Comparison of the hydrogen permeation rate of the argon filled tubing and the vacuum insulated tubing

**Figure 1** The principle diagram of the hydrogen permeation

From the microscopic point of view, hydrogen permeation process is carried out according to the following steps:

1. First, the hydrogen molecules impact to the outer surface of the vacuum environment, and adsorbed by the outer surface;
2. Second, part of the hydrogen molecules which are adsorbed by the outer surface can be dissociated into atomic state;
3. Third, hydrogen atoms reaches an equilibrium solubility on the outer surface;
4. Fourth, because of the existence of concentration gradient, hydrogen atoms are diffused to the surface of the vacuum side;
5. Fifth, hydrogen atoms are released into the vacuum environment after combined into the molecular state.

According to the law of diffusion, the formula of permeation rate of gas can be deduced:

$$Q = \frac{K \cdot A \cdot \Delta p^{1/2}}{h}$$

Where:
- $Q$ is the permeation rate of gas;
- $K$ is the permeability coefficient of a gas to a solid;
- $A$ is the area of surface;
- $\Delta p$ is the difference of gas pressure between the two sides of the wall;
- $j$ is the dissolution constant, if the solid is metal and the gas is diatomic molecule, such as hydrogen, $j=2$;
- $h$ is the wall thickness.

According to the above formula, we can see that the rate of hydrogen permeation($Q$) is proportional to the pressure difference of $1/2$ times ($\Delta p$). Existing in the insulated tubing is about 350℃ water vapor, and its pressure is about 21MPa. The pressure of argon filled tubing is about 1MPa, and the pressure of vacuum insulated tubing is close to 0. Therefore, we may safely draw the conclusion that $\Delta p$ of the argon filled tubing is smaller than that of the vacuum insulated tubing, namely hydrogen permeation of the argon filled tubing is slower than that of the vacuum insulated tubing.

**Table 1** thermal conductivity of N80 steel as the change of temperature

<table>
<thead>
<tr>
<th>T(℃)</th>
<th>100</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$(W/(m·℃))</td>
<td>41.9</td>
<td>41.9</td>
<td>38.9</td>
<td>32.7</td>
<td>26.0</td>
</tr>
</tbody>
</table>

Table 1 thermal conductivity of N80 steel as the change of temperature

The thermal conductivity of $H_2$, Ar and $H_2$–Ar gas mixture at different temperatures

According to the chemical compositions, standard steels can be classified into three major groups: carbon steels, alloy steels, and stainless steels. Carbon Steel is defined as follows: alloying elements do not exceed these limits: 1% carbon, 0.6% copper, 1.65% manganese, 0.4% phosphorus, 0.6% silicon, and 0.05% sulfur.

According to the N80 Steels from Sumitomo, Mannesmann, the United States, the Czech Republic and other places, we can get its chemical composition: 0.3%-0.4% carbon, 0.02% copper, 1.25%-1.62% manganese, 0.013%-0.022% phosphorus, 0.25%-0.38% silicon, 0.005%-0.008% sulfur, therefore, it can be concluded that N80 is a typical carbon steel.

Carbon content is the main factors affecting the thermal conductivity of carbon steel. Smithells Metals Reference Book has provided the thermal conductivity of carbon steel whose carbon content is 0.4%, its value is as follows:

**Figure 2** Temperature maps
Besides, heat–flux densities of vacuum insulated tubing at different levels were calculated, as shown in the following table:

Table 2  
<table>
<thead>
<tr>
<th>Level</th>
<th>C(λ=0.02)</th>
<th>B(λ=0.04)</th>
<th>Failure critical point(λ=0.08)</th>
<th>After hydrogen permeation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat–flux density</td>
<td>1013</td>
<td>2023</td>
<td>4043</td>
<td>13629</td>
</tr>
</tbody>
</table>

Table 2 heat–flux densities of vacuum insulated tubing at different levels  
In addition, the heat–flux density of argon filled tubing containing different content of hydrogen were calculated, as shown in the following table:  
Table 3  
<table>
<thead>
<tr>
<th>The content of hydrogen</th>
<th>0</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat–flux density</td>
<td>1329</td>
<td>1841</td>
<td>2438</td>
<td>3090</td>
<td>3858</td>
<td>3858</td>
</tr>
</tbody>
</table>

Figure.3 heat–flux maps

Table 3 Heat–flux of argon filled tubing containing different content of hydrogen  

<table>
<thead>
<tr>
<th>3</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
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<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

By comparing the tables of (2) and (3), we can see that the insulation effect of argon filled tubing is slightly inferior to the vacuum insulated tubing of C class at the initial stage, however, it is enough to meet the requirement of thermal insulation effect.

When a certain amount of hydrogen is penetrated, the heat–flux density of the vacuum insulated tubing will reach to more than 13 thousand, so, the tubing cannot meet the requirements of thermal insulation effect at all.

However, when the content of hydrogen permeated into the argon filled tubing is above 40%, the tubing will be near to the critical value of failure. So that the heat insulated tubing life is greatly extended in the premise of perfect heat insulation effect. Therefore, the insulated tubing filled with high pressure argon is better than the vacuum insulated tubing considering the lifetime and heat insulation effect.

Reference


