium Industry Co., Ltd., purity by mass fraction > 0.999) with HCl (Beijing Chemical Works, G. R.), then

**Table 4**

The measured solubility of the binary systems and their comparison with the experimental data reported in literature.<sup>a</sup>

system	T/K	Solubility		equilibrium solid phase	ref
		$m/\text{mol} \cdot \text{kg}^{-1}$	w%		
LiCl–H <sub>2</sub> O	323.15	22.05	48.30	LiCl·H <sub>2</sub> O	[3]
		22.07	48.34	LiCl·H <sub>2</sub> O	This work
	348.15	25.64	52.08	LiCl·H <sub>2</sub> O	This work
SrCl <sub>2</sub> –H <sub>2</sub> O	323.15	4.61	42.30	SrCl <sub>2</sub> ·6H <sub>2</sub> O	[4]
		4.60	42.20	SrCl <sub>2</sub> ·6H <sub>2</sub> O	[5]
		4.59	42.09	SrCl <sub>2</sub> ·6H <sub>2</sub> O	This work
	348.15	5.72	47.40	SrCl <sub>2</sub> ·2H <sub>2</sub> O	[4]
		5.76	47.75	SrCl <sub>2</sub> ·2H <sub>2</sub> O	[6]
		5.76	47.73	SrCl <sub>2</sub> ·2H <sub>2</sub> O	This work

*m*, molality, moles per kilogram of solvent (pure water). For the solubility data measured in this work, the uncertainty of temperature and pressure are  $u(T) = 0.1$  K,  $u(p) = 0.1$ ; the relative standard uncertainty of molality and mass fraction are  $u_r(m) = 0.03$ ,  $u_r(w) = 0.03$ , respectively.

crystallization and recrystallization two times, and the final purity of the LiCl·H<sub>2</sub>O by mass fraction is higher than 0.9997. The SrCl<sub>2</sub>·6H<sub>2</sub>O (Shanghai McLean biochemical Technology Co., Ltd.) was purified by double recrystallization, and the contents of each main impurity element were detected to be less than 0.01%. Ethylenediamine tetraacetic acid disodium salt (Tianjin Kermel Chemical Reagent Co., Ltd., A. R.) and silver nitrate (Sinopharm Chemical Reagent Co., Ltd., A. R.) were utilized for chemical analysis. The impurities of these salts were detected by ICP-AES (ICAP 6500 DUO, Thermo Scientific).

## 2.2. Apparatus and experimental procedures

### 2.2.1. Apparatus

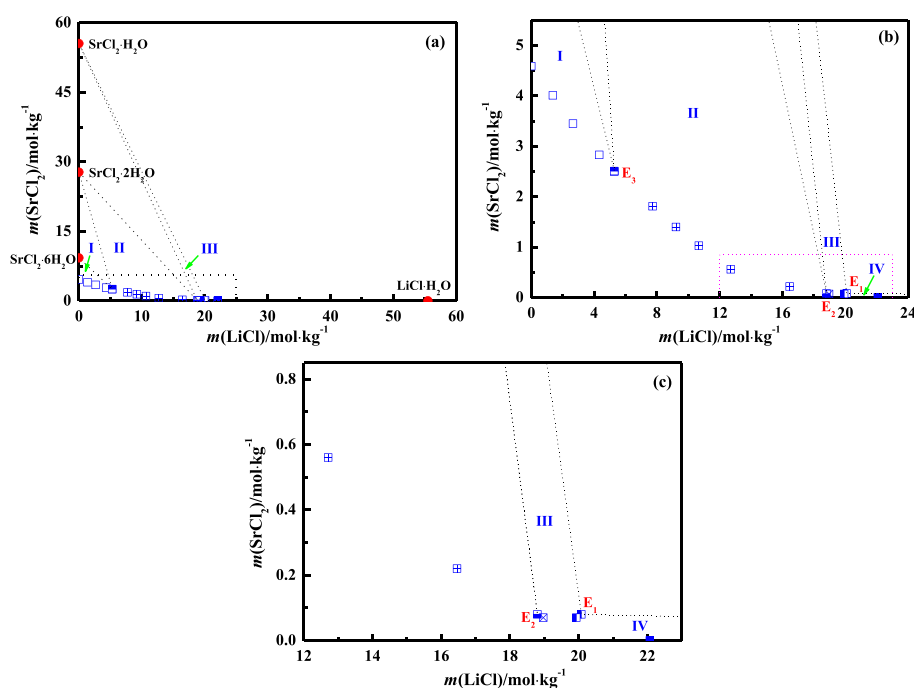
The solubility isothermal measurement apparatus used in this work are the same with that reported in literature [15,16]. The

thermostatic bath (DZKW-S-4, Beijing Ever Light Medical Equipment Co., Ltd.) with a temperature stability of  $\pm 0.1$  K was used, also a standard analytical balance (TB-114, Beijing Sartorius Instrument System Co., Ltd.) with 110 g capacity and 0.1 mg readability was adopted for weighing. Additionally, a multisite magnetic stirrer (84-1 A, Shanghai Si Le Instrument Co., Ltd.), was employed to stir the samples in the cylindrical glass bottle as well as an electro-thermal blowing dry oven (101-QABS, Shanghai boxun Industrial Co., Ltd.) and circular water vacuum pump (SHB-III, Zhengzhou Great Wall Science and Trade Co., Ltd.) were served for liquid and solid separation in the salt crystallization and recrystallization process.

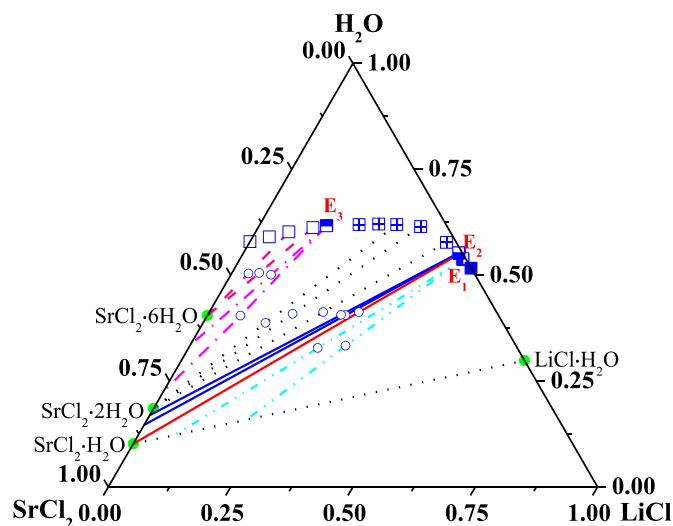
### 2.2.2. Analysis method

The compositions of the liquid phases and their corresponding wet solid phases were analyzed as following. The Cl<sup>−</sup> concentration of the pure and mixture solutions was determined by gravimetric method [17] with AgNO<sub>3</sub> as precipitant agent, and the uncertainty can be controlled within 0.05%.

The Sr<sup>2+</sup> concentration was determined by mass titration instead of volumetric method, as detailed in our previous work [18]. As the name implied, the mass titration method count the consumed titration by mass, instead of volume, to avoid the deviation during the volume recording of the beginning and ending of the titration. The Sr<sup>2+</sup> concentration in pure SrCl<sub>2</sub> solution was determined by EDTA complexometric titration at pH 9.5–10 with ammonia as buffer agent, Eriochrome black T as the indicator, and 3 mL of Mg-EDTA [19,20] as auxiliary indicator. For the SrCl<sub>2</sub> and LiCl mixture solutions, the Sr<sup>2+</sup> concentration was determined by eliminating the interference of Li<sup>+</sup> through adding different amounts of mixed alcohol [21] which is composed of n-butyl alcohol and anhydrous ethanol following volume ratio of 1:9. The Li<sup>+</sup> ion concentration was determined by the subtraction method. The relative uncertainty of the measurement could be controlled below 0.2%.



**Fig. 1.** Measured solubility of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at  $T = 323.15$  K. (b) is local enlarged of (a); (c) is local enlarged of (b). Symbols are the experiment points:  $\square$ , SrCl<sub>2</sub>·6H<sub>2</sub>O;  $\blacksquare$ , E<sub>3</sub>, SrCl<sub>2</sub>·6H<sub>2</sub>O + SrCl<sub>2</sub>·2H<sub>2</sub>O;  $\boxplus$ , SrCl<sub>2</sub>·2H<sub>2</sub>O;  $\boxdot$ , E<sub>2</sub>, SrCl<sub>2</sub>·2H<sub>2</sub>O + SrCl<sub>2</sub>·H<sub>2</sub>O;  $\boxtriangle$ , SrCl<sub>2</sub>·H<sub>2</sub>O;  $\circ$ , E<sub>1</sub>, SrCl<sub>2</sub>·H<sub>2</sub>O + LiCl·H<sub>2</sub>O;  $\diamond$ , LiCl·H<sub>2</sub>O; I, II, III and IV present the crystal regions of different solid phases: I, SrCl<sub>2</sub>·6H<sub>2</sub>O; II, SrCl<sub>2</sub>·2H<sub>2</sub>O; III, SrCl<sub>2</sub>·H<sub>2</sub>O; IV, LiCl·H<sub>2</sub>O.



**Fig. 2.** The measured wet solid compositions and corresponding liquid-solid lines for the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at  $T = 323.15$  K. Symbols are the experiment points:  $\square$ , SrCl<sub>2</sub>·6H<sub>2</sub>O;  $\blacksquare$ , SrCl<sub>2</sub>·6H<sub>2</sub>O + SrCl<sub>2</sub>·2H<sub>2</sub>O;  $\boxplus$ , SrCl<sub>2</sub>·2H<sub>2</sub>O;  $\boxminus$ , SrCl<sub>2</sub>·2H<sub>2</sub>O + SrCl<sub>2</sub>·H<sub>2</sub>O;  $\boxtimes$ , SrCl<sub>2</sub>·H<sub>2</sub>O;  $\blacksquare$ , LiCl·H<sub>2</sub>O;  $\circ$ , wet solid point; --- (red dash line), corresponding liquid-solid line for SrCl<sub>2</sub>·6H<sub>2</sub>O; -·- (pink dash dotted line), corresponding liquid-solid lines for co-saturated points of E<sub>3</sub> (experiment No. 12 E<sub>3a</sub> and No. 13 E<sub>3b</sub>); ... (dotted line), corresponding liquid-solid line for SrCl<sub>2</sub>·2H<sub>2</sub>O; - - (cyan dash dot line), corresponding liquid-solid line for E<sub>1</sub> (experiment No. 2 E<sub>1a</sub> and No. 3 E<sub>1b</sub> in Table 2).

### 2.2.3. Experimental procedures

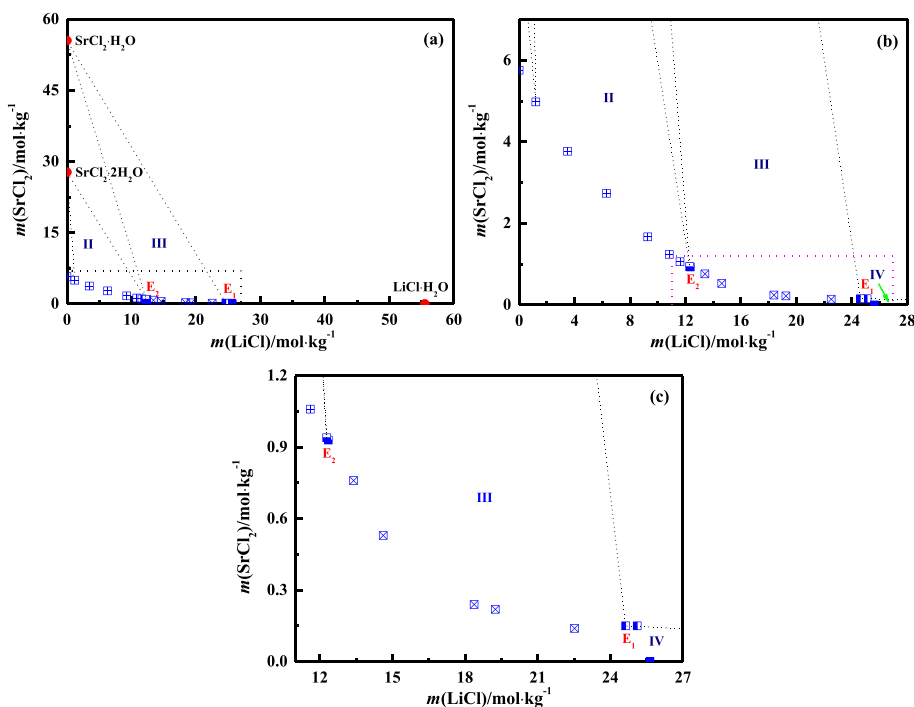
The solid-liquid equilibrium experiments were carried out by adding a second salt into the invariant points of the binary system

in a 270 mL cylindrical glass bottle immersed in a glycerin-water bath. The solution and solid in the glass bottle were stirred by a magnetic stirrer placed under the thermostat bath. Each sample in equilibrium with solids was stirred at a certain constant temperature for 7–9 days and then kept static for approximately 24 h. A certain amount of liquid was extracted through a G4 sand-core filter tube connected to a 50 mL syringe under sealing and then transported to a vacuum tube, cooled, weighed, diluted. Finally, the concentration of the diluted solution was analyzed with the method described above. The rest of the solid and solution were stirred continuously for two more days, after which another liquid sample was removed for analysis. When the relative deviation between two consecutive samples was less than 1%, the results for the latter sample were taken as the solubility. The wet solid phase was quickly transferred by glass colander into a weighed 20 mL glass-stoppered weighing bottle and then its concentrations were analyzed. The solid phase types were determined by Schreinemakers's method. The next group of equilibrium experiments was started by adding a small amount of salt or water to the remainder of the mixture of the solid and solution.

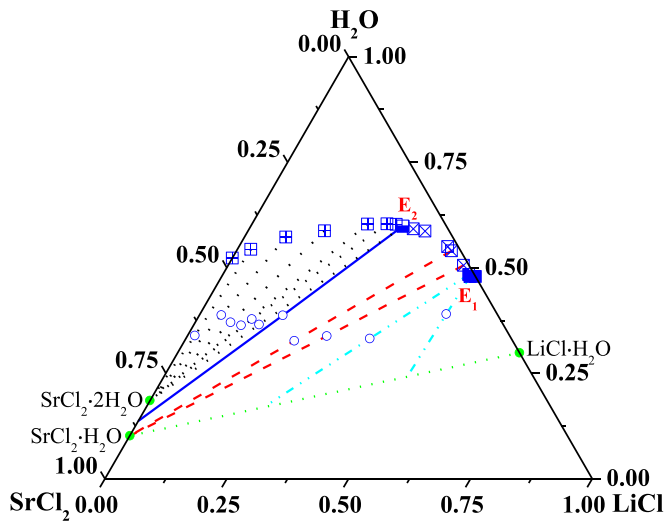
## 3. Results and discussions

### 3.1. Results

The solubility, corresponding wet solid compositions and solid phases for the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system and its sub-binary LiCl–H<sub>2</sub>O and SrCl<sub>2</sub>–H<sub>2</sub>O systems at 323.15 K and 348.15 K, measured with isothermal method, are tabulated in Table 2 and Table 3 respectively. Table 2 is for the solubility at 323.15 K, the experiment No. 2 (E<sub>1a</sub>) and No. 3 (E<sub>1b</sub>) are the co-saturated point E<sub>1</sub> of LiCl·H<sub>2</sub>O and SrCl<sub>2</sub>·H<sub>2</sub>O; the experiment No. 5 (E<sub>2a</sub>) and No. 6 (E<sub>2b</sub>) are E<sub>2</sub> of SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O; the experiment No. 12 (E<sub>3a</sub>) and No. 13 (E<sub>3b</sub>) are E<sub>3</sub> of SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O. Table 3



**Fig. 3.** Measured solubility of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at  $T = 348.15$  K. (b) is local enlarged of (a); (c) is local enlarged of (b). Symbols are the experiment points:  $\blacksquare$ , LiCl·H<sub>2</sub>O;  $\blacksquare$ , E<sub>1</sub>, SrCl<sub>2</sub>·H<sub>2</sub>O + LiCl·H<sub>2</sub>O;  $\boxtimes$ , SrCl<sub>2</sub>·H<sub>2</sub>O;  $\boxplus$ , E<sub>2</sub>, SrCl<sub>2</sub>·2H<sub>2</sub>O + SrCl<sub>2</sub>·H<sub>2</sub>O;  $\boxminus$ , SrCl<sub>2</sub>·2H<sub>2</sub>O. II, III and IV represent the crystal regions of different solid phases: II, SrCl<sub>2</sub>·2H<sub>2</sub>O; III, SrCl<sub>2</sub>·H<sub>2</sub>O; IV, LiCl·H<sub>2</sub>O.



**Fig. 4.** The measured wet solid composition and corresponding liquid-solid lines for the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at  $T = 348.15$  K. Symbols are the experiment points: ■, LiCl·H<sub>2</sub>O; □, E<sub>1</sub>, SrCl<sub>2</sub>·H<sub>2</sub>O + LiCl·H<sub>2</sub>O; ▤, SrCl<sub>2</sub>·H<sub>2</sub>O; ▥, E<sub>2</sub>, SrCl<sub>2</sub>·2H<sub>2</sub>O + SrCl<sub>2</sub>·H<sub>2</sub>O; ▦, SrCl<sub>2</sub>·2H<sub>2</sub>O; ○, wet solid points; lines are corresponding liquid-solid lines: ···, for SrCl<sub>2</sub>·2H<sub>2</sub>O; —, for E<sub>2</sub> (experiment No. 10 in Table 3); ---, for SrCl<sub>2</sub>·H<sub>2</sub>O; -·-·-, for E<sub>1</sub> (experiment No. 2 E<sub>1a</sub> and No. 3 E<sub>1b</sub> in Table 3).

lists the solubility at 348.15 K, the experiment No. 2 (E<sub>1a</sub>) and No. 3 (E<sub>1b</sub>) are the co-saturated point E<sub>1</sub> of LiCl·H<sub>2</sub>O and SrCl<sub>2</sub>·H<sub>2</sub>O; the experiment No. 10 (E<sub>2</sub>) is E<sub>2</sub> of SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O.

### 3.2. Discussions

#### 3.2.1. Measured solubility of the binary systems

The solubility measured in this work and reported in literature for the LiCl–H<sub>2</sub>O and SrCl<sub>2</sub>–H<sub>2</sub>O binary systems was tabulated in Table 4. The measured solubility for the LiCl–H<sub>2</sub>O binary system at 323.15 K is in accordance with the result reported in literature [3] with the absolute and relative difference is only 0.02 mol·kg<sup>−1</sup> and 0.091%, respectively. For the SrCl<sub>2</sub>–H<sub>2</sub>O binary system at 323.15 K is 4.59 mol·kg<sup>−1</sup> which is agreed with the reported solubility 4.61 mol·kg<sup>−1</sup> [3] 4.60 mol·kg<sup>−1</sup> [4]. And for the SrCl<sub>2</sub>–H<sub>2</sub>O binary system at 348.15 K is 5.76 mol·kg<sup>−1</sup> that is the same with the reported data of Assarsson [5] and a little bit deviation with

5.72 mol·kg<sup>−1</sup> resulted by Linke [3].

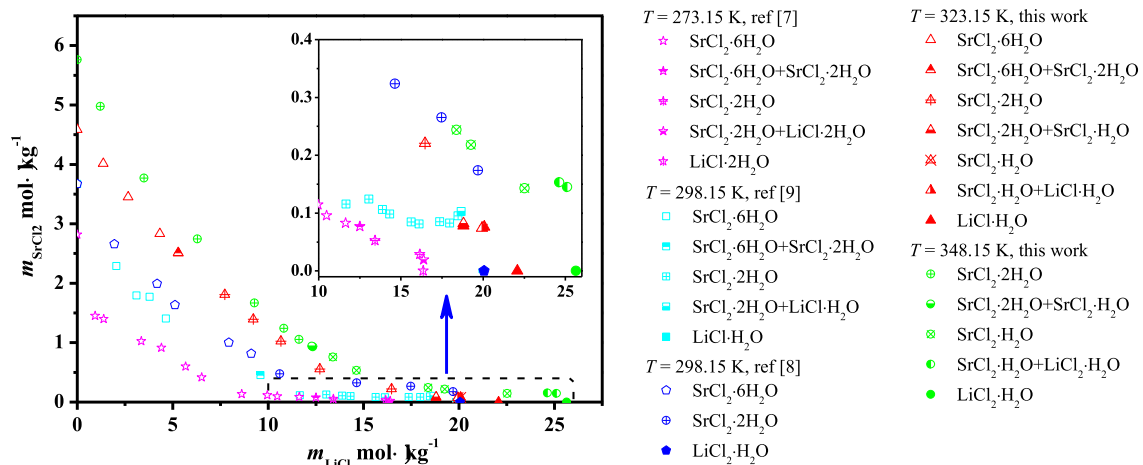
#### 3.2.2. Solubility for LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 323.15 K

The measured solubility and phase diagram for the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 323.15 K are shown in Fig. 1. There are four solid phases including LiCl·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O, SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O with the corresponding crystal regions I (SrCl<sub>2</sub>·6H<sub>2</sub>O crystal region), II (SrCl<sub>2</sub>·2H<sub>2</sub>O crystal region), III (SrCl<sub>2</sub>·H<sub>2</sub>O crystal region) and IV (LiCl·H<sub>2</sub>O). Accordingly, exist three invariant points in the phase diagram of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 323.15 K which are E<sub>1</sub>, the co-saturated point of SrCl<sub>2</sub>·H<sub>2</sub>O and LiCl·H<sub>2</sub>O, E<sub>2</sub>, the co-saturated point of SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O, meanwhile E<sub>3</sub>, the co-saturated point of SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O.

The measured corresponding liquid-wet solid lines are depicted in Fig. 2. According to the Schreinemaker's rule, the solid composition points should be the end point of the liquid-wet solid extended line. The liquid-wet solid-solid lines are also presented in the phase diagram shown in Fig. 2. These relevant liquid-wet solid-solid lines can give the evidence for evaluation of the equilibrium solid phases, and simultaneously the identified solid phases are displayed in Table 2. The solid composition of points E<sub>1</sub> (experiment No. 2 E<sub>1a</sub> and No. 3 E<sub>1b</sub> in Table 2) fall on the connection line of SrCl<sub>2</sub>·H<sub>2</sub>O and LiCl·H<sub>2</sub>O, which suggests the E<sub>1</sub> is the co-saturated point of these two solid phases. Consequently, the points E<sub>2</sub> (experiment No. 5 E<sub>2a</sub> and No. 6 E<sub>2b</sub> in Table 2) and E<sub>3</sub> (experiment No. 12 E<sub>3a</sub> and No. 13 E<sub>3b</sub>) are the co-saturated points of SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O, SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O, respectively.

#### 3.2.3. Solubility for LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 348.15 K

The measured solubility and phase diagram for LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 348.15 K are hinted in Fig. 3. Comparing to measured phase diagram at 323.15 K, the SrCl<sub>2</sub>·6H<sub>2</sub>O crystallization region disappeared, and just three equilibrium solid phases exist, i.e. LiCl·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O, and moreover their corresponding crystallization regions are distinguished as II, III and IV, respectively. The invariant points for the solid phases of LiCl·H<sub>2</sub>O and SrCl<sub>2</sub>·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O are E<sub>1</sub> (experiment No. 2 and 3 in Table 3) and E<sub>2</sub>, (experiment No. 10 in Table 3), separately, as shown in Figs. 3 and 4. Compared with the phase diagram at 323.15 K, the crystallization region of SrCl<sub>2</sub>·H<sub>2</sub>O is enlarged distinctly. The measured wet solid composition and the corresponding liquid-wet solid-solid lines for LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 348.15 K are displayed in Fig. 4.



**Fig. 5.** Solubility of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at different temperatures.



### 3.2.4. Solubility of the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at different temperatures

Except the solubility data at 323.15 K and 348.15 K measured in this work, the solubility data for LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O ternary system at 273.15 K [7] and 298.15 K [8,9] is also reported and the comparison at different temperatures are shown in Fig. 5. Noticeably, with the decrease of temperature, the crystallization region of SrCl<sub>2</sub>·6H<sub>2</sub>O will become larger meanwhile the crystallization region of SrCl<sub>2</sub>·2H<sub>2</sub>O will move to the direction of higher LiCl concentration. The solid phase of SrCl<sub>2</sub>·H<sub>2</sub>O exists merely at relative high temperature, such as 323.15 K and 348.15 K nevertheless the LiCl·2H<sub>2</sub>O is only at relative low temperature, such as 273.15 K.

## 4. Conclusions

The solubility of the ternary system LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O, and its sub-binary systems LiCl–H<sub>2</sub>O and SrCl<sub>2</sub>–H<sub>2</sub>O, at 323.15 K and 348.15 K has been measured by the Isothermal Dissolve Equilibrium (IDE) method. The determined solubility for the LiCl–H<sub>2</sub>O and SrCl<sub>2</sub>–H<sub>2</sub>O binary systems is consistent with the reported results in literature. The measured solubility and corresponding liquid-solid line results for the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 323.15 K advised that there are four equilibrium solid phases, namely LiCl·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O, SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O, and four independent crystallization regions for these solid phases correspondingly, in the meanwhile three co-saturated points E<sub>1</sub>, E<sub>2</sub>, E<sub>3</sub> for LiCl·H<sub>2</sub>O and SrCl<sub>2</sub>·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O, SrCl<sub>2</sub>·2H<sub>2</sub>O and SrCl<sub>2</sub>·6H<sub>2</sub>O respectively. The phase diagram for the LiCl–SrCl<sub>2</sub>–H<sub>2</sub>O system at 348.15 K also has been drawn according to the measured solubility, wet solid and corresponding liquid-solid lines. The solid phase equilibrated with the saturated solutions are LiCl·H<sub>2</sub>O, SrCl<sub>2</sub>·H<sub>2</sub>O and SrCl<sub>2</sub>·2H<sub>2</sub>O. Compared with the phase diagram at 323.15 K, the crystallization region of SrCl<sub>2</sub>·6H<sub>2</sub>O disappeared, but for SrCl<sub>2</sub>·H<sub>2</sub>O became larger.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### CRedit authorship contribution statement

**Hongxia Li:** Methodology, Data curation, Investigation,

Validation. **Lijiang Guo:** Conceptualization, Data curation, Writing - original draft, Visualization, Investigation, Supervision, Validation, Writing - review & editing.

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