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RESEARCH ARTICLE

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Novel methods by using non-vacuum insulated tubing to extend the lifetime of the tubing

Abstract The analysis of the failure mechanics, namely hydrogen permeation of vacuum insulated tubing (VIT), indicated that the failure of VIT could be decreased but could not be avoided. To solve this problem, some measures by using non-vacuum materials were proposed and analyzed in this paper. The results show that to fill the tubing with foam-glass beads or high pressure argon may lead to a good performance.

Keywords hydrogen permeation, vacuum insulated tubing, cyclic steam stimulation, insulation material, thermal conductivity, foam-glass

1 Introduction

Heavy oil, extra heavy oil and asphalt account for nearly 70% of the reserves of crude oil in the world. The viscosity of heavy oil is very high, so the cost and the difficulty of mining is a great challenge. Nowadays, there is little recovery of heavy oil in the world, especially in the heavy oil reservoir of the sea. Because China is not rich in crude oil, a lot of heavy oil has been mined considering the energy security in the country. For example, the annual heavy oil production in China is more than 15 million tons, of which more than 60% are developed by the cyclic steam stimulation (CSS) technology [1].

Due to the fact that the viscosity of heavy oil decreased rapidly with increasing temperature [2], heavy oil is mainly mined by heating steam injection in the world. Critical or supercritical steam is injected into the insulated tubing so that the pressure and the temperature can reach approximately 22 MPa and 370°C, respectively. As a result, the thermal insulation effect and strength requirement of the insulated tubing are very high. Vacuum insulated tubing (VIT) is widely used after years of improvement.

The theoretical lifetime of VIT is approximately seven years. However, in reality, a VIT is often used for less than one year before it is scrapped. Considering the high maintenance costs of offshore oil production, the improvement of the lifetime of tubing has become a prominent problem.

2 Main factors affecting service lifetime of VIT

2.1 What is VIT?

Figure 1 is the sectional view of a VIT. A VIT is mainly made of the inner tube, the outer tube and the heat insulation system etc. Both the inner tube and the outer tube are made of the N80 steel. Prestressing force treatment is taken on the inner tube before welding, some Aluminum foil insulation layers are filled between the inner and outer tube in order to reduce the radiation heat transfer, and some gas adsorbent is placed between the insulation layers. Therefore, the VIT can effectively reduce the energy loss caused by heat conduction, convection and radiation heat transfer at the initial stage.

According to the apparent thermal conductivity of VIT at 350°C, the VIT can be divided into five levels: $0.002 \leqslant E < 0.006$; $0.006 \leqslant D < 0.02$; $0.02 \leqslant C < 0.04$; $0.04 \leqslant B < 0.06$; $0.06 \leqslant A < 0.08$. The unit of the thermal conductivity is $\mathrm{W/(m \cdot K)}$.

2.2 Main failure mode of VIT

A lot of field research on the steam injection process evidently proves that "hydrogen permeation" is the main reason for the VIT failure. The principle diagram of

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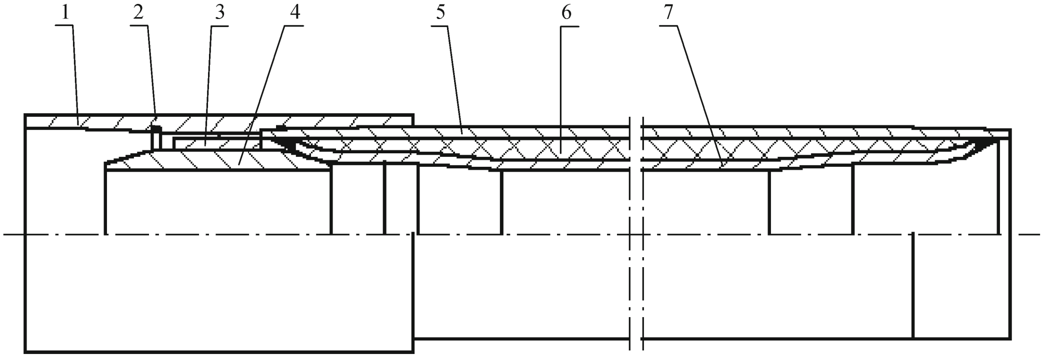

Fig. 1 Sectional view of a VIT

1—collar; 2—seal ring; 3—insulating bushing; 4—screened pipe; 5—outer tube; 6—heat insulating material (vacuum space); 7—inner tube

hydrogen permeation is shown in Fig. 2.

Due to the very small molecular size, hydrogen molecules penetrate through sheet metal without defects and come into the vacuum heat insulation layer. Free motion of hydrogen molecules between the inner and outer tube causes the very high thermal conductivity, which is approximately seven times of that of air and destroys the thermal insulation performance of the VIT at a pressure of 10 kPa in a vacuum space. The strong hydrogen permeability allows the molecular hydrogen to penetrate through rubber and latex tube at atmospheric pressure, and penetrate through palladium, nickel, steel and other metal films at a higher pressure in the mine.

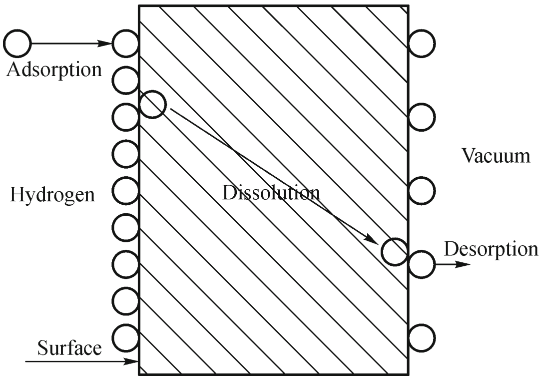

Fig. 2 Principle diagram of hydrogen permeation

From a microscopic point of view, the hydrogen permeation process occurs according to the following steps [3–5]. First, the hydrogen molecules impact onto the outer surface of the vacuum environment, and are absorbed by the outer surface. Then, part of the hydrogen molecules which are absorbed by the outer surface are dissociated into an atomic state. Next, the hydrogen atoms reach an equilibrium solubility on the outer surface. After that, because of the existence of concentration gradient, the hydrogen atoms are diffused to the surface of the vacuum side. Finally, the hydrogen atoms are released into the vacuum environment after combined into the molecular state.

By analyzing the process of hydrogen permeability, it is not hard to find that it is impossible to avoid hydrogen permeability, although some measures can be taken to moderately slow down the process. Besides, CRC Handbook of Chemistry and Physics has described that the data of the thermal conductivity of hydrogen (λ_{H_2}) vary with temperature (T), as shown in Table 1 [6].

Table 1 demonstrates that the thermal conductivity of hydrogen increases with the increase in temperature quickly. Its thermal conductivity has reached 0.2304 W/(m·K) when the temperature is 400 K (approximately 127°C), which is far greater than the minimum requirement of VIT (0.08 W/(m·K)). It is noteworthy that the working temperature of VIT is approximately 350°C. Therefore, its thermal conductivity is much larger than 0.2304 W/(m·K).

Table 2 lists the test data of hydrogen permeation of VIT for steam injection well from a Canadian company. As can be seen from Table 2, the tubing which is working for more than 300 days has very high hydrogen content, and its thermal conductivity has risen to an unacceptable level. So, the conclusion may safely be drawn that the VIT will fail with intensification of hydrogen permeation and cannot meet the insulation requirements.

Table 1 Variation of thermal conductivity of H_2 with the change of temperature

	T/K			
	100	200	300	400
λ_{H_2} /(W·(m·K)$^{-1}$)	0.0686	0.1317	0.1869	0.2304

Table 2 Test data of hydrogen permeation of a VIT for steam injection well from a Canadian company [7]

Depth/m	Working time/d			Thermal conductivity/(W·(m·K)$^{-1}$)	
	Steam injection	Oil recovery	Total	Initial	Final
24	108	213	321	0.028	0.155
12	108	425	533	0.023	0.190
305	108	213	321	0.020	0.155

Note: Insulated tubing 127 mm×89 mm, no adsorbent

3 Feasibility of non-vacuum insulated tubing

3.1 Feasibility of filling with organic insulation materials

The thermal conductivity of common organic foaming materials is low, but the allowable maximum temperature is not high enough, as is listed in Table 3.

Table 3 Specific parameters of filling materials

	Thermal conductivity / (W·(m·K)$^{-1}$)	Allowable maximum temperature/°C
Phenolic foam	0.035	⩽200
Polyurethane foam	0.024	⩽190

The on-site inspection demonstrates that at depths of several kilometers underground, geothermal heat may increase above 100°C and critical or supercritical steam temperatures may reach above 350°C or more. Therefore, materials such as phenolic foam obviously do not meet the requirements of the working temperature.

The best high temperature resistant organic material is polyether ether ketone (PEEK) and polyimide (PI), continuous use temperature of PEEK can be up to 250°C, and long-term use temperature of PI reaches 300°C–350°C, however, their temperature resistance will be a certain decline when they are made of foaming materials.

The PEEK and PI raw materials are very expensive, thus, they are mainly used in aircraft and spacecraft at present, but rarely used in general industry. In conclusion, the use of organic insulation material for the insulation tubing is extremely difficult, and it is not an ideal choice.

3.2 Feasibility of filling with inorganic foaming insulation materials

Inorganic insulation materials can be divided into inorganic foaming insulation materials and inorganic non-foaming insulation materials. Considering unavoidable hydrogen permeation, mineral wool, glass wool and other inorganic non-foaming insulation materials cannot barrier the free movement of hydrogen between the inner and outer walls of the tubing. When hydrogen permeation occurs, the insulation performance of inorganic non-foaming insulation materials will drop significantly. Therefore, only inorganic foaming insulation materials can be considered.

If the composite which has the substrate of hollow glass bead is used, the free movement of hydrogen between the inner and outer walls of the tubing will be blocked, thereby reducing its damage to the insulation properties of tubing. Lattice structure of boron silicate glass also has some functions to prevent hydrogen molecules across the insulation materials.

As one of the insulation materials which have very good insulation properties under high temperature, hollow glass beads (Fig. 3) have the characteristics of fine particles, hollow, light, temperature, alkali, chemical stability and so on [8]. Generally, its particle size ranges from 15 μm to 135 μm, its wall thickness is up to 3 μm, its true density is approximately 120 kg/m^3, its mechanical strength can reach 1.7 MPa, and its thermal conductivity is smaller than 0.035 W/(m·K). So, theoretically, foam-glass beads have the insulation effect of VIT at level C, and have a high research value.

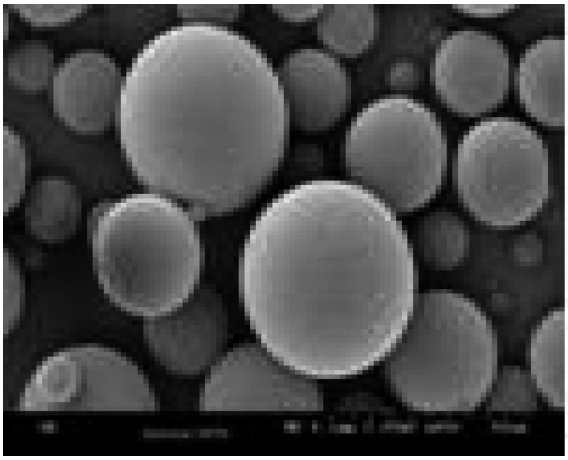

Fig. 3 Hollow glass beads (HGB)

In addition, molding foam-glass blocks have good insulation properties. Figure 4 illustrates a foam-glass block whose density is approximately 140 kg/m^3 and thermal conductivity is approximately 0.045 W/(m·K) at normal temperature. Besides, the relationship between the

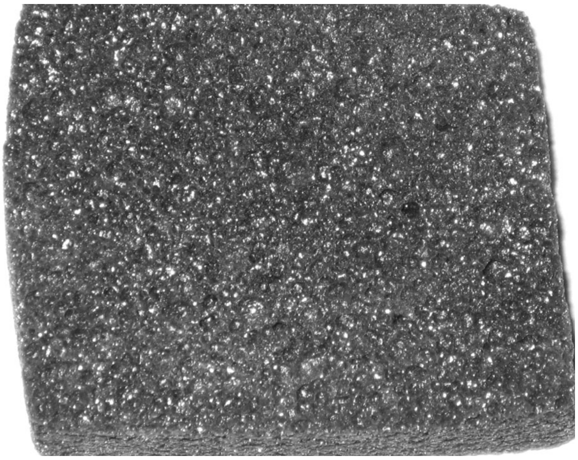

Fig. 4 Foam-glass block

temperature and the thermal conductivity is obtained, which is $\lambda_{\mathrm{H_2}} = \lambda_{25^\circ\mathrm{C}} + 0.000183(t–25)$.

As the thermal conductivity of inorganic foaming materials insulation tubing should be slightly higher than that of the VIT, the thickness of the insulation layer can be appropriately increased to reduce the flux density of inorganic foaming materials insulation tubing, so as to achieve an equivalent insulation effect of unused VIT.

The main advantage of inorganic foaming materials is that the bubbles of inorganic foaming materials play the role of restricting the movement of hydrogen molecules when hydrogen molecules penetrate into them, and thus largely limit the heat transfer performance of hydrogen.

The foam-glass blocks are chosen as an example to illustrate the insulation effect of inorganic foaming materials after hydrogen permeation. The gas inside the bubbles of the foam-glass is mainly carbon dioxide whose thermal conductivity is approximately 0.014 W/(m·K) at atmospheric pressure and 0°C, which meets the requirements of VIT at level D.

The thermal conductivity of the mixture of hydrogen and carbon dioxide at 25°C is provided by Tsederberg [9], as is shown in Table 4.

Table 4 shows that the thermal conductivity of mixed gas (λ_{m}) can meet the requirement of VIT at level C when q is approximately 20%. Considering the rise of temperature and the presence of solids in foam-glass, the thermal insulation effect of foam-glass insulation tubing will be weakened, but it will still be far better than that of an invalid VIT. What is needed is only to increase the thickness of the insulation layer appropriately.

3.3 Feasibility of filling with high pressure argon

3.3.1 Thermal conductivity of argon

Bich et al. [10] have discovered that the thermal conductivity of argon varies with the change of temperature at atmospheric pressure, as shown in Table 5.

Table 5 indicates that the thermal conductivity of argon at 700 K (about 427°C) is only 0.034 W/(m·K), meeting the VIT at level C. Therefore, it must be able to meet the insulation requirement at the operating temperature (350°C).

3.3.2 Effect of pressure on thermal conductivity of argon

According to Table 6, it is easy to find that the influence of pressure on the thermal conductivity of argon is extremely small. When the pressure increased from 0.1 MPa to 1 MPa, the thermal conductivity of argon at 260 K increased by only 3.16%, and with the increase of temperature, this value is reduced: the thermal conductivity of argon at 380 K increased by only 1.38% when the pressure increased from 0.1 MPa to 1 MPa. So, it will not introduce too much error if the thermal conductivity at atmospheric pressure is used instead of the thermal conductivity at 1 MPa.

Table 4 Thermal conductivity of mixture of hydrogen and carbon dioxide at 25°C

	q				
	0.047	0.193	0.496	0.906	0.964
λ_{m}	0.01855	0.03173	0.06335	0.1466	0.16841

Notes: q—the mole fraction of hydrogen; λ_{m}—the thermal conductivity of the mixture of hydrogen and carbon dioxide

Table 5 Variation of thermal conductivity of argon with the change of temperature at atmospheric pressure

	T/K																
	270	280	290	300	320	340	360	380	400	420	440	460	480	500	550	600	700
$\lambda_{\mathrm{Ar}}/(\mathrm{W}\cdot(\mathrm{m}\cdot\mathrm{K})^{-1})$	0.01627	0.01678	0.01729	0.01779	0.01876	0.01972	0.02065	0.02156	0.02244	0.02331	0.02416	0.02499	0.02580	0.02660	0.02855	0.03041	0.03395

Table 6 Variation of thermal conductivity of argon with temperature and pressure [6] Unit: $(\mathrm{W\cdot(m\cdot K)^{-1}})$

T/K	p/MPa		
	0.1	1	10
260	0.0158	0.0163	0.0214
280	0.0169	0.0173	0.0218
300	0.0179	0.0183	0.0223
320	0.0189	0.0192	0.0229
340	0.0199	0.0202	0.0235
360	0.0208	0.0211	0.0242
380	0.0217	0.022	0.0249

Table 7 Thermal conductivity of hydrogen-argon mixtures at 0°C

	q						
	0	0.09	0.18	0.4	0.6	0.802	1
$\lambda_m/(\mathrm{W\cdot(m\cdot K)^{-1}})$	0.01633	0.02303	0.03057	0.05276	0.07830	0.11305	0.16915

Notes: q—Mole fraction of H_2, λ_m—thermal conductivity of hydrogen-argon mixtures

3.3.3 Thermal conductivity of hydrogen-argon mixtures

Table 7 presents the thermal conductivity of hydrogen-argon mixtures at 0°C.

From the data of the thermal conductivity of hydrogen-argon mixtures at 0°C provided by Brokaw [11], it is not hard to find that the thermal conductivity of mixtures (λ_m) is approximately 0.03 W/(m·K) at 0°C when the mole fraction of hydrogen is approximately 18%, which is equivalent to the VIT of C-level. Nobody can deny the fact that the thermal conductivity must be higher than 0.03 in the working temperature (100°C–350°C), but the increase is limited.

Assume that the pressure of the initial argon is 1 MPa, and then there is hydrogen permeation of 0.22 MPa, at this time, the mole fraction of hydrogen is approximately 18% and λ_m approximates 0.03057 W/(m·K) at 0°C. This means that there is still a long service lifetime, since it takes a long time for hydrogen to penetrate into insulated layers at a pressure of 0.22 MPa compared with the lifetime of VIT. However, when the vacuum layer is filled with hydrogen at 0.22 MPa, the VIT has already become a waste tubing. Besides, the pressure difference of VIT is greater than that of argon-filled insulated tubing. So the hydrogen permeability rate of VIT is faster, which means that the VIT is easier to fail.

3.4 Insulated tubing filled with both high-pressure argon and foam-glass beads

It is advisable to fill the insulated tubing with high-pressure argon which has excellent thermal insulation properties when there is certain hydrogen permeability. On the other hand, although the thermal insulation property of the insulated tubing filled with foam-glass beads is poorer than that filled with high-pressure argon, the insulated tubing filled with foam-glass beads has its unique advantages. First, it is not high demanding for the seal of the insulated tubing. When hydrogen permeation occurs, the thermal insulation property of tubing with high-pressure argon will degrade rapidly, while the thermal insulation property of tubing filled with foam-glass beads is not so sensitive to hydrogen permeation. Second, the tubing filled with foam-glass beads is less expensive because the foam-glass beads are easy to get and process.

However, the foam-glass beads are fragile as their walls are only 3 μm. Moreover, the heat loss of the gap between the walls must be prevented, so the gap is to be filled. Therefore, it is advisable to fill the insulated tubing with both foam-glass beads and argon.

4 Conclusions

By analyzing the failure mechanics of VIT, a conclusion can be drawn that the failure of VIT caused by hydrogen permeation is inevitable although there are ways to slow it down. To solve this problem, ways of using non-vacuum materials were proposed and analyzed. The results show that it is not feasible to fill the tubing with organic foaming insulation materials, while it is advisable to fill the tubing with inorganic foaming materials or high-pressure argon. It may lead to a better performance to fill the tubing with both foam-glass beads and argon.

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