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Energy-Efficient Design and Preliminary Validation of a Tertiary Oil Vapor Recovery System

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Abstract: In recent years, China has gradually increased its support for tertiary oil vapor recovery at petrol stations. Under this call, this paper aims to improve the existing condensation and membrane separation combined process. A low-power Pressure Control Device is designed to replace the compressor and vacuum pump, which greatly saves the energy consumption of the main system. A newly designed composite membrane is used to simultaneously perform the condensation and separation steps to improve the efficiency of oil vapor condensation and separation. Moreover, the whole system also takes into account the effects of temperature variations and residual vapor on the separation efficiency to further improve the overall efficiency. Finally, a preliminary feasibility verification of the designed system is carried out to prove its feasibility in principle.

1. Introduction

With the gradual increase in the number of cars in China, the number of petrol stations is also showing an increasing trend year by year. At present, the phenomenon of oil and gas spillage in petrol stations has become one of the key concerns of the government, and the overflow of oil and gas not only causes economic losses, but also causes environmental pollution, endangers public health, and creates potential safety hazards. In recent years, governments around the world have introduced relevant policies to strongly support petrol stations to install three oil and gas recovery systems to liquefy the oil and gas exhaled from the storage tanks. The characteristics of the common recovery methods are shown in Table 1. At present, technologies such as condensation or membrane separation are usually adopted for the treatment of oil vapor.

However, in practice, the use of a single technology to deal with the traditional programme will produce poor results or high cost of the problem, it is difficult to meet the relevant technical standards, so it is usually a variety of technologies used in conjunction, such as as early as 2003 Shie, JL et al [1] began to explore the combined process. Currently, common combined recovery processes include condensation and membrane separation, absorption and adsorption, and condensation and adsorption. In this study, a new combined process of condensation and membrane separation is designed to improve the current high energy consumption of the condensation process, compared to the one represented by Shi Li et al [2]. And a preliminary feasibility analysis is carried out. The technology integrates the principles of capillary condensation, pressure difference, and a composite membrane designed using the results of Lingli Zhu et al [3]. Both aim to improve the economic efficiency of petrol stations by reducing the overall energy consumption of the combined process.

Table 1: Characteristics of common methods of tertiary oil vapor recovery

Comparison Project	Atmospheric pressure absorption	Low pressure absorption	Adsorption	Condensation	Membrane
Volume fraction of imported oil vapor	high	relatively high	low	high	average
Safety	high	relatively high	low	average	high
Footprint	average	small	average	large	relatively small
Service life	long	relatively long	short	relatively long	relatively long
Investment cost	high	low	relatively high	low	relatively low
Running cost	relatively high	low	high	low	low

2. Properties

2.1 Pressure Control Device

The core part of the combined process of condensation and membrane separation revealed disclosed herein is the Pressure Control Device, as shown in Fig. 1. Structurally, it is a Sealed Cylinder divided by a piston driven by an electric actuator. The Upper Cavity accommodates the exhaust gas to be discharged, which is mainly composed of air. The Lower Cavity holds the condensed gasoline and a small amount of residual oil vapor, with a Heat Exchange Layer at the bottom to stabilise the temperature. The Pressure Control Device performs the same function as a compressor or vacuum pump, i.e. it drives the oil vapor through the composite membrane by generating a pressure difference. The key lies in the fact that the pressure difference generated by the new device is cyclical, although it will reduce the amount of oil vapor handled per unit of time, the recovery efficiency of the system is basically unchanged from the viewpoint of the long time span of a single oil vapor recovery cycle, and it will only shorten the interval of the system's operating cycle.

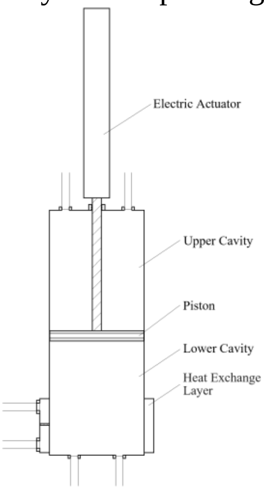

Figure 1: Schematic structure of the pressure control device

2.2 System workflow

The system can periodically process overpressurised oil vapor and its overall process flow is shown in Fig. 2. At the beginning of each cycle, the Solenoid Valve S2 is briefly opened, and the piston in the Pressure Control Device moves to exhaust the gas in the cylinder to generate negative pressure. Subsequently, the Solenoid Valve S1 and S2 are opened, and the high-pressure oil vapor in the storage tank passes through the Heat Exchange Layer and the condenser in sequence, and then enters the Membrane Separation Liquefier. Among them, the composite membrane consists of carbon fibre layer, gas separation membrane and inorganic ceramic membrane, and each membrane is bent into a hollow cylinder after stacking. Oil vapor enters from the inside, and then most of the condensed gasoline and a small portion of the uncondensed oil vapor pass through the Composite Membrane into the Lower Cavity of the Pressure Control Device, while the remaining air enters the Upper Cavity, because it cannot pass through the Composite Membrane. During this process, the Pressure Control Device needs to dynamically maintain the pressure ratio between the two cavities. When the flow rate at the inlet decreases to a threshold value, the Solenoid Valve S1 and S2 are closed, and the contents of the Lower Cavity are finally pushed into the storage tank, completing one treatment cycle. The solenoid valves work in a similar way to an existing optimisation system [4].

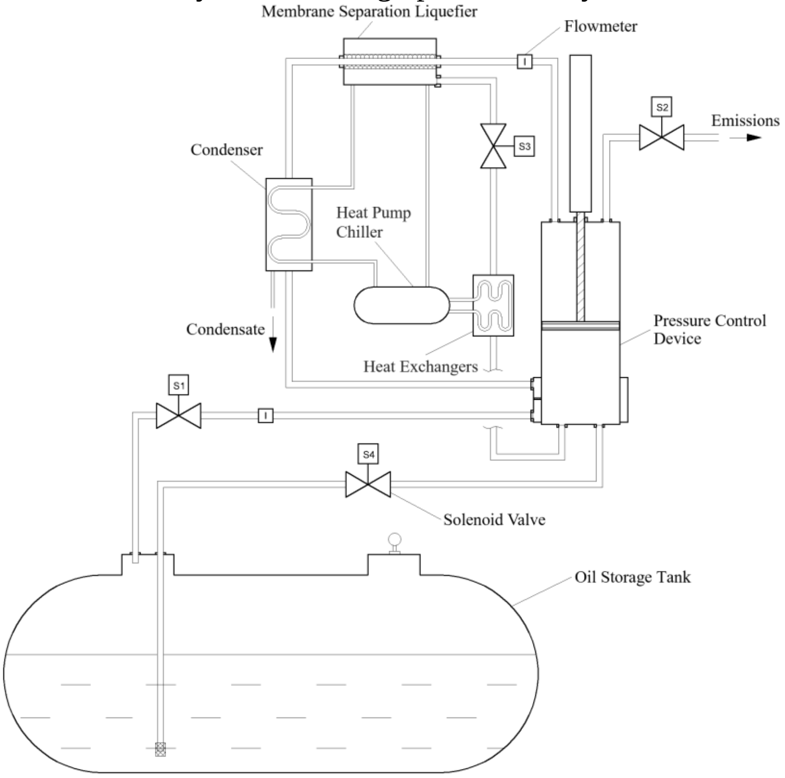

Figure 2: Overall process flow of the system

2.3 Supplementary note

It is worth noting that in order to reduce the power consumption of the condenser, a heat pump chiller is used, the hot end of which is controlled to exchange heat with the condensed gasoline to ensure that the temperature of the gasoline ends up being slightly lower than that in the storage tank. In addition, the oil vapor undergoes both cooling condensation and capillary condensation as it passes through the Composite Membrane, increasing the minimum temperature required to be achieved using a single condensation process and reducing the overall energy consumption of the system. At the same time, to further improve system efficiency, a Corrosion Screen is installed at the end of the return line to partially dissolve the incompletely condensed oil vapor into the gasoline, reducing the energy consumption associated with repeated treatment of this portion of the oil vapor.

3. Theoretical feasibility analysis

3.1 Process modelling

In order to theoretically verify that the system designed in this paper is feasible, the overall process of the system is equivalently simulated using Aspen Plus V14. Its simulation flow in Aspen Plus is shown in Fig. 3. At the same time, in order to highlight the energy-saving benefits of the new system, the existing condensation and membrane separation combined process for comparative analysis, one of the typical simulation process shown in Figure 4. Considering that the system designed in this paper has obvious periodic characteristics, dynamic simulation is carried out for the new system, and finally the average values of the two system parameters are compared.

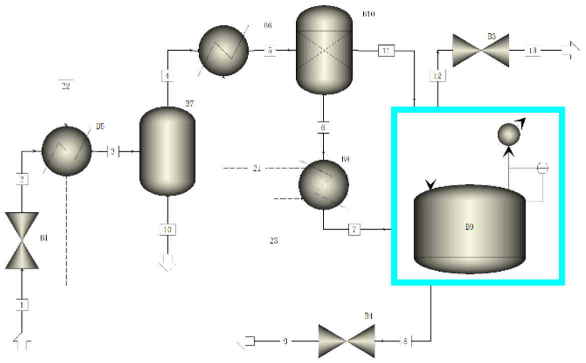

Figure 3: New design process

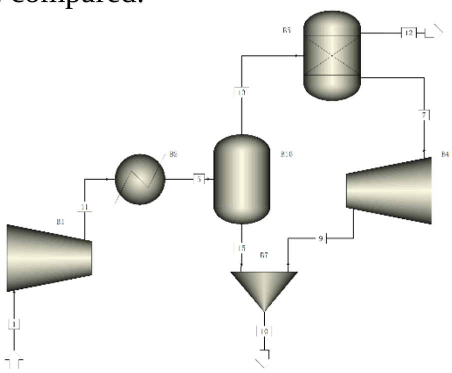

Figure 4: Traditional process

3.2 Main parameter settings

Because the oil vapor recovery system mainly involves non-polar or weakly polar system substances such as alkanes and air, the physical property calculation method is selected as PENG-ROB equation of state. The oil vapor components used in this simulation are shown in Table 2, and the temperature is 28 degrees Celsius. The pressure inside the oil storage tank is selected to be 2 bar and 3.5 bar according to the system design.

Table 2: Oil vapor components

Components	Mole fraction / %	Components	Mole fraction / %
Methane	0.71	Hexane	3.85
Ethane	1.24	Heptane	0.32
Propane	3.71	Octane	0.10
n-Butane	8.21	water vapor	0.86
Isobutane	8.12	oxygen	12.85
n-Pentane	0.68	nitrogen	52.40
Isopentane	6.95		

3.3 Simulation results

The simulation results show that the single-cycle processing time of the new system is 227 s, the processing volume is 0.12 m3, so the calculation shows that the processing efficiency is 1.9 m3/h. And the processing efficiency of the traditional system is 5 m3/h. According to the actual data of the petrol stations in China, the average daily gasoline volatility can be calculated as 36 m3, which shows that the new system designed in this paper meets the needs of the existing petrol stations for the oil vapor processing. In terms of energy consumption, the new system consumes a total of 961 kJ in a single cycle, i.e., the average power is 4.2kW. Comparing the operating power of the conventional system of 4.8kW, it can be seen that the new system has energy-saving benefits.

4. Conclusions and Discussion

This paper reports a new combined condensation and membrane separation process that uses a Pressure Control Device instead of a compressor and vacuum pump, and employs the principle of capillary condensation to simultaneously integrate the separation and condensation functions on a Composite Membrane. Compared to conventional process device, the process device described herein maximises system efficiency and reduces overall energy consumption, while ensuring that the treatment effect remains unchanged. The system processing efficiency and energy usage were checked by Aspen Plus simulation. The results show that the oil vapor recovery system designed in this paper has the same theoretical recovery effect compared to the same type of system, but the energy consumption is reduced, which is in line with the expectation. In conclusion, it can be further constructed for physical verification.

At present, with the development of new energy vehicles, the proportion of traditional fuel vehicles is gradually declining [5]. However, considering the existence of hybrid vehicles and special vehicles, the petrol stations in China will still be the focus of attention in the next twenty years, so the Tertiary Oil Vapor Recovery System designed in this paper still has a large energy-saving benefit at present. In addition, the design can also be applied to the recovery of oil vapor from small oil storage tanks, and the energy-saving ideas can also be used in the recovery of other gases with similar properties. In conclusion, this study has a wide range of application prospects.

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