International Journal of Innovative Research in Engineering & Management (IJIREM)
ISSN: 2350-0557, Volume-2, Issue -5, September 2015

Study of Volume Contraction and Energy Storage for the Thermal Engine of Thermal Underwater Glider

Wenliang Zhang
National Ocean Technology
Center, China

Zhesong Ma
School of Mechanical Engineering
Tianjin University
Tianjin , China
mazs@tju.edu.cn

ABSTRACT

A simplified phase-change energy storage system for the thermal engine of thermal underwater glider was presented in this paper. Based on the simplified system, the stored energy of each operation cycle and volume contraction during PCM solidification process was analyzed. The effect of four main factors which can affect the volume contraction and energy storage was studied analytically and simulated, including air solubility in liquidus PCM, residual air within the system, pressure of low pressure oil tank and pressure of high pressure oil tank. In usual parameter configuration, system pressure increases gently until 53% of PCM melts, it means actual PCM for energy storage is less than half and its utilization ratio is very low. Dissolved air in the liquidus PCM and residual air in the phase-change energy storage system can seriously reduce the stored energy during each operating cycle of thermal underwater glider. So the residual air needs to be strictly eliminated. Besides that, under reasonable parameter configuration, such as improving the pressure of high pressure oil tank can greatly improve the stored energy.

Keywords

thermal underwater glider, phase change,volume contraction, energy storage, residual air.

1. INTRODUCTION

Underwater glider as autonomous underwater vehicle has got more and more attention, because it has the characteristics of low energy consumption, large cruising range and low noise, etc. It is increasingly widely used in ocean science research. How to further reduce its energy consumption and improve efficiency is of great significance. There are various forms of energy system which are used in underwater vehicles [1,2].

According to its energy source, underwater glider can be divided into electrical underwater glider and thermal underwater glider roughly. The electrical underwater glide has got a great development recently, the most three successful commercial underwater gliders include slocum, spray and seaglider [3-5], while the thermal underwater glider is still in the lab development stage. It takes advantage of phase change [6] to realize energy conversion and storage from the sea water.

Thermal underwater glider has a special component which is called thermal engine. During its process, it ascends and descends between the upper and lower layer of sea water. When it is in the upper layer of sea water, Phase change Material (PCM) which is stored in the thermal engine absorbs heat from the warm sea water thus becoming in liquidus phase; while in the deep layer of sea water, PCM releases heat to the sea water thus becoming in solidus phase. During the phase change process in every operation cycle, the volume of PCM also changes because of its liquidusand solidus density difference thus it can be used to harvest energy from the outer environment [7].

Zang et al. [8] developed a unique interlayer thermal engine in order to decrease heat transfer time during phase change process, and experimental results showed significant improvement in the hydraulic system for the new designed configuration. Kong et al. [9] investigated the phase change process of the thermal glider numerically and experimentally, and optimized the gliding process in order to improve the energy harvest efficiency from the thermocline. Yang et al. [10] studied the effects of thermocline on the performance of thermal engine. They indicated that for the normal work of the thermal engine, there exists the threshold value of the thermocline’s depth and upper thickness. Kong et al. [11] also presented a numerical model of volumetric change rate for the phase change process within a cylindrical container. A special experimental device was designed and constructed to verify the numerical model.

In the usual modeling of the thermal engine, compressibility of air and liquidus PCM during phase change process is ignored, while it could have a remarkable effect on volume contraction and energy storage. In this paper a simplified phase-change energy storage system of the thermal engine was presented. Based on the model, detailed analysis of volume contraction and energy storage is raised, taking consideration of dissolved and residual air in the actual component. Ways to improve energy storage in each operation cycle was also putted forward.

2. NUMERICAL MODELING

2.1 Simplified phase-change energy storage system

Through appropriately simplifying the actual component of thermal engine, the schematic diagram of phase-change energy storage system is shown in figure 1 and figure 2. Phase change material (PCM) of fixed quality is stored in the heat exchange tube, the heat exchange tube is connected with two oil pipelines through one-way valves. The inlet oil pipeline is connected to an oil tank with low pressure, while the outlet oil pipeline to an oil tank with high pressure. In the actual component, PCM and oil are isolated by rubber diaphragm which is simplified as a moving boundary in this paper. The resistance which is introduced by the rubber diaphragm and the one-way valves during oil transfer is ignored in the following analysis.

When the heat exchange tube is in deep ocean with low water temperature, PCM changes from liquidus phase to solidus phase with volume contraction, consequently under the action of the low pressure, oil of the low pressure tank transfers into the heat exchange tube; while the heat exchange tube is on the ocean surface with high water temperature, PCM changes from solidus phase to liquidus phase with volume expansion, consequently the oil in the heat exchange tube is extruded into the high pressure tank, overcoming the high pressure. In the process of volume expansion and contraction of PCM, the phase-change energy storage system periodically transfers oil from low pressure tank to high pressure tank, thus realizing energy conversion and storage from the sea water.

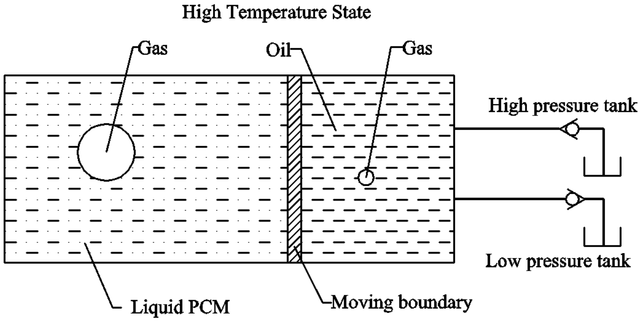

Figure 1. Heat exchange tube on the ocean surface, PCM melts with volume expansion

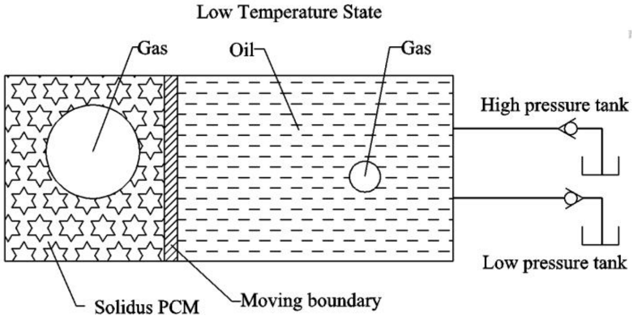

Figure 2. Heat exchange tube in deep ocean, PCM solidifies with volume contraction

2.2 Compressibility of PCM

Ignore the thermal expansion and the compression of solidus PCM. When PCM is in solidification process, due to the pressure value of low pressure tank (generally less than 0.2MPa), the compression of liquidus PCM can also be ignored. When PCM is in melting process, according to the set value of high pressure tank, system pressure can reach more than 10MPa, so the compressibility of liquidus PCM needs to be considered during melting process, namely the density of liquidus PCM changes with system pressure [13]. The current density of liquidus PCM is given by Equation (1).

$$\rho_l = \rho_{l0}[1+\frac{1}{B}(P-P_0)] \quad (1)$$

Where B is the bulk modulus of liquidus PCM.

2.3 Dissolution and evolution of air within the system

Because the variation range of sea water temperature is small, its influence on air solubility is negligible. During PCM solidification process, liquidus PCM transforms into solidus PCM continuously, the phenomenon that air bubble might form in solidus PCM is not considered. According to Henry's law, when system pressure increases, air solubility increases proportionally. It can be expressed by Equation (2).

$$s = s_0 \frac{P}{P_0} \quad (2)$$

3. ANALYSIS OF PHASE CHANGE PROCESS

3.1 Volume contraction during PCM solidification process

Under the condition of atmospheric pressure and ambient temperature, fixed quality of liquidus PCM is filled in the heat exchange tube, assuming dissolved air in liquidus PCM is saturated. There is also small amount of residual air with volume fraction of a in the phase-change energy storage system. Before the beginning of PCM solidification process, pressure of the phase-change energy storage system is Pl which is the same as low pressure tank, and the system temperature is Th which is surface sea water temperature. At the start of the solidification, temperature changes steeply to Tl which is deep sea water temperature. The system pressure maintains for Pl during the whole PCM solidification process.

3.1.1 Volume contraction of residual air caused by sudden cooling

At the start of PCM solidification process, the system temperature drops from Th to Tl, while system pressure keeps constant as Pl. The volume of undissolved air is

$$V_u = [\frac{a}{1-a} - \frac{s_0}{P_0}(P_l - P_0)]\frac{M}{\rho_{l0}} \quad (3)$$

Where Vu is the volume of undissolved air measured under standard conditions (P0,T0). While the initial condition for solidification is (Pl,Th), according to ideal gas state equation, the actual volume of undissolved air within the system is

$$V = V_u \cdot \frac{P_0}{P_l} \cdot \frac{T_h}{T_0} \quad (4)$$

When system temperature changes from Th to Tl, volume contraction of residual air caused by sudden cooling is

$$\Delta V_1 = V \cdot \frac{T_h - T_l}{T_h} \quad (5)$$

By equation (3),(4),(5), volume contraction of residual air can by expressed by

$$\Delta V_1 = \frac{T_h - T_l}{T_0} \cdot \frac{P_0}{P_l}[\frac{a}{1-a} - \frac{s_0}{P_0}(P_l - P_0)]\frac{M}{\rho_{l0}} \quad (6)$$

The heading for subsubsections should be in Times New Roman 11-point italic with initial letters capitalized and 6-points of white space above the subsubsection head.

3.1.2 Volume contraction of PCM caused by liquid-solid phase change

During PCM solidification process, because of the density difference of liquidus and solidus PCM, volume contraction caused by phase change of PCM is given in equation (7).

$$\Delta V_2 = M\omega\left(\frac{1}{\rho_{l0}}-\frac{1}{\rho_{s0}}\right) \quad (7)$$

Where   is the mass fraction of solidus PCM.

3.1.3 Volume expansion caused by evolution of dissolved air

Due to the solidification of liquidus PCM, part of dissolved air is emitted thus causing a certain amount of volume expansion, the actual volume of emitted air is measured under the actual working condition (Pl,Tl). So the negative volume contraction is

$$\Delta V_3 = -\frac{M\omega}{\rho_{l0}} s_0 \frac{P_l}{P_0}\cdot\frac{P_0}{P_l}\cdot\frac{T_l}{T_0} = -\frac{M\omega}{\rho_{l0}} s_0 \frac{T_l}{T_0} \quad (8)$$

Where   is the mass fraction of solidus PCM.

The total volume contraction during PCM solidification process is the sum of the above three parts, namely

$$\begin{aligned}\Delta V = {} & \frac{T_h - T_l}{T_0}\cdot\frac{P_0}{P_l}\left[\frac{a}{1-a}-\frac{s_0}{P_0}(\mathrm{P}_l-\mathrm{P}_0)\right]\frac{M}{\rho_{l0}} \\ & + M\omega\left(\frac{1}{\rho_{l0}}-\frac{1}{\rho_{s0}}-\frac{s_0}{P_{l0}}\cdot\frac{T_l}{T_0}\right)\end{aligned} \quad (9)$$

Substituting   into Equation (9), then

$$\begin{aligned}\Delta V \Big/ V_{l0} = {} & \frac{T_h - T_l}{T_0}\cdot\frac{P_0}{P_l}\left[\frac{a}{1-a}-\frac{s_0}{P_0}(\mathrm{P}_l-\mathrm{P}_0)\right] \\ & + \omega\left(1-\frac{\rho_{l0}}{\rho_{s0}}-\mathrm{s}_0\frac{T_l}{T_0}\right)\end{aligned} \quad (10)$$

The Equation (10) shows under normal condition the relative volume contraction is proportional to the mass fraction of solidus PCM.

3.2 Energy storage during PCM melting process

At the beginning of PCM melting process, PCM in the heat exchange tube completely solidifies, and in the phase-change energy storage system exists in the form of free gas. Temperature of the system is Tl which is the deep sea water temperature, and current pressure of the system is pl which is the pressure of low pressure tank. At the start of melting, system temperature changes steeply to temperature Th which is surface sea water temperature. The system pressure increases continuously until reaching the pressure of high pressure tank during the whole PCM melting process.

At the start of melting, the volume of residual air and solidus PCM is

$$V_1 = \frac{M}{\rho_{l0}}\left(\mathrm{s}_0+\frac{a}{1-a}\right)\frac{P_0}{P_l}\cdot\frac{T_l}{T_0}+\frac{M}{\rho_{s0}} \quad (11)$$

During the melting process, system volume remains constant until the system pressure reaches the set value of high pressure tank. Sine part of air will be dissolved in melted PCM, total volume of solid PCM volume and liquid PCM volume and undissolved air within the system can be expressed as

$$\begin{aligned}V2 = {} & \left[\frac{M}{\rho_{l0}}\left(\mathrm{s}_0+\frac{a}{1-a}\right)-\frac{M\omega}{\rho_{l0}}\mathrm{s}\right]\cdot\frac{P_0}{P}\cdot\frac{T_h}{T_0} \\ & + \frac{M(1-\omega)}{\rho_{s0}}+\frac{M\omega}{\rho_l}\end{aligned} \quad (12)$$

where   is the mass fraction of liquidus PCM,   is the system pressure.

Before the system pressure reaches the pressure of high pressure tank, total value remains constant, namely

$$\begin{aligned}& \frac{M}{\rho_{l0}}\left(\mathrm{s}_0+\frac{a}{1-a}\right)\frac{P_0}{P_l}\cdot\frac{T_l}{T_0}+\frac{M}{\rho_{s0}} = \\ & \left[\frac{M}{\rho_{l0}}\left(\mathrm{s}_0+\frac{a}{1-a}\right)-\frac{M\omega}{\rho_{l0}}\mathrm{s}\right]\cdot\frac{P_0}{P}\cdot\frac{T_h}{T_0} \\ & + \frac{M(1-\omega)}{\rho_{s0}}+\frac{M\omega}{\rho_l}\end{aligned} \quad (13)$$

3.2.1 Increasing pressure phase 1

In the above analysis, it is assumed the system pressure is less than critical pressure, so air within the system is not completely dissolved, the system pressure increases gently .This stage is called increasing pressure phase 1 which is described by the following constraint Equation (14).

$$\frac{M}{\rho_{l0}}\left(\mathrm{s}_0+\frac{a}{1-a}\right)-\frac{M\omega}{\rho_{l0}}\mathrm{s} \ge 0 \quad (14)$$

$$P_c = P_0\left(\mathrm{s}_0+\frac{a}{1-a}\right)\Big/ s_0\omega \quad (15)$$

Where   is the critical pressure.

3.2.2 Increasing pressure phase 2

When the system pressure exceeds the critical pressure, air within the system completely dissolves, system pressure increases sharply until it reaches the pressure of high pressure tank. This stage is called increasing pressure phase 2. Total volume is composed of melted liquidus PCM and solidus PCM.

$$V_3 = \frac{M(1-\omega)}{\rho_{s0}}+\frac{M\omega}{\rho_l} \quad (16)$$

Since the system volume remains constant, we can get the Equation (17).

$$P = B(1-\frac{\rho_{l0}}{\rho_{s0}}) + P_0 - (s_0 + \frac{a}{1-a})\frac{P_0}{P_l}\cdot\frac{T_l}{T_0}\cdot\frac{B}{\omega} \quad (17)$$

3.2.3 *Energy storage phase*

When the system pressure reaches the pressure of high pressure tank, energy begins to be stored with volume expansion under the constant pressure of high pressure tank. It lasts until PCM completely melts. This stage is named as energy storage phase. At the end of increasing phase 2, when the system pressure reaches Ph, the current mass fraction of liquidus PCM is .

$$\Delta V = M(1-\omega_h)(\frac{1}{\rho_l} - \frac{1}{\rho_{s0}}) \quad (18)$$

$$B(1-\frac{\rho_{l0}}{\rho_{s0}}) + P_0 - (s_0 + \frac{a}{1-a})\frac{P_0}{P_l}\cdot\frac{T_l}{T_0}\cdot\frac{B}{\omega_h} = P_h \quad (19)$$

After the system establishes a stable and continuous cycle, transferred oil volume during the solidification and melting process is equal. After deducting the input work during PCM solidification process, the net output work of each operation cycle can be expressed in Equation (20).

$$E = \Delta V(\mathrm{P}_h - \mathrm{P}_l) \quad (20)$$

Substituting $E_0 = \frac{M}{\rho_{l0}} P_0 = V_{l0} P_0$ into Equation (20), the relative stored energy within the system is given by Equation (21)

$$E/E_0 = (1-\omega_h)[1 - \frac{P_h - P_0}{B} - \frac{\rho_{l0}}{\rho_{s0}}](P_h - P_l)/P_0 \quad (21)$$

4. SIMULATION AND DISCUSSION

Under ambient pressure, density of liquidus PCM is *773kg/m3*, density of solidus PCM is *773kg/m3* [14], and the bulk modulus of liquidus PCM is *1800MPa*. Generally, High temperature of surface sea water is *301.5 K*, and low temperature of deep sea water is *278.5 K* [15]. Pressure of low pressure tank is *1.0 ~ 2.0atm*, with typical value of *1.5atm*, and pressure of high pressure tank is *10 ~ 300atm*, with typical value of *100 atm*. Under ambient pressure, air solubility in liquidus PCM is 0.06 ~ 0.1, with typical value of 0.08, and residual air in the phase-change energy storage system is 0.02 ~ 0.05, with typical value of 0.002 [13]. Based on the above numerical model and analysis, characteristic curves of PCM solidification and melting process are drawn by *MATLAB* software, as shown in figure 3 ~ 13.

4.1 Analysis of PCM solidification process

Figure 3 shows the effect of solidus PCM mass fraction and air solubility in liquidus PCM on volume contraction, figure 4 shows the effect of solidus PCM mass fraction and residual air in the system on volume contraction, and figure 5 shows the effect of solidus PCM mass fraction and the pressure of low pressure tank on volume contraction. These three figures show the relative volume contraction increases linearly with the increase of solidus PCM mass fraction. Among the three factors of air solubility,residual air and pressure of low pressure tank, air solubility has greatest effect on the relative volume contraction. With the increase of air solubility, relative volume contraction decreases obviously, while the effect of residual air and pressure of low pressure tank are not so remarkable.

With the increase of residual air in the system, relative volume contraction increases because of air volume contraction by sudden cooling, while the effect of the pressure of low pressure tank is the opposite, because before starting PCM solidification process, the initial pressure of the system is also *Pl*, which makes the residual air compressed, so the contribution of residual air to the relative volume contraction decreases.

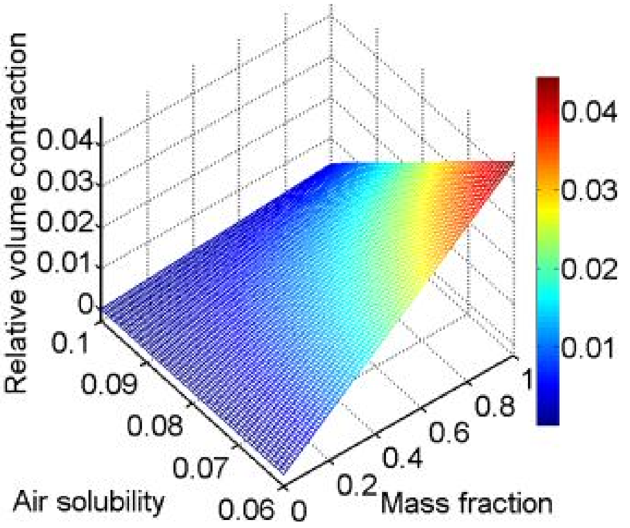

Figure 3. Effect of air solubility on volume contraction

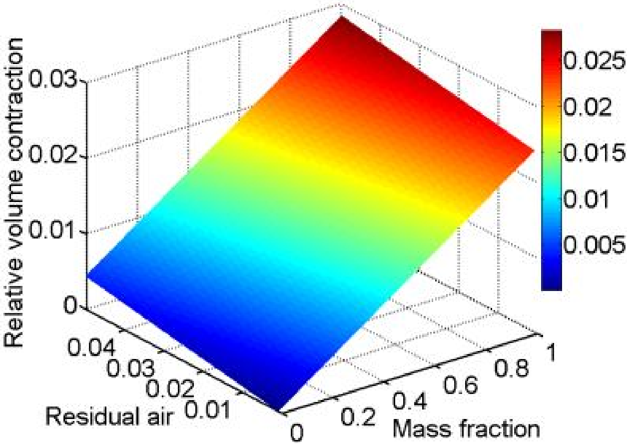

Figure 4. Effect of residual air on volume contraction

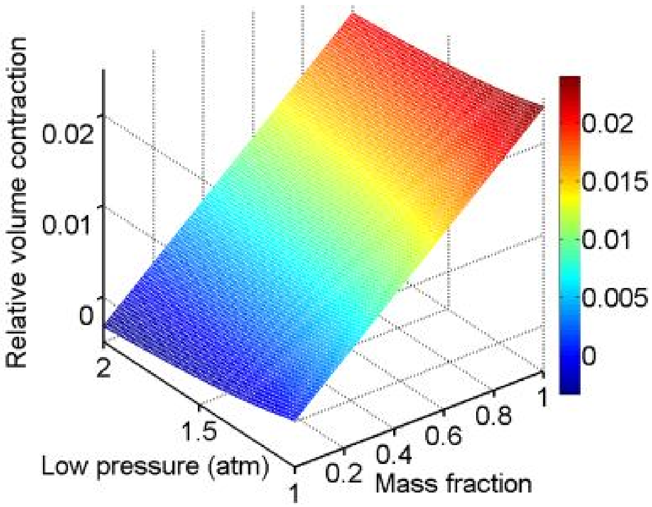

Figure 5. Effect of the pressure of low pressure tank on volume contraction

4.2 Analysis of PCM solidification process

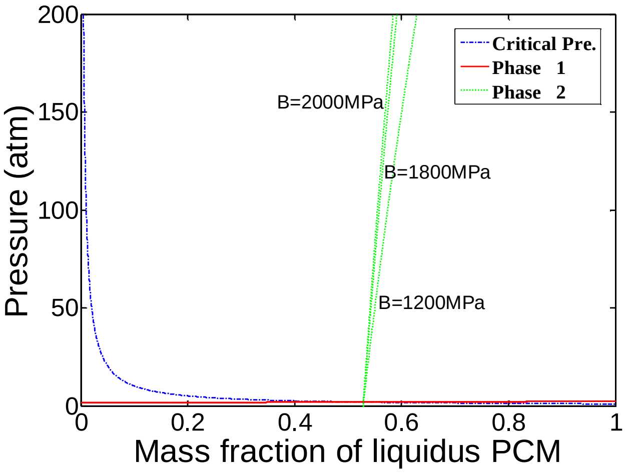

Figure 6. Typical curves of increasing pressure phase

Figure 6 is the typical curves of increasing pressure phase during PCM melting process. With the increase of liquidus PCM mass fraction, the pressure of the phase-change energy storage system increases. All the influence factors are set to be their respective typical value. The blue curve shows the critical pressure when residual air completely dissolves in liquidus PCM. In the beginning of PCM melting process, the system pressure increases gently because of residual air, as shown in red curve, this stage is named as increasing pressure phase 1. When the system pressure exceeds critical pressure, residual air completely dissolves, then the system pressure increases sharply since the bulk modulus of liquidus PCM is much higher, as shown in green curve approximately linear. This stage is named as increasing pressure phase 2. After the system pressure reaches as high as the pressure of high pressure tank, the system pressure maintains constant until PCM completely melts. There is a turning point between increasing pressure phase1 and increasing pressure phase2.

Curves also show that in usual parameter configuration, , system pressure increases gently until 53% of PCM melts, it means actual PCM for energy storage is less than half and its utilization ratio is very low.

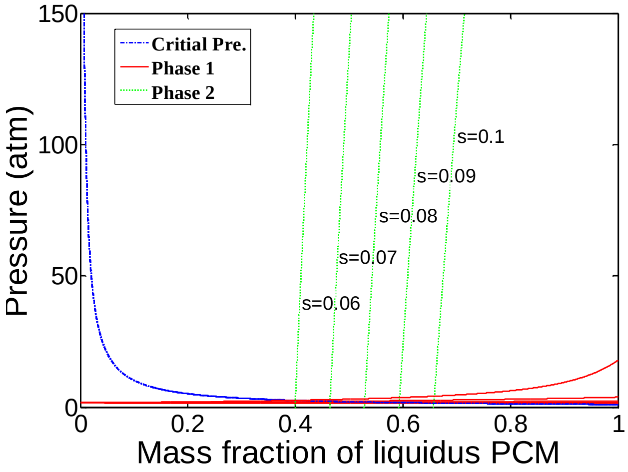

Figure 7. Effect of air solubility on increasing pressure phase

Figure 7 shows the effect of air solubility in liquidus PCM on increasing pressure phase, each air solubility value corresponds to a set of pressure curves. With the decrease of air solubility, the turning point between increasing pressure phase 1 and increasing pressure phase 2 shifts to the left obviously. Air solubility mainly affects increasing pressure phase 1, but because air solubility in liquidus PCM is a constant value under ambient pressure, it cannot be treated as a configurable parameter in practical application.

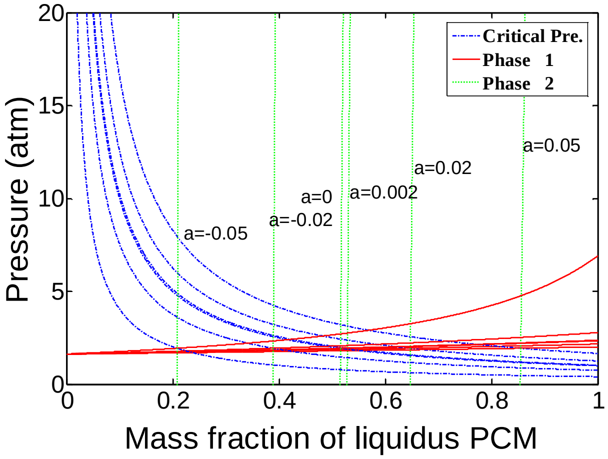

Figure 8. Effect of residual air on increasing pressure phase

Figure 8 shows the effect of residual air in the system on increasing pressure phase, each residual air value corresponds to a set of increasing pressure curves. With the decrease of residual air, the turning point shifts to the left, similar to the condition of air solubility. Residual air affects both the critical pressure curve and increasing pressure phase 1. Negative residual air value actually refers to emitted air through negative ambient pressure when filling liquidus PCM in the heat exchange tube. Curves show that decreasing the residual air can be used as an effective way of improving the utilization ratio of PCM.

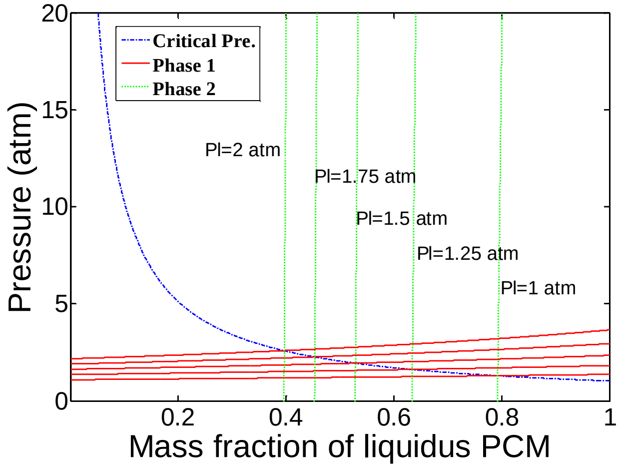

Figure 9. Effect of the pressure of low pressure tank on increasing pressure phase

Figure 9 shows the effect of the pressure of low pressure tank on increasing pressure phase, each pressure value corresponds to a set of increasing pressure curves. With the increase of the pressure of low pressure tank, the turning point shifts to the left. It only affects increasing pressure phase 1, and its effect is not so remarkable relatively.

4.3 Analysis of PCM solidification process

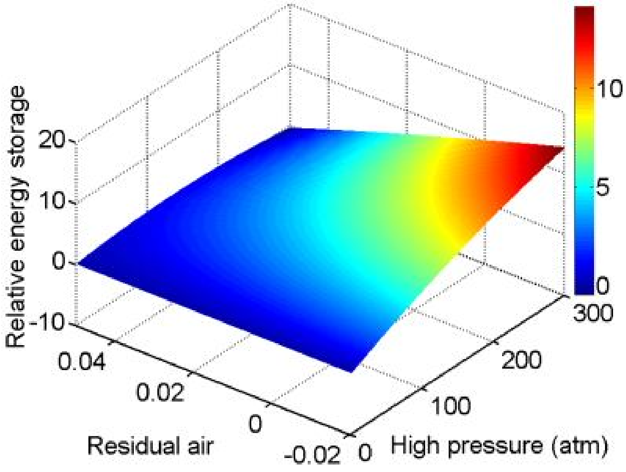

Figure 10. Effect of residual air on stored energy

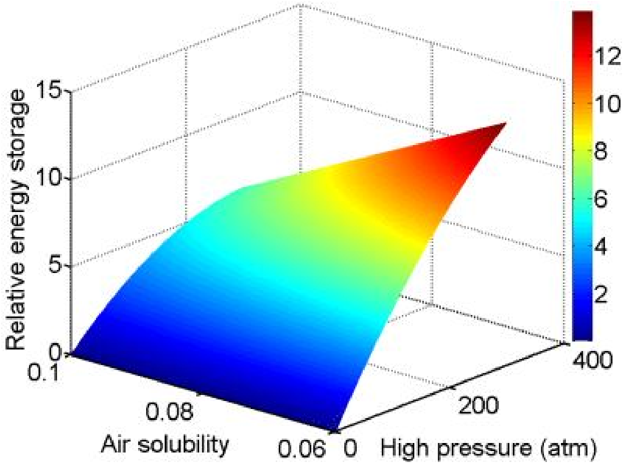

Figure 11. Effect of air solubility on stored energy

Figure 10 shows the effect of residual air within the system on stored energy. Figure 11 shows the effect of air solubility on stored energy. The influence of these two factors are similar, Under the same pressure of high pressure tank, the smaller the air solubility in liquidus PCM is, the more energy can be stored within the system, the same as with residual air. And the higher the pressure of high pressure tank is set, the more remarkable the effect of these two factors on stored energy becomes.

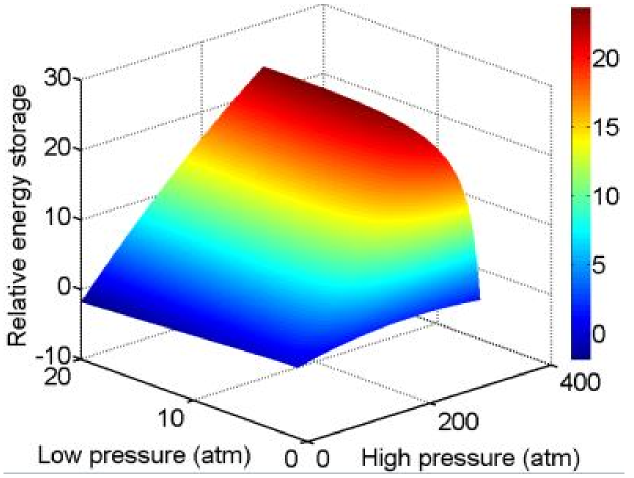

Figure 12. Effect of pressure of high pressure tank on stored energy

Figure 12 shows the effect of pressure of high pressure tank on stored energy. Under the condition of appropriately increased pressure of low pressure tank, such as pl> 5 atm, with the increase of pressure of high pressure tank, the stored energy increases nearly proportionally.

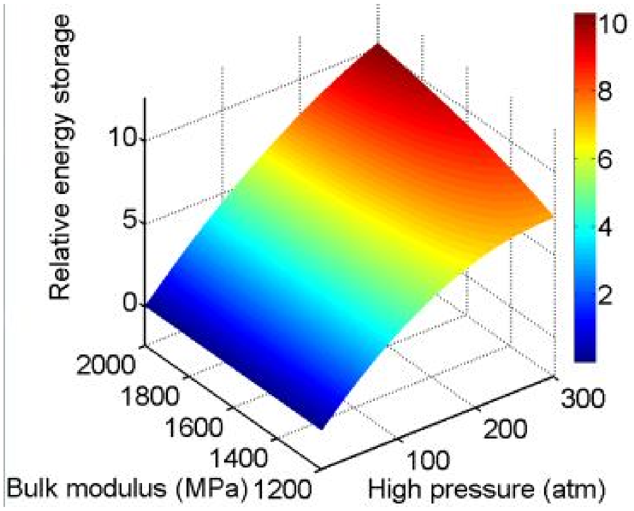

Figure 13. Effect of bulk modulus of liquidus PCM on stored energy

Figure 13 shows the effect of the bulk modulus of liquidus PCM on stored energy. When pressure of high pressure tank is within 200 atm, large variation range of bulk modulus can be reached while the stored energy shows no obvious change. It means the compressibility of liquidus PCM is also negligible.

5. SIMULATION AND DISCUSSION

During each operating cycle of thermal underwater glider, four main factors which can affect the net volume of transferred oil and stored energy within the phase-change energy storage system are analyzed, including air solubility in liquidus PCM, residual air within the system, pressure of low pressure tank and pressure of high pressure tank. The main results are as follows:

(1) Dissolved air in the liquid PCM and residual air in the phase-change energy storage system will seriously reduce the stored energy during each operating cycle. So the residual air is needed to be strictly eliminated, even filling liquid PCM in the heat exchange tube under negative ambient pressure.

(2) The bulk modulus of liquidus PCM can change in large variation range and has little effect on the stored energy since the system pressure is not high enough relatively. It is not the key factor influencing the stored energy within the system, so the compressibility of liquidus PCM can be also ignored.

(3) Under reasonable parameter configuration, such as improving the pressure of high pressure tank can greatly improve the stored energy.

The heat transfer process versus time has not been introduced in this paper, namely, it doesn’t include time variable, and this numerical model needs to be further analyzed in the future work.

6. ACKNOWLEDGMENTS

This research is supported by the National Hi-tech Research and Development Program of China (No. 2012AA091001). The authors are greatly thankful to the financial support.

REFERENCES

[1] Wang X, Shang J, Luo Z, Tang L, Zhang X, Li J. Reviews of power systems and environmental energy conversion for unmanned underwater vehicles. Renewable and Sustainable Energy Reviews 2012; 16:1958-1970.

[2] Hasvold Ø, Størkersen NJ, Forseth S, Lian T. Power sources for autonomous underwater vehicles. Journal of Power Sources 2006; 162:935-942.

[3] Sherman J, Davis RE, Owens WB, Valdes J. The autonomous underwater glider "spray". IEEE Journal of Oceanic Engineering 2001; 26:437-446.

[4] Eriksen CC, Osse TJ, Light RD, Wen T, Lehman TW, Sabin PL, et al. Seaglider: A long-range autonomous underwater vehicle for oceanographic research. IEEE Journal of Oceanic Engineering 2001; 26:424-436.

[5] Davis RE, Eriksen CC, Jones CP. Autonomous buoyancy-driven underwater gliders. Taylor and Francis, London. 2002; p. 37-58.

[6] Zalba B, Marín JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied thermal engineering 2003; 23:251-283.

[7] Webb DC, Simonetti PJ, Jones CP. SLOCUM: An underwater glider propelled by environmental energy. IEEE Journal of Oceanic Engineering 2001; 26:447-452.

[8] Zhang H, Wang Y, Lian Z. Application and Improvement of the Interlayer Thermal Engine Powered by Ocean Thermal Energy in an Underwater Glider. Power and Energy Engineering Conference (APPEEC), 2009 Asia-Pacific: IEEE 2009; p. 1-4.

[9] 9. Kong Q, Ma J, Xia D. Numerical and experimental study of the phase change process for underwater glider propelled by ocean thermal energy. Renewable Energy 2010; 35:771-779.

[10] Yang H, Ma J. Experimental Study of Effects of Thermocline on the Performance of Underwater Glider's Thermal Engine. Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific: IEEE 2010; p. 1-4.

[11] Kong Q, Ma J, Che C. Theoretical and experimental study of volumetric change rate during phase change process. International Journal of Energy Research 2009; 33:513-525.

[12] Shi P, Wang Y, Wang L. Study on Modeling and Simulation of the Hydraulic Fluid. Journal of Agricultural Machinery 2007; 38:148-151(in Chinese).

[13] Kumano H, Saito A, Okawa S, Takeda K, Okuda A. Study of direct contact melting with hydrocarbon mixtures as the PCM. International journal of heat and mass transfer 2005; 48:3212-3220.

[14] Jenkins SA, Humphreys DE, Sherman J, et al. Underwater Glider Systems Study: Pressure Case Design Displacement as a Function of Depth. Technical Report submitted to the ONR Committee. 2003.