Research on NH₃-SCR reductant technology progress for diesel vehicles

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Abstract. This paper describes the technical principle, research status and application status of four reducing agents (aqueous urea solution, solid ammonium salt, solid ammonia compound and liquid ammonia) which supply NH₃ for SCR of diesel vehicles, introduces the replacement methods of solid ammonia, and analyzes the application feasibility of liquid ammonia. A comprehensive comparative study of the four reducing agents is carried out in terms of storage and validity requirements, low temperature performance, ammonia storage capacity, replacement mode, replacement frequency, safety, cost and future application prospect. It is found that the ammonia storage density of solid ammonia and liquid ammonia is 2.5 ~ 3.5 times of that of aqueous urea solution. And there is no significant difference in the theoretical use cost of several reducing agents, however, the actual use cost of aqueous urea solution is higher than the theoretical value on account of its actual decomposition rate less than 100%. The analysis shows that the requirements for NH₃-SCR reductant technology in the future are excellent low temperature supply capacity, small space occupation, convenient use, low cost and guaranteed quality, and etc.. As a traditional technology, aqueous urea solution is easy to crystallize at low temperature and can not meet the requirements of low temperature performance. Solid ammonium salt also has the problem of crystallization at low temperature. Solid ammonia compounds meet the above requirements, and the market application is gradually mature. If liquid ammonia wants to be applied in large-scale engineering, its safety problem of storage tank should be solved..

1 Introduction

Air pollution and global warming are the main environmental problems facing China at present. “World air quality report 2019” issued by Swiss air quality technology company on
February 25, 2020, points out that the air quality of Chinese cities has improved significantly, however, there are still 48 cities among the 100 cities with the most serious air pollution level in the world. On September 22, 2020, our General Secretary Xi Jinping solemnly declared in the general debate of the 75th UN General Assembly that "China will enhance the state's independent contribution, adopt more effective policies and measures, strive to achieve the carbon peak value before 2030, and strive to achieve carbon neutralization by 2060". In order to achieve the overall goal, diesel vehicles, as an important contributor of air pollutants and carbon emission, have to set their emission reduction goals and improve fuel economy at the same time. According to the “Annual Report of China Mobile Source Environmental Management (2019)”, the total NOx emission of diesel trucks in 2018 will reach 3.13 million tons, accounting for 60% of the total vehicle emission, which is the key point of mobile source NOx emission control. At present, ammonia selective catalytic reduction (NH3-SCR) technology is the key technology for diesel vehicle to remove NOx, which uses NH3 as reductant to convert NOx to N2 and H2O. Since NH3 is a kind of toxic gas with pungent odor, the safety of NH3 application become the primary technical requirement for selecting SCR reductant for vehicles at the beginning. Aqueous urea solution, which is a precursor of NH3, has the outstanding advantages of low price, non toxicity, no pungent smell, safe storage and convenient transportation. Therefore, it has become the earliest commercial NOx reducing agent technology for diesel vehicles in the world and is still widely used now.

In order to further reduce the carbon emission of diesel engine, the non-EGR route of optimizing the engine combustion is likely to be the main route of diesel engine technology. However, this technology will also increase the NOx emission and further decrease the exhaust temperature at the same time. Then more stringent requirements will be imposed on the De-NOx capacity of NH3-SCR system, especially the low temperature performance. And it is becoming an important technical requirement to supply NH3 at low temperature. Unfortunately, aqueous urea solution, which is easy to crystallize with low decomposition rate at low temperature, is difficult to meet the requirements of emission regulations. For this reason, the researchers has made a feasibility study on new replacement technologies of reactant such as solid ammonia and liquid ammonia. In this paper, the principles, the latest research progress, advantages and disadvantages, and application prospects of these different technologies are compared, and the future development direction of reductant technology is summarized and analyzed.

2 Aqueous urea solution

2.1 Working principle of ammonia supply by aqueous urea solution

The commercial name of aqueous urea solution is "DEF" in America, "AdBlue" in Europe and "AUS 32" in China. The matching system of aqueous urea solution and SCR is called Urea-SCR system, and the working principle of the system is shown in Fig. 1.
And it is becoming an important technical requirement to supply NH₃ at low temperature. Aqueous urea solution, which is a precursor of NH₃, is widely used in diesel vehicles in the world and is still widely used now. It has the outstanding advantages of low price, non-toxicity, no pungent smell, safe storage and convenient transportation. Therefore, it has become the earliest commercial NOx reducing reductant to convert NOx to N₂ and H₂O. Since NH₃ is a kind of toxic gas with pungent odor, the safety of NH₃ application became the primary technical requirement for selecting SCR reactant such as solid ammonia and liquid ammonia. In this paper, the principles, the latest research progress, advantages and disadvantages, and application prospects of these different technologies are compared, and the future development direction of reductant technology is summarized and analyzed.

2.1 Working principle of ammonia supply by aqueous urea solution

The technical principle of the system is that the aqueous urea solution is pumped out from the urea tank through the urea pump, and then the aqueous solution is atomized and sprayed into the engine exhaust pipe through the injection system. When the spray impinges on the exhaust pipe, it absorbs heat rapidly then evaporates, dehydrates, and precipitates granular or molten urea (Reaction 1). And then it absorbs heat at temperatures above 152 °C to release HCNO and NH₃ (Reaction 2). After contacting with the catalyst, HNCO is further hydrolyzed to NH₃ (Reaction 3) [1,2] at temperature above 180 °C.

\[
\begin{align*}
(NH₂)₂CO \cdot 7H₂O & \rightarrow (NH₂)₂CO(s) + 7H₂O(g) \quad (1) \\
(NH₂)₂CO(s) & \rightarrow NH₃(g) + HNCO(g) \quad (2) \\
HNCO(g) + H₂O(g) & \rightarrow NH₃(g) + CO₂(g) \quad (3)
\end{align*}
\]

2.2 Status of aqueous urea solution technology

Due to its inherent physical and chemical properties, aqueous urea solution exposes some technical defects after it was put into use, such as easy crystallization, low decomposition efficiency and complex by-product at low temperature and leading to inaccurate injection[3-5]. To solve the problems of low temperature application, the urea tank defrosting and heating function is equipped in the north area of China. When the temperature of aqueous urea solution is lower than -5 °C, the engine coolant, which runs from the engine water to the urea tank, will open the circulation flow to thaw the urea tank once it has reached 60 °C. And this way will bring great energy consumption.

In addition, some researchers have researched on low temperature resistant type of aqueous urea solution. However, due to the strict cleaning requirements of SCR system, the range of modifiers available is very limited, for example, metal salt can significantly reduce the freezing point of water solution. However, metal ions will make SCR catalyst toxic and inactive, so the optional improver can not contain metal elements, and the range of selection is very limited. For example, the inorganic modifier can only select ammonium substances, such as ammonium formate (NH₄HCO₂), ammonium carbonate ((NH₃)₂CO₂), and ammonium bicarbonate (NH₄HCO₃), etc., but the ammonium substances in crystal or powder are easy to dissolve unevenly, which affects the overall stability of the solution. Among them, the emission exhaust after the reduction reaction of ammonium formate is acidic, which also has corrosion effect on the vessel and pipeline, and can be decomposed into highly toxic gas HCN at 180 °C, and the high price of NH₄HCO₂ causes the cost increase greatly [6,7]. If organic improvers are used, small molecular liquid alcohols, such as ethanol, methanol,
ethylene glycol, etc., can effectively reduce the freezing point, but they have strong volatility and inflammable and explosive properties; Alcohol ethers, alcoholamines or amides can avoid the disadvantages of small molecular liquid alcohols, but increase a lot of cost too[9,10]. Recently, there are some aqueous urea solution products declared being suitable for low temperature present in the market, however, since the price is some higher than that of ordinary type and the application effect is not obviously outstanding, the market reaction is relatively cold.

### 2.3 Storage and quality guarantee period requirements of aqueous urea solution

SCR system is very sensitive to pollution, so the cleanliness of SCR reductant is very strict. If the qualified aqueous urea solution does not be stored and transported under the specified conditions, it will also have a great impact on its quality. The storage conditions of aqueous urea solution directly affect the product quality, and the suitable storage condition is to keep it in a closed and light free condition at the temperature between -5 ℃ to 25 ℃. The quality guarantee period of aqueous urea solution recommended under different storage temperatures is shown in Fig. 2.

![Fig. 2. Recommended shelf life of urea aqueous solution at different storage temperatures.](image)

It can be seen from Fig. 2 that the quality guarantee period of aqueous urea solution decreases linearly with the storage temperature. When the storage temperature is 35 ℃, the quality guarantee period is only 6 months. When the storage temperature is higher than 35 ℃, it is recommended to check the alkalinity and other indicators before use. Since the quality guarantee period of aqueous urea solution after unsealing does not exceed 30 days, it should be used up as soon as possible after filling in hot weather to avoid algae breeding and urea decomposition deterioration caused by high ambient temperature or exposure to the sun. At the same time, in the process of urea solution filling, it should be ensured that the filling environment and filling equipment are clean, and the dust, water, oil and other kinds of pollution will affect the SCR system function.

### 3 Solid ammonia technology

#### 3.1 Working principle of SSCR system
According to the different precursors containing ammonia, there are solid ammonia salt and solid ammoniate two types of solid ammonia technology. The principles of the two technologies applied in SCR system are similar, which is collectively referred to as Solid-SCR (SSCR) system. The working principle of the SSCR system is shown in Fig. 3.

![Fig. 3. Schematic diagram of SSCR system.](image)

Compared with Urea-SCR system, SSCR system uses direct injection of gaseous ammonia into the exhaust pipe, which has no pyrolysis and hydrolysis process and the mix of ammonia with exhaust components is much easier, and the system is more simple: 1) The configuration of vulnerable parts such as liquid pump and high-pressure atomizer is omitted; 2) Specific injection angle and position constraint is not necessary; 3) The exhaust pipe from nozzle to SCR catalyst is shortened; 4) The hydrolysis catalyst is omitted and the catalyst volume is reduced.

### 3.2 SSCR technology based on solid ammonium salt

#### 3.2.1 Technical principle of ammonia supply by solid ammonium salt

Ammonium carbamate (NH$_4$COONH$_2$), ammonium carbonate and ammonium bicarbonate are widely used in agriculture. Due to the low price of raw materials, simple technical principle, low decomposition temperature, convenient and safe storage and transportation, they have become the first solid ammonia research objects. The release of NH$_3$ from the three ammonium salts is all a one-step reaction without any intermediate products. Their order of decomposition ability is ammonium carbamate > ammonium carbonate > ammonium bicarbonate. The reaction formulas are as follows[11].

\[
NH_4COONH_2 \leftrightarrow CO_2 + 2NH_3 \tag{4}
\]

\[
(NH_4)_2CO_3 \leftrightarrow CO_2 + H_2O + 2NH_3 \tag{5}
\]

\[
NH_4HCO_3 \leftrightarrow CO_2 + H_2O + NH_3 \tag{6}
\]

However, as a reducing agent, ammonium salt also has the problem of low temperature crystallization similar to aqueous urea solution which is due to the reversible decomposition reaction of ammonium salt. At low temperature, the decomposed gas will recompose solid
ammonium salt crystals in the injection system and block up the nozzle. Therefore, it is also
need to keep the outside of the system at an appropriate temperature.

3.2.2 Technical research and application of SSCR system based on solid ammonium
salt

The current research on the system mainly focuses on two aspects: one is the decomposition
and crystallization characteristics of solid ammonium salt[12,13]; The other is how to
improve the response speed and reduce energy consumption of ammonium salt heating
system. Some OEMs and catalyst enterprises have also developed and designed their own
system models.

In 2003, Tenneco company of the United States and FEV company of Germany jointly
developed and designed a SSCR system based on ammonium carbamate[11,14]. The
principle is that ammonium carbamate is stored in a sealed storage tank, and diesel or water
with high temperature is injected onto the bottom of the tank as a heating agent to generate
ammonia. The heating agent has a separate circulating heating path, and the decomposition
rate of ammonium salt can be controlled by changing the pump speed and the heating agent
temperature. The disadvantage of this system is that the heating response time is too long to
deal with the frequent changes of exhaust conditions.

In 2009, FEV company in North America also announced the development of SSCR
system based on ammonium carbamate. Fig. 4 shows the system model of the SSCR system
verified on Dodge Ram 2500 pickup truck[15,16].

Fig. 4. Application model of SSCR system in Dodge pickup truck.

In 2014, Korean Hongsuk Kim et al. [17] established the SSCR system based on
ammonium carbonate, which decomposes the ammonium salt by electric heating. In order to
prevent the recrystallization of ammonium carbonate, the temperature of injection unit is
maintained between 100 ℃ and 115 ℃.

3.3 SSCR technology based on solid ammoniate

3.3.1 Technical principle of ammonia supply by solid ammoniate

Solid ammoniate, also known as metal complex of ammonia, is a kind of ammonia storage
active material with high specific surface area and rich micropores, and is prepared by mixing
alkaline earth metal chloride of magnesium chloride, calcium chloride or strontium chloride
with expanded graphite and other inorganic fillers, then is machined to form a solid unit. The
metal cations on the surface of the active material will form a coordination bond with the
uncoordinated electrons of NH₃ to form the corresponding metal complex after being put into
a closed pressure vessel full of NH₃[18]. The adsorption and desorption of NH₃ is a reversible
reaction. In this process, metal chlorides are only used as the carrier for storing ammonia, and can be reused. 1mol ammoniated magnesium chloride (Mg(NH₃)₆Cl₂), ammoniated calcium chloride (Ca(NH₃)₂Cl₂) and ammoniated strontium chloride (Sr(NH₃)₆Cl₂) contains 6, 8 and 8mol NH₃ molecules respectively. During the thermal decomposition, ammonia is gradually released according to the coordination bond position of ammonia molecules. The reaction equations are as follows [19].

\[
\begin{align*}
Mg(NH_3)_6Cl_2 & \leftrightarrow Mg(NH_3)_4Cl_2 + 2NH_3(g) \quad (7) \\
Mg(NH_3)_4Cl_2 & \leftrightarrow Mg(NH_3)_2Cl_2 + 2NH_3(g) \quad (8) \\
Mg(NH_3)_2Cl_2 & \leftrightarrow MgCl_2 + 2NH_3(g) \quad (9) \\
Ca(NH_3)_9Cl_2 & \leftrightarrow Ca(NH_3)_2Cl_2 + 6NH_3(g) \quad (10) \\
Ca(NH_3)_2Cl_2 & \leftrightarrow Ca(NH_3)Cl_2 + NH_3(g) \quad (11) \\
Ca(NH_3)Cl_2 & \leftrightarrow CaCl_2 + NH_3(g) \quad (12) \\
Sr(NH_3)_8Cl_2 & \leftrightarrow Sr(NH_3)Cl_2 + 7NH_3(g) \quad (13) \\
Sr(NH_3)Cl_2 & \leftrightarrow SrCl_2 + NH_3(g) \quad (14)
\end{align*}
\]

Compared with ammonium salt, the process of releasing ammonia from ammoniate can be finished at atmospheric pressure and temperature slightly higher than room temperature with lower energy [20,21]. In addition, the release of ammoniate is only ammonia without other by-product, and there is no risk of low temperature crystallization, thus it shows great application value. However, the solid ammonia also needs to continue to improve the technology: since the metal chlorides will expand and agglomerate after adsorbing ammonia and the pores will become smaller, resulting in the greatly reduced flow rate and adsorption capacity of ammonia, it is necessary to improve the production process of solid ammonia so as to extend the service life [22-26].

3.3.2 Research and application of SSCR system based on solid ammoniate

During the three kinds of solid ammoniate, the strontium chloride can release ammonia at the lowest temperature, the ammonia storage capacity is the strongest, the temperature range is the narrowest, consequently it has the most related research and application cases. In 2010, Johannessen T. etc. of Amminex A/S company in Denmark took the lead in the research and development of a solid ammonium storage and transportation system based on strontium chloride [27]. The commodity is called ASDS (Ammonia Storage and Delivery Systems). Three types of ASDS products were designed for three diesel vehicles with different displacement and uses, including medium and small passenger car, large and medium-sized bus and large truck. When the system starts to work, a small start-up tank is heated first to release ammonia to meet the cold start condition. Meanwhile, two main storage tanks are heated. Once the gas pressure reaches the release value, the heating start tank is stopped, and the ammonia is released by the main storage tank. Then the start tank starts to absorb ammonia until it reaches the storage design value again.

Faurecia began to promote their ASDS products in 2014 [28]. In June 2016, London Metropolitan Bus Company announced that they will use ASDS technology to retrofit 55 of Euro IV/V buses to reach Euro VI emission level. In November 2016, Faurecia and China Jiangling Automobile Group signed a strategic cooperation agreement to promote ASDS technology in response to China VI emission regulations. At present, ASDS technology has
been used in some buses in Beijing and Shanghai. In June 2017, the Seoul of South Korea assembled 20,000 buses and trucks using ASDS technology.

In 2009, China FAW Technology Center started the research on SSCR system based on strontium ammoniate chloride, and in 2016, Jilin Zhongxin independently developed the first set of SSCR system based on strontium ammoniate chloride. The technical principle of the system is to use the heat of engine exhaust gas to release ammonia from solid ammoniate, which saves energy remarkably more than the electric heating method of ASDS technology[18]. The environmental performance test of the whole vehicle shows that the system can meet the NOx emission standard of China VI in low temperature, high temperature, plateau and other harsh environmental conditions, and has passed the reliability and service life assessment[29,30]. In April 2021, FAW Jiefang and its supplier Clean Blue TEC Environment Technology Co., Ltd jointly completed the bench verification of the solid ammonia products of China VI, and the test results meet the emission requirements of WHSC and WHTC.

3.4 Storage and quality guarantee period requirements of solid ammonia

As the solid ammonia is a closed tank, it is not easy to be polluted, and it only injects gas into SCR system, so there is nearly no possibility of introducing other impurities, so it is very beneficial to maintain the cleanliness of SCR system. In addition, the process of releasing and absorbing ammonia is reversible, and the increase of storage temperature will not affect the quality of solid ammonia, so there is no special requirement for the shelf life of solid ammonia. However, in order to avoid potential safety hazards caused by excessive pressure in the solid ammonia tank, the solid ammonia tank should be stored in a cool and dark environment.

3.5 Replacement and supplement of solid ammonia

Unlike the way in which aqueous urea solution is sold in plastic drums at gas stations and car owners can purchase and fill it on their own, solid ammonia is in a sealed tank, and the supplement of ammonia requires professional service to replace the solid ammonia tank. At present, the replacement service of solid ammonia tank is mainly provided by the OEMs through 4S shop and after-sales service station, door-to-door service and network. The consumption of solid ammonia and the replacement cycle of large fleet users are relatively stable, and the door-to-door service of regular delivery of solid ammonia storage tank can be adopted. At the same time, it can also provide convenient services through the APP information management platform of the user's mobile terminal. The system will issue a warning to the users to remind them when the ammonia tank needs to be replaced. The user can purchase and quickly replace the ammonia tank at the designated outlets, or place an order on the APP, and the special transportation personnel will deliver the new tank to the door on time for replacement. For example, FAW Jiefang and Clean Blue TEC have built a "Blue Station" network system together based on FAW Jiefang's service system and social resources to provide users with solid ammonia tank replacement service. Based on the emerging Internet of vehicles technology, the system can track the use status and flow direction of each solid ammonia tank in the whole life cycle, and provide users with ammonia tank replacement reminder service. Users can purchase solid ammonia tanks online through “Jie Fang Xing” APP developed by FAW Jiefang. Meanwhile, the system can also realize the functions of automatic collection, automatic upload and automatic reminder of vehicle data, which can ensure that the relevant data and information of solid ammonia can be collected and traced in real time, and this can greatly facilitate the national supervision of the quality and application effect of solid ammonia.
Besides, as the endurance of solid ammonia system can reach several thousand kilometers or more, the replacement of solid ammonia is not frequent. Furthermore, the service network of OEMs is responsible for the whole tank replacement. This is in favor of ensuring the consistency of product quality from the source. Unlike the aqueous urea solution, solid ammonia is hardly to appear the counterfeit products on the market. Therefore, the quality of solid ammonia is much more credible than that of aqueous urea solution.

4 Liquid ammonia

4.1 Working principle of liquid ammonia SCR system

Liquid ammonia can release 100% ammonia at low temperature, and the cost of raw materials is low, therefore, it is very suitable to be applied as the SCR reductant. As a result, researchers at home and abroad have begun the study on the feasibility of using liquid ammonia in SCR system once more. The working principle of liquid ammonia SCR system is shown in Fig. 5.

Fig. 5. Schematic diagram of NH₃ supply system for SCR with liquid ammonia.

The working principle of the system is very similar to that of SSCR system on the whole. The main difference is that liquid ammonia tank replaces solid ammonia tank. The system uses the internal pressure sensor to detect the pressure of the liquid ammonia tank, so as to judge the ammonia supply capacity of the ammonia source. When the evaporation capacity of the liquid ammonia is insufficient, the heating device will be started to make the NH₃ supply stable and continuous. After the calculation of the predictive control unit, it acts on the ammonia flow control valve and ammonia nozzle to spray the specified amount of ammonia. Fig. 6 is a special vehicle mounted liquid ammonia tank designed by Yang Hu et al. [31].

Fig. 6. Liquid ammonia storage tank used on vehicle.
4.2 Safety and feasibility of liquid ammonia

According to the provisions of GB 12268-2012[32], liquid ammonia belongs to the category of toxic gas, and the secondary hazard is corrosivity, with hazard code No. 23003 and UN code No. 1005. Once liquid ammonia leaks, it will not only cause ammonia poisoning, but also cause frostbite and corrosion to human body. As the liquid ammonia is a low-pressure liquefied gas, as long as the liquid ammonia can be stored in a special liquid ammonia tank with standardized design and a reasonable tank loading dose is limited, the safe use of liquid ammonia can be ensured theoretically. It is technically feasible to use liquid ammonia as SCR reductant for vehicles. If the safety problem of liquid ammonia storage tank can be further enhanced, corresponding technical specifications can be formulated, and then people's concerns about the safety of transportation and use of liquid ammonia can be eliminated, the market prospect will be more considerable.

5 Comparison of advantages and disadvantages of various technologies

5.1 Comparison of ammonia storage capacity

Due to the different physical form of ammonia storage, the density of ammonia storage is also different. For example, 201g NH₃ can be obtained by the complete decomposition of AUS 32 of 1 L; 697 g NH₃ and 531 g NH₃ can be obtained from 1 L ammonium carbamate and 1 L ammonium carbonate respectively; A tank of solid ammoniate with the volume of 50 L can store 25 kg NH₃; The allowable weight filling coefficient of vehicle mounted liquid ammonia storage tank is 0.53 kg/L. The comparison of NH₃ storage density of different technologies is shown in Fig. 7.

Fig. 7. Comparison of ammonia storage density per unit volume of different technologies.

It can be seen from Fig. 7 that the ammonia storage density per unit volume of the solid ammonia technologies and liquid ammonia technology has obvious advantages over that of aqueous urea solution, which is 2.5 ~ 3.5 times of that of aqueous urea solution. It can be seen that the use of solid ammonia and liquid ammonia is conducive to reducing the volume of reductant storage tank, reducing the supplement frequency, and prolonging the service mileage.
5.2 Comparison of cost

Heavy duty diesel vehicles (HDDV) are mainly used for long-distance freight transportation, with large operating load, long mileage and result in fast consumption of reductant, so the cost of reductant is also the focus of attention. Taking the injection metering ratio of NH₃ and NOₓ as 1, NOₓ is calculated with NO/NO₂ = 1, and the corresponding calculation formula of NH₃ consumption is shown in equation (15).

\[
N = \frac{17 \times P \times \eta}{38 \times V}
\]

(15)

where, N——NH₃ consumption, g/km;
\(P\)—— tractor power under high speed and high load condition, kW;
\(\eta\)—— NOₓ emission reduction, g/kWh;
\(V\)—— tractor speed under high speed condition and high load, km/h.

Based on the experience of PEMS test results, the average power under high speed condition is about 100 ~ 120 kW for the tractor which is in the total weight of 49 t with normal standard load. Accordingly, 110 kw is taken as the power calculation value, while the speed is 80 km/h and the average NOₓ emission is 11 g/kWh. In order to meet the requirements of China VI, NOₓ emission should be reduced by 10.6 g/kWh at least according to WHSC test, then the corresponding NH₃ consumption is calculated to be 6.5 g/km. The cost of aqueous urea solution, solid ammoniate and liquid ammonia are calculated and shown in Table 1.

Table 1. Consumption and cost of aqueous urea solution and liquid ammonia.

<table>
<thead>
<tr>
<th>Reductant type</th>
<th>AUS 32</th>
<th>Solid ammoniate</th>
<th>Liquid NH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃ storage density</td>
<td>184 g/kg</td>
<td>25 kg/tank</td>
<td>998 g/kg</td>
</tr>
<tr>
<td>Mileage per NH₃ storage unit</td>
<td>28.2 km/kg</td>
<td>3834 km/tank</td>
<td>121 km/kg</td>
</tr>
<tr>
<td>Unit Price</td>
<td>3.5 yuan/kg</td>
<td>475 yuan/tank</td>
<td>20 yuan/kg</td>
</tr>
<tr>
<td>Theoretical cost</td>
<td>0.12 yuan/km</td>
<td>0.12 yuan/km</td>
<td>0.13 yuan/km</td>
</tr>
</tbody>
</table>

It can be seen from Table 1 that the unit price of AUS 32 is about 3.5 yuan/kg, the unit price of liquid ammonia is 20 yuan/kg, and the price of replacing a tank of solid ammonia compound is 475 yuan. When the same amount of NOₓ is treated, the theoretical cost of the three reducing agents is almost the same, ranging from 0.12 to 0.13 yuan/km. Since the decomposition rate of AUS 32 is not 100%, the actual consumption of AUS 32 is higher than the theoretical value, both the solid ammonia and liquid ammonia shows a certain price advantage. Moreover, if solid ammonia and liquid ammonia can be applied by diesel vehicles in a large-scale, the cost will be further reduced.

5.3 Comprehensive comparison

Due to the different principles, the reductant technologies are different in terms of user convenience, equipment failure ratio and safety. The results of comprehensive comparative analysis are shown in Table 2.

Table 2. Comprehensive comparative analysis of four reductant technologies.

<table>
<thead>
<tr>
<th>Reductant type</th>
<th>AUS 32</th>
<th>Solid ammonium salt</th>
<th>Solid ammoniate</th>
<th>Liquid NH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of validity</td>
<td>30 days after opened</td>
<td>Not required</td>
<td>Not required</td>
<td>Not required</td>
</tr>
</tbody>
</table>
6 Summary and prospect

With the further tightening of emission regulations, the key requirements for NH3-SCR reductant technology in the future are excellent low-temperature supply capacity, small space occupation, convenient use, low energy consumption, low cost and guaranteed quality. There are four main routes of NH3-SCR reductant technology for diesel vehicles: aqueous urea solution, solid ammonium salt, solid ammonia compound and liquid ammonia, each of which has its own advantages and disadvantages. Although the aqueous urea solution for vehicle and Urea-SCR system have complete and mature production, sales and supervision chains, they still cannot effectively solve the problems of easy crystallization, low pyrolysis and hydrolysis rate at low temperature. Solid ammonium salt is cheap and easy to decompose, however, it also has the problem of low temperature crystallization, which is not conducive to popularization and application. Solid ammonia and liquid ammonia not only have the above advantages, but also have the outstanding advantages that the products are not easy to be polluted, deteriorate or fake, and convenient to be conducted comprehensive network supervision on their use. At present, SSCR technology has been already applied in a small amount in China. Although there are still some engineering problems to be solved in the application of liquid ammonia SCR technology in vehicles, with the breakthrough of some key technologies, it will gradually realize engineering application.

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