**HEFAT2014**
**10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics**
**14 – 16 July 2014**
**Orlando, Florida**

# PROCESS SELECTION FOR NATURAL RESOURCE UTILIZATION

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## ABSTRACT

An experimental investigation of natural gas hydration processes and an evaluation of the production processes of different scales from the laboratory to industrialization were used to provide methods to guide the general scientific development and natural resource utilization. In this investigation, a process evaluation parameter is introduced to evaluate a variety of processes. The analyses indicate that the process evaluation parameter is relevant to the technological level and resource consumption of the system, and the parameter has some features of the thermodynamic state functions. The process investigation shows that the parameter change can identify the direction of an actual process. Finally, the process evaluation parameter is useful to select a process, where it can be used to guide the decision-making regarding resource development and the venture forecasting of capital utilization. It is useful in science, where it can play a predictive role to guide scientific research, such as research into the renewable energy storage technology of natural gas hydrate storage. It is also useful in engineering practice, where it can play a practical role in guiding process improvements and process management.

## INTRODUCTION

Non-regenerative resources have received significant attention because of their limited supply, the standards regarding their use and how they are used, which is directly linked to the economy [1, 2]. All of these issues determine whether the economy can maintain sustainable development [3, 4]. Therefore, means for scientific development should be adopted to exploit non-regenerative resources to maximize the efficiency of use and the economic value.

Natural resource exploitation generally occurs under the following circumstances: (1) a lack of developed technology, (2) a single option for developed technology and (3) multiple options for developed technology.

To address these issues, we must design and compare current schemes of scientific research, production schemes and monitoring schemes in current industry for each circumstance. We can select an appropriate project to implement various processes of natural resource utilization from these comparisons and analyses [5].

## NOMENCLATURE

| | | |
|---|---|---|
| $a$ | [J·mol$^{-1}$·K$^{-1}$] | Parameters of heat capacity at constant pressure |
| $b$ | [J·mol$^{-1}$·K$^{-2}$] | Parameters of heat capacity at constant pressure |
| $c$ | [J·mol$^{-1}$·K$^{-3}$] | Parameters of heat capacity at constant pressure |
| $CO_p$ | [W/W] | Coefficient of performance |
| $C$ | [V·V$^{-1}$] | Volume of gas stored in a unit volume of hydrate or combustion |
| $C_P$,$C_V$ | [J·mol$^{-1}$·K$^{-1}$] | Heat capacity at constant volume |
| $f$ | [-] | Function |
| $m$ | [g] | Mass |
| $n$ | [mol] | Molecular number of the methane gas |
| $P$ | [MPa] [W] | Pressure or power |
| $Q$ | [kJ] [kJ·kg$^{-1}$] | Energy consumption, heat or heat value |
| $q$ | [[kJ·kg$^{-1}$]] | Combustion heat of methane hydrates |
| $R$ | [J·mol$^{-1}$·K$^{-1}$] | Gas constant |
| $RC$ | [-] | Resource consumption |
| $T$ | [K] | Absolute temperature |
| $t$ | [s] | Time |
| $U$ | [kJ] | Internal energy |
| $V$ | [dollar] | Resources utilization or volume |
| $W$ | [kJ] | Work or work consumption |
| Special characters | | |
| $\mathit{\Delta}$ | [-] | Change value of a parameter |
| $\varepsilon$ | [-] | Ratio of resources input to total resources known |
| $\theta$ | [-] | Methane gas mass fraction of methane hydrates |
| $\eta$ | [-] | Efficiency factor |
| $\lambda$ | [-] | Ratio of the heat capacity at constant pressure to the heat capacity at constant volume |
| $\tau$ | [-] | Run times in a day |
| $\varphi$ | [-] | Pressure ratio of the gas compression process or |

| | | |
|---|---|---|
| | | load coefficient |
| $\psi$ | [-] | Correction coefficient |
| $\Omega$ | [-] | A parameter of process evaluation or a parameter of energy consumption evaluation |
| Subscripts | | |
| $1,2$ | | Initial state and final state |
| $i,f$ | | Parameter values at initial state and final state |
| $cp$ | | Compress process |
| $ad$ | | Adiabatic compression process |
| $min$ | | Minimum value |
| $i,o$ | | Input and output |
| $r$ | | Refrigerator or reaction |
| $s$ | | Stirrer |
| $t$ | | Total |
| 0 | | Ambient or reference value |

However, use processes of the natural resource must be optimized before they can be implemented. Thus, process evaluation and optimal selection methods will be introduced in this work, which will advance the actualization of resource conserving efforts and environmentally friendly production [6, 7].

As an undeveloped resource, natural gas hydrate has received significant attention in recent years. Not only does it constitute an abundant new energy resource, but it can also be used as a medium for natural gas storage and transportation. Thus, the development process of the investigations for natural gas hydrate has become particularly important. Among these investigations, natural gas hydrate synthesis technologies appear to be the most crucial, because the development of the processes not only directly affects the mode of transport for natural gas [8], but also the resource tapping of natural gas hydrate from the seafloor and permafrost zones [9, 10, and 11]. Thus, the development processes of natural gas hydrate synthesis technology will be investigated in this work. Scientific researches studies have shown that 1 volume of natural gas hydrate can contain 150-180 volumes of natural gas (standard temperature, pressure) [12]. As a result of utilizing the storage properties of natural gas in hydrates, natural gas storage and transportation will be more economical than liquefied natural gas transportation and pipeline transportation in the near future, especially for the development of a middle- or small-scale natural gas field [13]. To achieve this goal earlier, many laboratories have studied the synthesis of natural gas hydrates in different countries during recent decades. These studies are mainly divided into two groups. One group consists of fundamental research; the other group consists of applied background research. In fundamental studies, natural gas hydrates are synthesized in gas and liquid reaction systems when the conditions of the reactants or mediums are gases of different compositions [14], liquids of different compositions [15] and different combinations of liquid-solid systems [16]. In applied background studies, the formation and process evaluations of natural gas hydrate formations and process evaluations are investigated in reactors of varying scale and type [17, 18]. In all the above studies, the economic efficiency of natural gas hydrate synthesis was the crucial problem that needed to be solved. At present, the gas capacity in hydrates and the hydrate rate remain the main factors to improve the technical levels. Generally, the mass transfer and heat transfer are enhanced to promote the hydrate process in a reactor. However, none of the endeavors for natural gas hydrate transportation currently show economical advantages over liquefied natural gas transportation and pipeline transportation. These endeavors merely have theoretical significance and are not valuable to natural gas fields with middle- or small-scale exploitation. To allow natural gas hydrate transportation to compete with liquefied natural gas transportation and pipeline transportation and promote the effective utilization of natural resources, the development processes of chemical production, including laboratory experiments, scaled-up plant tests and industrialization tests for natural gas hydrate synthesis technology, will be treated as a target of process investigation and provide various methods of evaluation and selection for the effective utilization of natural resources in this work. In addition, an economic analysis of several potential industrial processes will be conducted for undeveloped resources to identify the optimal resource extraction strategy [2, 19].

## PROCESS INVESTIGATION OF CHEMICAL PRODUCTION

In general, the industrial production of chemicals involves various processes, such as laboratory trials, middle scale trials and industrialization production phases [20]. Thus, common procedures of chemical production will be introduced and form the basis of development processes of chemical production in this section. In addition, since natural gas hydrates as a type of chemical compound, they can be made by artificial means. Thus, their synthesis is also subject to requisite procedures and the production of other industrial chemicals. Thus, the synthesis of natural gas hydrate was investigated in reactors of different scales, and the technological development of this synthesis was used as a sample process to investigate the industrial product in this section. Finally, the conclusions of this work will help to determine a direction of process development.

### Common procedures of chemicals production

The following procedures usually need to be performed before chemical tests, including the investigation of different scales. They are usually accomplished in a laboratory, pilot-plant and industrialization chemical plant.

1. Search for relevant literature and build the research basis of a compound;
2. Purchase apparatus and material;
3. Design a reasonable experimental procedure [21];
4. Perform bench-scale experiments in a laboratory;
5. Analyze experimental results and identify optimal conditions;
6. Set protocol of process evaluation and write a report for an environmental assessment and a construction analysis of pilot-plant;
7. Build pilot-plant and perform a series of experiments when conditions are permitted [22, 23];
8. Evaluate experimental results after pilot-plant is run for a period of time and analyze the investment and market prospect estimate for a certain material resource;
9. Form an industrial chemical plant and produce various industrial chemicals if the above analysis results are considered reasonable;

10. Analyze the economic benefit for the industrial chemical plant and write a report of the cost-effectiveness and technical analyses.

The above procedures require that scientific and technical factors, including the scales of chemical production and process implementation for a scale of chemical production, be comprehensively considered. Furthermore, various factors related to resources and the market should also be weighed.

### Sample process and direction’s determination for a process

Based on the aforementioned procedures, natural gas hydrates are synthesized in reactors of different scales and the results of the process development are analyzed in this subsection. This analysis provides a method to evaluate the process development. Finally, a method to determine the direction of development for an actual production process is provided.

### *Laboratory test of natural gas hydrate synthesis*

With respect to the last sub-sections, natural gas hydrate synthesis experiments are performed in various laboratories of different countries [13, 17 and 24]. Here, we can choose an experimental process that comes from several references [13, 17] as an example and form a principle of identification for a real production process, which will be used to investigate the process of natural resource utilization.

#### (I) Experimental apparatus and material

A one-liter semi-continuous stirred tank reactor is used to experimentally investigate the synthesis of natural gas hydrate. Various equipments, such as a thermoregulation bath with temperature control, gas pressure regulator, and mass gas flow meter, is installed in the reactor system. Other accessorial apparatuses, such as an electronic balance, are also appropriately arranged. A schematic diagram of the experimental apparatus is shown in Figure 1. In addition, methane, distilled water and sodium dodecylsulfate are selected to serve as the experimental material of the hydrate formation reaction.

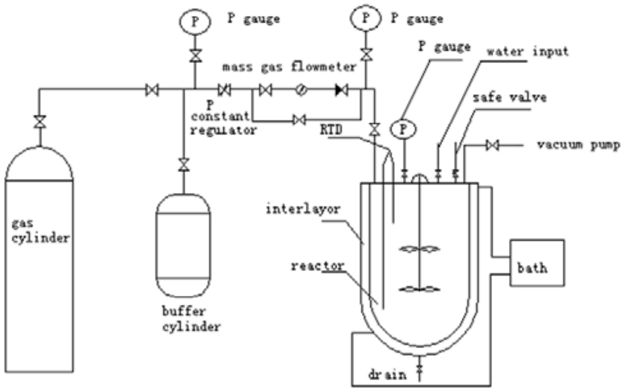

**Figure 1** Schematic diagram of methane hydrate setup

#### (II) Experimental procedure

The experiments are performed according to the following procedures for the natural gas hydrate synthesis:

First, the experimental reactor is cleaned and necessary preparations are undertaken. Three hundred and ten grams of 0.001 mol/L sodium dodecylsulfate solution at a temperature of 283 K are charged into the empty reactor. The reaction liquids are then adjusted to the test temperature of 274.4 K by controlling the constant temperature of the bath.

Second, methane gas at 290 K is pressurized into the reactor until an experimental pressure of 5.0 MPa is reached in a 3–5 min span. The stirrer is then driven at a stirring velocity of 320 rpm, while the hydration formation rate and flux are displayed and recorded by a data collector system.

Third, nine experiments evaluate the effect of the stirring time, stirring velocity and load coefficient of the reactor on the formation of methane hydrate.

#### (III) Experimental results and discussion

Based on the aforementioned experimental procedures, we can draw various curves in a rectangular coordinate system and analyze the results they describe. Finally, we can draw some useful conclusions from these analyses and discussions. Curves that show the effect of stirring time, stirring velocity, and load coefficients of the reactor on storage capacity in hydrates are plotted for the process of methane formation. Here storage capacity in hydrates can be calculated by using following equation:

$$C = \frac{V_{NG}}{V_{NGH}} = \frac{V_{NG}}{V_L * (1 + \Delta V)} \qquad (1)$$

where C is the volume of gas stored in a unit volume of hydrate, $V_{NG}$ is the volume of gas consumed, $V_{NGH}$ is the volume of hydrate when the reaction ends, and $V_L$ is the volume of water added.

Because experimental gas substance is methane, the molar volume change $\Delta V$ is 4.6 $cm^3 \cdot mol^{-1}$. Schematic diagrams of the curves are drawn in Figure 2, Figure 3 and Figure 4.

The effects of the stirring time on the formation of methane hydrate show that 30 min is an appropriate stirring time that yielded a higher storage capacity and hydrate rate. The effects of the stirring velocity on the formation of methane hydrate show that 320 rpm is a better stirring velocity that also results in a higher storage capacity and hydrate rate. The effects of the load coefficients of the reactor on the formation of methane hydrate indicate a specific load coefficient, 0.289, that serves as the basis for hydrate reactor scale-up. However, we are most interested in the daily throughput and purity of the product in the process units. The daily throughput can be calculated from the following equation:

$$m_t = m * \tau \qquad (2)$$

where $m_t$, m and $\tau$ are the total mass of hydrates formed in a day, the mass of hydrates formed in a run and run times in a day, respectively.

However, the mass of hydrates formed in a run can be obtained from a mass balance. If the mass of the surfactant (sodium dodecylsulfate) is neglected, the mass balance equation of can be expressed as follows:

$$m = m_W + m_{CH4} \qquad (3)$$

where $m_w$ and $m_{CH4}$ are the mass of the added water solution and the mass of the reacted methane gas, respectively, during a run.

In addition, we can use the methane gas fraction of methane hydrates to express the purity of the product:

$$\theta = \frac{m_{CH4}}{m} * 100\% \tag{4}$$

where $\theta$ is the methane gas mass fraction of methane hydrates.

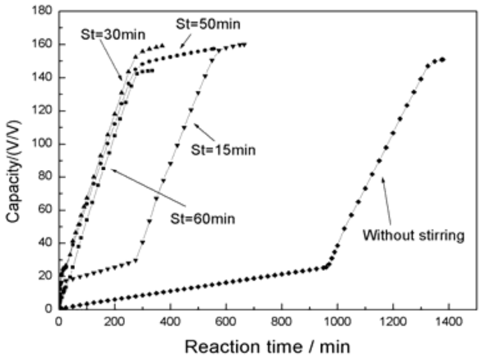

**Figure 2** Effect of stirring time on hydrate storage capacity

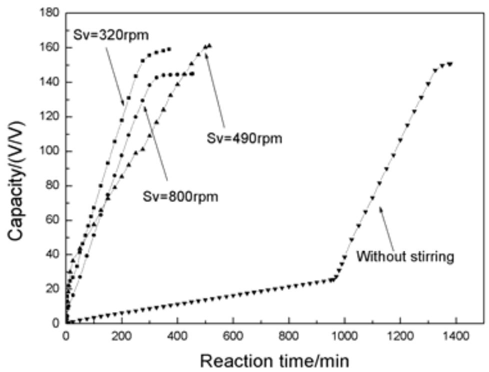

**Figure 3** Effect of stirring velocity on hydrate storage capacity

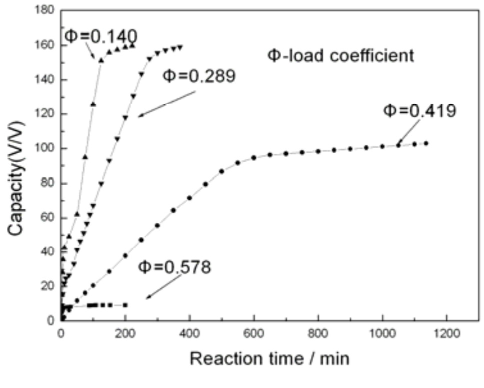

**Figure 4** Effect of load coefficient on storage capacity of methane hydrate at 5MPa

**Table 1** Throughput and purity of methane hydrates

| Parameter | $m_w$(g) | $m_{CH4}$(g) | m(g) | τ | $m_t$(kg) | θ (%) |
|---|---|---|---|---|---|---|
| Value | 310 | 44 | 354 | 3 | 1.06 | 12.4 |

According to these equations, a mass balance is calculated for the appropriate operational condition, and the results calculated are shown in Table 1.

All of the aforementioned analytic results are used to form experimental conclusions and lay the foundations for middle-scale trials and industrialized production.

### (IV) Experimental conclusions

After the experimental results and discussion are summarized and the batch operations are fully considered, the following experimental conclusions could be drawn: 44 g of methane gas is stored when a 310 g solution is added to the reactor selected under the appropriate operational conditions in the experiment. The process reaction takes 6 h and the supplementary time is 0.5 h, which allows three runs per day. Ultimately, 1.06 kg of methane hydrate could be produced with 12.4% methane gas.

## *Test process evaluation of natural gas hydrate synthesis*

The technological development of natural gas hydrate synthesis comes from those laboratory experiments. Therefore, the aforementioned laboratory-scale hydrate preparation processes are analyzed and evaluated in this sub-section. The results and analyzed methods are gradually introduced to the scaled-up device and the industrial scale. The development tendency of the process could ultimately be judged from a macroscopic view. The derived methods or theories from the developing process are then used to appraise the process of natural resource utilization and guide the optimized allocation of natural resources in social production.

### (I) Process evaluation of laboratory methane hydration

Generally speaking, the production cost is the most crucial factor to a chemical product. Thus, fixed costs and variable cost must be fully considered. For this laboratory production process, we assume that the equipment investment and labor costs are stable and lower than the variable cost for the laboratory methane hydration. Thus, these two terms could be neglected when the total cost values are calculated. However, as the values of the variable depended on the daily energy consumption and the preceding daily throughput. Therefore, the computational process of daily energy consumption is introduced in the following parts.

### (A) Energy balance

For convenience, the temperature changes in the inlet gas and the inlet water could be neglected in terms of their consumption of the hydration process (alternatively, their temperatures could be controlled). The total energy consumption during a run can be expressed as follows, including the energy consumption of the compression process, energy consumption of the cooling process, and the power for driving the stirrer:

$$Q^* = Q_{cp} + W_r + W_s \tag{5}$$

where $Q^*$, $Q_{cp}$, $W_r$, and $W_s$ are the total energy consumption, energy consumption of the compression process, work consumption of the refrigeration unit, and work for driving the stirrer during a run, respectively.

### (1) Compression of methane gas

The following assumptions, which are common to all of the cases studied, were made when estimating the process energy consumption [25].

The initial pressure of the feed gas is set to $P_1$, and the initial temperature is set to $T_1$. The feed gas is pressurized to the hydrate operation pressure, $P_2$, by an adiabatic compression process with an efficiency factor, $\eta_{ad}$. The final temperature, $T_2$, after compression can be calculated from the initial temperature using Equation (5):

$$T_2 = \left[1 + \frac{\phi^{\left(\lambda-1/\lambda\right)} - 1}{\eta_{ad}}\right] T_1 \tag{6}$$

where $\lambda$ is the ratio of the heat capacity at constant pressure to the heat capacity at constant volume, which is expressed as follows:

$$\lambda = {}^{C_P}\!/_{C_V} \tag{7}$$

where $C_P$ is the heat capacity at constant pressure and $C_V$ is the heat capacity at constant volume.

$\Phi$ is the ratio of the final pressure $P_2$ to the initial pressure $P_1$ of the compression process:

$$\phi = {}^{P_2}\!/_{P_1} \tag{8}$$

The temperature of the compression process is calculated using the above equation. The results for the model parameters are given in Table 2.

**Table 2** Calculated final temperature of the compression process

| Parameter | $T_1$ (K) | $P_1$ (MPa) | $P_2$ (MPa) | $\eta_{ad}$ | $\Phi$ | $\lambda$ | $T_2$ (K) |
|---|---|---|---|---|---|---|---|
| Value | 298 | 0.1 | 7 | 0.8 | 70 | 1.29 | 894 |

Assuming that the work performed on the methane gas is $W_{cp}$, the compression process energy consumption $Q_{cp}$ can be expressed as follows:

$$W_{cp} = Q_{cp} \times \eta_{ad} \tag{9}$$

where $\eta_{ad}$ is the efficiency factor under adiabatic conditions.

The internal energy change, $\Delta U$, can be expressed as follows:

$$\Delta U = Q_{cp} - W_{cp} = \left(1 - \eta_{ad}\right) Q_{cp} \tag{10}$$

The compression process energy consumption $Q_{cp}$ can then be written as follows:

$$Q_{cp} = {}^{\Delta U}\!/_{\left(1 - \eta_{ad}\right)} \tag{11}$$

On the other hand, the internal energy change, $\Delta U$, can also be expressed as follows:

$$\Delta U = n \int_{T_1}^{T_2} C_V \, dT \tag{12}$$

where n is the number of molecules of the methane gas.

The heat capacity at constant volume $C_v$ can be expressed using the heat capacity at constant pressure, $C_P$, which in turn is related to the absolute temperature, T. Thus, the heat capacity at constant volume $C_v$ is related to the absolute temperature, T. The relationship between the heat capacity at constant pressure and the absolute temperature can be expressed as follows:

$$C_p = a + bT + cT^2 \tag{13}$$

where a, b, and c are parameters of the heat capacity at constant pressure.

The relationship between the heat capacity at constant pressure and the heat capacity at constant volume can be expressed as follows:

$$C_V = C_P - R \tag{14}$$

where R is the gas constant.

Therefore, substituting Equations (12) and (13) into Equation (11), $\Delta U$ takes the following form:

$$\Delta U = n \int_{T_1}^{T_2} \left(a + bT + cT^2\right) dT \tag{15}$$

Integrating the right-hand side of Equation (14), the internal energy change, $\Delta U$, can be rewritten as follows:

$$\Delta U = n\left[\left(a - R\right)\left(T_2 - T_1\right) + \frac{b}{2}\left(T_2^2 - T_1^2\right) + \frac{c}{3}\left(T_2^3 - T_1^3\right)\right] \tag{16}$$

In Equation (15), the values of $T_1$ and $T_2$ can be found in Table 2, and the values for a, b, c, and R can be found in Table 3[17].

**Table 3** Parameter of heat capacity at constant pressure and gas constant

| Methane Parameter | a ($\mathrm{J\cdot mol^{-1}\cdot K^{-1}}$) | $b\times10^3$ ($\mathrm{J\cdot mol^{-1}\cdot K^{-2}}$) | $c\times10^6$ ($\mathrm{J\cdot mol^{-1}\cdot K^{-3}}$) | R ($\mathrm{J\cdot mol^{-1}\cdot K^{-1}}$) |
|---|---|---|---|---|
| Value | 14.15 | 75.496 | -17.99 | 8.314 |

Substituting these data into Equation (15), the internal energy change, $\Delta U$, can be rewritten as follows:

$$\Delta U = 26.17n \tag{17}$$

Substituting Equation (17) into Equation (11), the compression process energy consumption, $Q_{cp}$, can be expressed as follows:

$$Q_{cp} = 130.85n \tag{18}$$

**(2) Cooling of the methane hydration process**

The methane hydration process releases a substantial heat of reaction [26], 54.2kJ/mol, from the following chemical reaction:

$$CH_4 + 5.75H_2O \rightarrow CH_4 \cdot 5.75H_2O + 54.2\,{}^{kJ}\!/_{mol}$$

Therefore, the heat of reaction released can be expressed as follows:

$$Q_r = 54.2n \tag{19}$$

where $Q_r$ is the heat of reaction released and n is number of molecules of the methane gas.

The heat exchanged in the cooling system is equal to heat of reaction released:

$$Q_e = 54.2n \tag{20}$$

where $Q_e$ is the heat exchanged in the cooling system.

The work consumption of the refrigeration unit, $W_r$, can be expressed as follows:

$$W_r = \frac{Q_e}{CO_P} = \frac{54.2n}{CO_P} \tag{21}$$

where $W_r$ is the work consumption of the refrigeration unit and $CO_p$ is the performance coefficient.

**(3) Power for driving the stirrer**

The power for driving the stirrer can be calculated as follows:

$$W_S = P_S t_S \tag{22}$$

where $W_S$, $P_S$ and $t_S$ are the work consumption for driving the stirrer, stirrer power, and stirring time, respectively.

The stirrer power, $P_S$, should increase with the fifth power of the impeller diameter and the third power of the velocity. Idiographic calculation methods for the stirrer power, $P_S$, are available in the literature [13]. The power required to drive the stirrer, $W_S$, may be neglected when the hydration reactor is a small-scale laboratory apparatus and is therefore considered to be zero in this work.

### (4)Total energy consumption of the methane hydration process

The total energy consumption of the methane hydration process during a run can be calculated from equation (5). This value is then substituted into the following equation (23):

$$Q_t = Q^* \times \tau \qquad (23)$$

where τ and $Q_t$ are the daily run time and the total daily energy consumption of the methane hydration process, respectively.

Finally, the total daily energy consumption of the methane hydration process can be calculated from equation (23).

Because the total mass of the methane hydrates produced per day is $m_t$, the energy consumption for each kilogram of methane hydrates produced can be written as follows:

$$Q_0 = \frac{Q_t}{m_t} \qquad (24)$$

where $Q_0$ is the energy consumption per kilogram of methane hydrate produced and $m_t$ is the total mass of methane hydrates produced each day. The parameter values for the methane hydration process are given in Table 4.

**Table 4** Energy consumption of the methane hydration process in the semi-CSTR

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $m_{CH4}$ (g) | 44 | Q* (kJ) | 409.52 |
| $n_{CH4}$ (mol) | 2.75 | τ | 3 |
| $Q_{cp}$ (kJ) | 359.84 | $Q_t$ (kJ) | 1228.56 |
| $CO_P$ | 3 | $m_t$ (kg) | 1.06 |
| $W_r$ (kJ) | 49.68 | $Q_0$ (kJ·kg$^{-1}$) | 1159.02 |

### (B) Evaluation of the energy consumption of the methane hydration process

To provide a single rule for evaluating the energy consumption in different hydration reactors, an energy consumption evaluation parameter, Ω, is introduced here, which is defined as the ratio of energy consumption per kilogram of methane hydrate produced to the heat value of 1 kg of methane hydrate:

$$\Omega = \frac{Q_0}{Q_C} \qquad (25)$$

where $Q_0$ is the energy consumption per kilogram of methane hydrate produced and $Q_C$ is the heat value of 1 kg of methane hydrate.

The heat value of 1 kg methane hydrate can be expressed as follows:

$$Q_C = 1 \times \theta \times q \qquad (26)$$

where θ is the methane gas mass fraction of methane hydrates and q is the heat obtained from methane combustion.

The results of the heat quality evaluation of the methane hydration process are shown in Table 5.

### (II) Evaluation of scaled-up test and industrialization test for methane hydration process

### (1) Analysis of energy consumption evaluation parameter

According to the above definition, the energy consumption evaluation parameter, Ω, can be considered as a constant that can be applied to the evaluation of reactors, scaled-up devices or processes. If the experimental gas comes from a small-scale natural gas field, then the energy consumption of methane gas compression can be neglected. Therefore, the total energy consumption in such a run can be replaced by the energy consumption of the cooling process. The results of the relevant calculations are shown in Table 6.

As shown in Table 6, the energy consumption evaluation parameter has a value of 0.02, which is 87.9 percent lower than that in Table 5. Thus, the energy consumption of methane gas compression was 87.9 percent of the total energy consumption in the experiment.

### (2) Introduction of process evaluation parameter

The energy savings must be considered for the scaled-up plant tests, especially the industrialization test. Here, the energy consumption evaluation parameter should decrease. However, decreasing the energy consumption evaluation parameter requires the development of new technology. The Ω value described above can therefore also be applied as an economic criterion for the process evaluation of scaled-up plant tests and industrialization tests.

**Table 5** Calculated heat quality in the methane hydration process

| Parameter | q (kJ·kg$^{-1}$) | θ | $Q_C$ (kJ·kg$^{-1}$) | $Q_0$ (kJ·kg$^{-1}$) | Ω |
|---|---|---|---|---|---|
| Value | 50010 | 0.124 | 6201.24 | 1159.02 | 0.19 |

**Table 6** New heat quality data for the methane hydration process

| Parameter | Q* (kJ) | $Q_t$ (kJ) | $Q_C$ (kJ·kg$^{-1}$) | $Q_0$ (kJ·kg$^{-1}$) | Ω |
|---|---|---|---|---|---|
| Value | 49.68 | 149.04 | 6201.24 | 140.60 | 0.02 |

In addition, our analysis reveals that the Ω parameter is a dimensionless quantity similar to an input-output ratio in economics. Therefore, a more extensive definition in terms of the economic efficiency is provided here, in which the Ω parameter is referred to as a process evaluation parameter and can be expressed as follows:

$$\Omega = \frac{V_i}{V_O} \qquad (27)$$

where Ω is the process evaluation parameter for the systems and $V_i$ and $V_O$ are the resource inputs and outputs, respectively.

$V_i$ and $V_O$ can be generally replaced by the monetary value of the input and output resources. A diagram of the relevant process systems is shown in Figure 5. The origin of the process evaluation parameter indicates that the Ω value has double meanings in terms of the technical efficiency and economic efficiency. Thus, the analysis of the variations in the process evaluation parameter is vital to further quantize the effects of the scaled-up plant and industrialization tests.

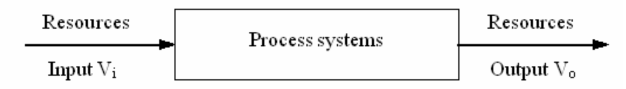

**Figure 5** Schematic diagrams of process systems

### (3) Variation analysis of the process evaluation parameter

Here, the variation of the process evaluation parameter is assessed [29] using economics.

Let

$$V_i + V_O = V_t \tag{28}$$

where $V_t$ is the total known resources, expressed as the sum of the input resources and undeveloped resources, which can also be replaced by the monetary value of the resources.

In addition, that the following can be assumed:

$$V_t = \varepsilon V_t \tag{29}$$

where ε is the ratio of the input resources to the total known resources.

Then,

$$V_O = (1-\varepsilon)V_t \tag{30}$$

Substituting Equation (28) and Equation (29) into Equation (26), the process evaluation parameter can be expressed as follows:

$$\Omega = \varepsilon / 1-\varepsilon \tag{31}$$

As new resources are developed, the undeveloped resources, especially in the case of non-regenerative resources, will gradually decrease to zero [27]. That is,

$$\varepsilon \to 1 \tag{32}$$

Therefore, the process evaluation parameter Ω will approach infinity:

$$\lim_{t\to\infty} \Omega = \infty \tag{33}$$

where t is time.

Several conclusions can be drawn from the above development and economic analysis of the process evaluation parameter. On one hand, the process evaluation parameter will decrease with the advance of science and technology. On the other hand, the process evaluation parameter will increase with the consumption of resources. Therefore, the process evaluation parameter is a function of the level of science and technology advancement and resource consumption. This relationship can be written as follows:

$$\Omega = f(ST, RC) \tag{34}$$

where ST and RC denote the level of science and technology advancement and resource consumption and f is an arbitrary function.

The equation shows that the process evaluation parameter can be mathematically expressed in the form of equations that can be solved according to the state of scientific advancement, resource conditions, etc. If various game theory concepts [28, 29] are introduced into the model equation (33), the equation can be regarded as a game between the level of science and technology advancement and resource consumption. The final objective of Equation (33) is that the process evaluation parameter Ω is a constant in the actual work. In other words, the effects of the level of science and technology advancement and resources consumption on the process evaluation parameter are very small and can be neglected.

Therefore, the change in the process evaluation parameter can be used to evaluate different pilot phases of development technologies and identify the optimal scheme from the results. Moreover, the process evaluation parameter can provide several references to improve the process and manage the effects of human behavior in different test phases [30, 31].

## Identification of development's direction of an actual production process

The investigation of natural gas hydrate synthesis of different scales is introduced as a sample of an industrial production process in the last two sub-sections. Although the provided process evaluation parameter can help render a decision on the original process improvement or create a new process for an actual process, several necessary criteria must still be provided to develop the direction of an actual process. In other words, several mathematical expressions are necessary to judge the direction of development for an actual process. Here, we assume that the process evaluation parameter is a function of similar characteristics with a state function of thermodynamics [32]. Thus, every numerical value of the parameter should represent a state with a certain level of science and technology advance and resource consumption. Thus, the theory of a thermodynamic process can be used to determine the direction of development for an actual production process. We can use the calculated results of following equations to determine a direction of such a process:

$$\Delta\Omega = \Omega_f - \Omega_i \tag{35}$$

where ΔΩ, $\Omega_f$ and $\Omega_i$ are the change in the value of the process evaluation parameter between different states, the value of the process evaluation parameter at the final state and the value of the process evaluation parameter at the initial state.

If ΔΩ is less than zero, the process change is promising. In other words, this condition results in a driving force from an initial state to a final state; the process will continue to change from the levels of science and technology advancement or the conditions of resources consumption. The process change positively correlates with the value of the process evaluation parameter.

If ΔΩ equals zero, the process does not need to be changed. In other words, the initial and final process efficiencies of resource utilization are equal. If $\Omega_i$ and $\Omega_f$ are simultaneously equal to the average value of the process evaluation parameter of the entire society, then the production process at the final state cannot be improved. It can merely be reproduced at a same level of social production.

If ΔΩ is more than zero, the initial process is better than the final process. At this condition, the process cannot proceed from the initial state to the final state. In other words, an adverse direction is possible. Furthermore, the final process will be eliminated in social production because of lower efficiency of resource use.

However, if $\Omega_i$ is infinite and $\Omega_f$ is a constant for the development of the process, then ΔΩ will equal negative infinity. These values indicate that a significant amount of time is consumed from an impossible process to an available process. If $\Omega_i$ is a constant and $\Omega_f$ is infinite for the development of the process, then $\Delta\Omega$ is positive infinity, which indicates that the operating process will gradually lose its position and eventually disappear in social production.

These analyses indicate that the process evaluation parameter or its change in value can help to identify the direction of an actual process in social production and make a strategic decision. Moreover, size should be carefully considered and appropriately ranked based on the specific situations when using the parameter or change in the parameter value. Several examples of the use of natural resources will elaborate the use of the process parameter or its change in terms of different modes of production in the following section.

## USE AND APPLIED FUNCTION ANALYSIS OF THE PROCESS EVALUATION PARAMETER

The process evaluation parameter presented in this paper is an important guide for the development of the different stages of the pilot study. Furthermore, the change in the value of the process evaluation parameter can indicate the direction of process development and help to choose an appropriate process. However, the selection of a process to effectively utilize a natural resource is still quite complicated and requires diversified considerations. The identification of the best use of natural resources is a key issue. Therefore, the selection of the processes using process evaluation parameters is illustrated according to the aforementioned principle to identify the best utilization of natural resources [33].

### Use of the process evaluation parameter

For undeveloped resources, the resource consumption is zero; thus, the process evaluation parameter $\Omega$ will vary according to the following equation:

$$\Omega = f(ST) \tag{36}$$

where ST denotes the level of science and technology advancement and f is an arbitrary function.

In other words, the process evaluation parameter is related to the level of the natural and social sciences.

The following examples indicate methods to select the processes to maximize the use of natural resources, such as coal, oil, natural gas, natural gas hydrate, uranium mine, and iron ore [34, 35, and 36].

The utilitarian values of the process evaluation parameters will be revealed by analyzing following several common circumstances in process schemes' choice.

**(1) No developed technology**

Suppose a deposit of natural gas hydrate is found in a seabed, and the development objective is to obtain methane fuel [37]. However, the technology for industrial production is not currently available. Thus, the process evaluation parameter approaches negative infinity at this condition. The development of practical technology for the exploration of natural gas hydrates is still in its infancy. Furthermore, this development also requires many tests [38]. The selection of processes for a given resource can only be discussed after the process matures. Therefore, a process is not currently selected. .

**(2) A single option for developed technology**

If iron ore is found, the corresponding development goal is the use of its resources. The following steps can be performed for this analysis. First, the current market values and ultimate minable resource mass are estimated based on the ore grade. Second, the investment is calculated and an appropriate production model is selected according to the order of results to compare the process evaluation parameter of the different runs of iron and steel enterprises with the help of the above principles. In addition, capital states, the future market demand, the behavior of investors, national economic models, etc., must still be considered [39], after which the use of resources as raw materials or materials in a new plant should be decided. Only after the analysis and study are completed for the aforementioned process, can the optimal resource allocation and the best economic values be identified.

**(3) A number of options for developed technology**

The development goal is to use the coal resources if a coal mine is found. Because of the multidimensionality of the development objectives, such as coal combustion heating, coal gasification for clean fuel, coal liquefaction for oil substitute, and coal carbonization, the factors in the processes selection for the application of resources are complicated [4]. The following steps can generally be performed when considering these conditions. First, the current market values based on the coal quality and ultimate minable resource mass are estimated. Second, the developing routes are assessed. Third, suitable paths with the best process evaluation parameters in the different developing routes are selected according to steps cited for only a single option for developed technology. Fourth, the selected process evaluation parameters are compared, and the optimal process evaluation parameters, $\Omega_o$, are identified. Finally, certain concepts from having only a single developed technology are referenced to optimize the coal resource allocation.

Suppose that the utilization options only include the above four routes for the coal under perfect competition conditions [28]. In this situation, the best utilization of resources needs to be determined. The following steps lay out a specific process for selecting the optimal coal utilization.

**(I) Process selection analysis for development path**

**(i) Coal combustion heating**

First, the heat efficiencies of different coal combustion processes in industry are compared, and the process evaluation parameter values are given and ranked. Second, the appropriate process evaluation parameter, $\Omega_1$, is selected. Finally, the coal combustion process and devices are determined.

**(ii) Coal gasification for clean fuel**

The process evaluation parameters for different coal gasification processes in industry are compared and ranked, and the appropriate process evaluation parameters, $\Omega_2$, are given. Next, the coal gasification process and devices are determined.

**(iii) Coal liquefaction for oil substitute**

At present, the technology is limited to the small-scale and scaled-up experimental plant. Industrialized experiments must be processed. Therefore, the process evaluation parameter values, $\Omega_3$, are generally greater, and the experimental processes cannot be used to produce an oil substitute that is more competitive in the market.

**(iv)Coal carbonization**

The process evaluation parameters are compared for the different coal carbonization processes in industry, and the appropriate process evaluation parameter, $\Omega_4$, is given. Next, the coal carbonization process and devices are determined.

**(II) Processes comparison and selection**

The above resource utilization processes are compared, and the optimal process evaluation parameter, $\Omega_o$, is selected. Generally, the smallest process evaluation parameter, $\Omega_{min}$, is the best choice under perfect competition. That is,

$$\Omega_O = \Omega_{\min} \tag{37}$$

where $\Omega_o$ and $\Omega_{min}$ denote the optimal process evaluation parameter and the smallest process evaluation parameter, respectively.

Several concepts for the case of having only a single developed technology are referenced to optimize the coal resource allocation under the condition of a market economy [30, 31].

## Applied function analysis of the process evaluation parameter

The process evaluation parameters significantly affect not only the aforementioned undeveloped resource excavation, but also the existing resource utilization in financial terms. The parameter can be divided into two halves for analysis: dynamic resources with practical monetary value and steady resources with potential value. The process evaluation parameter is a ratio of these two sub-parameters. For steady or undeveloped resources, the identification of the most appropriate development pathway is often discussed, as stated in the last sub-section. However, accurate investment should also be fully considered for dynamic resources or capital. By observing different process evaluation parameters in the economy, the capital can identify the best investment choice, including the resource application, to avoid risk [40, 41]. If these functions of the process evaluation parameter are considered as predictive properties, they could serve as a practical property, which indicates that the process evaluation parameter will continue to decrease due to the effect of science and technology advancements on the process evaluation parameter for a specific production process. With the progress of the production process, process improvements and management enhancements would decrease the process evaluation parameter. In other words, it is a practical function that describes the decrease in the parameter. Generally, the process evaluation parameter should be compared with other parameters of a similar process in social production. The methods of process improvements and management enhancements should then be identified and performed to reach a final social average level. Thus, these analyses indicate that an appropriate method should be determined to solve various actual problems using predictive functions or practical functions of the process evaluation parameter.

Here, a predictive function and practical function of the process evaluation parameter were used to forecast the future possible tendency of the natural gas storage and transportation technology. If we assume that natural resources, such as natural cold energy, water power, solar energy, and wind energy, have zero cost in terms of the process evaluation parameter, then natural cold energy [42] or artificial cold energy converted from renewable energy, wind energy, or solar energy [43, 44, 45 and 46] by electric energy as a transitional energy can be stored as natural gas hydrate. Thus, the process evaluation parameter is smaller than for other conditions with resource costs. This parameter is therefore helpful to overcome the economic hurdle posed by the inability of natural gas hydrate storage and transportation technology to compete with pipeline natural gas transportation and liquefied natural gas transportation from a scientific viewpoint [47]. However, if we approach this problem from the perspective of the practical function of the process evaluation parameter, then natural gas hydrate cannot be currently used as an economic storage and transportation for natural gas, and process improvements and process management enhancements are necessary.

In summary, the process evaluation parameter is not only a provided parameter, but it also serves a workable purpose. The parameter includes the natural and social attributes of natural resource utilization, as well as a dual predictive role for future resource exploration or capital utilization and a practical role for process improvement and management enhancement. Whether considering resource extraction or capital utilization, the most basic function of the process evaluation parameter is the appraisal of the processes and the identification of levels, which will become an important basis and provide significant information for the development of resources and the venture forecasting of capital utilization. Moreover, the process evaluation parameter is predictive and practical of the process development direction and can thus serve to guide the direction of scientific research and engineering practice, such as the development of renewable energy storage technology for the storage of natural gas hydrate and the adjustment of the present preparation methods of natural gas hydrate.

## SUMMARY

The process evaluation parameter defined by the development processes of natural gas hydrate synthesis technology and the formative principles of the identification of process direction can guide the direction of general scientific development during resource utilization processes. This parameter can help by playing a predictive role for selecting the optimal use processes of natural resource and a practical role to improve the actual process for the utilization of resources or capital. Moreover, the use of the process evaluation parameter was described in detail using examples of resource application for different levels of science and technology. Finally, the process evaluation parameter is applicable in process selection, where it can be used to make decisions regarding resource exploitation and the venture forecasting of capital utilization. The process parameter can also predict future scientific pathways, which can guide the direction of scientific research, such as the renewable energy storage technology of natural gas hydrate storage.

## ACKNOWLEDGMENTS

The financial support from the Chinese Natural Science Foundation (No.50176051, 090410003 and 20490207), the Natural Science Foundation of Liaoning Province (No. 2013020150) and the Program for Liaoning Excellent Talents in University (No.LJQ2011134) in China are gratefully acknowledged.

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