Small and Medium-sized Ship Exhaust Heat Recovery Device Based on Vortex Tube Effect Verification

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Abstract. With the continuous development of China's economy, the number of Chinese ships has increased year by year. The problem of low utilization rate of waste heat energy of diesel exhaust in existing small and medium-sized ships has become increasingly prominent, and the distillation method in marine desalination has high energy consumption and large equipment volume. Reverse osmosis is a serious pollution. Based on this, we designed a small and medium-sized ship exhaust heat and lightening device based on vortex tube effect. Compared with the traditional lightening technology, the design advantages of this work are reflected in the following three aspects: 1) designing the vortex tube cold and heat separation effect, achieving the step utilization of the exhaust air, reducing the power consumption; 2) the device is small in size and can save the internal space of the ship; 3) The desalination process is simple, there is no influent pretreatment process, and the environmental pollution of the chemical agent is reduced; 4) The device can provide a negative pressure environment for the exhaust port of the diesel engine, reduce the exhaust back pressure of the diesel engine, and improve the working efficiency of the diesel engine.

1. Introduction

1.1. Development background and significance
As the Chinese economy continues to develop, the number of Chinese ships continues to increase. However, the energy efficiency of existing marine diesel engines is low, and up to 25% of the heat is taken out by the exhaust of 350°C. According to the statistics of the State Maritime Safety Administration, in 2018, Chinese sea-going vessels carried more than 90 million tons. Among them, a large number of ships (with a tonnage of ≥500 tons) have a total of 5,161 vessels. Most of them have used waste heat boilers to recover flue air heat; however, as many as 17,000 small and medium-sized vessels (tonage <500 tons) have no waste heat utilization devices. High energy consumption not only makes the ship run at a huge cost, but also leads to energy shortage and environmental pollution. At the same time, China issued the “Opinions on Strengthening Energy Saving and Emission Reduction of the Internal Combustion Engine Industry” in 2013, clearly stating that it is necessary to promote the application of waste heat recovery and reuse technology for marine low-speed diesel engine power systems.
The survey found that seawater desalination can be used as a breakthrough point for the utilization of waste heat in small and medium-sized ships. Marine desalination equipment can solve problems such as inconvenient supply of freshwater resources and short sailing time. The existing marine seawater desalination has a distillation method or a reverse osmosis method. The specific performance of the seawater desalination method as shown in Table 1 was obtained through field investigation. However, due to the small size of the cabin and the high cost of seawater desalination, the above method is not conducive to the promotion of small and medium-sized vessels.

Table 1. Performance Table of Existing Seawater Desalination Methods

| Comparative project      | Distillation method | Reverse osmosis method |
|--------------------------|---------------------|------------------------|
| Water production energy  | higher              | lower                  |
| device size              | higher              | lower                  |
| Environmental impact     | low pollution       | large pretreatment pollution |

Based on the above analysis, it is known that designing a light-reducing device with low energy consumption and no pollution and suitable for small and medium-sized ships has important research significance.

2. Design plan

2.1. Overall design

The main design ideas of the scheme are as follows: 1) designing the device to downplay the workflow based on exhaust air characteristics and vortex tube effect; 2) using MATLAB software to select the optimal intake air temperature for the vortex tube, and determining the eddy current tube parameters according to Ansys software simulation; 3) establishing the mathematical model of the heat exchanger determines the structural parameters of the heat exchanger, and calculates the working parameters of the mixer according to the air flow rate; 4) Calculates the water production efficiency according to the determined overall parameters of the device. According to the above ideas, the workflow shown in Figure 1 is designed:

![Diagram of device workflow]

Figure 1. Device work flow chart
The specific working mode of the device: the high-temperature exhaust air discharged from the diesel engine is passed into the evaporator, and exchanges heat with the pre-heated seawater to evaporate the seawater. The steam enters the condenser, and the off-air leaving the evaporator enters the mixer, and the compressed air produced by the compressor is mixed in proportion in the mixer. The mixed air enters the vortex tube from the mixer, and the mixed air is cooled and separated in the vortex tube. The cold-end air enters the condenser to condense the steam into fresh water, and the condensed water is collected in the water storage tank, and the cold air is exchanged and discharged to the device; at the same time, the hot-end air is introduced into the preheater to preheat the seawater and then discharge the device.

2.2. Vortex tube design

According to Fulton et al. [1~2], the principle of vortex tube effect is known: the vortex tube converts the kinetic energy in the high-pressure air stream into the heat energy of the air stream, and separates the air stream from heat and cold. The high-pressure airflow is in the vortex chamber: the inner airflow expands to do work, loses kinetic energy, and the temperature decreases; the outer airflow acquires kinetic energy, and converts kinetic energy into heat energy during friction with the hot-end pipe. The resulting vortex tube exhibits a temperature difference in the radial direction. The working principle of the vortex tube is shown in Figure 2.

![Schematic diagram of the vortex tube](image2)

2.2.1. Vortex tube parameters. The vortex tube parameters are designed and calculated. The optimum pressure of the vortex tube inlet airflow is $P_{in} = 0.6$ MPa. The optimum intake air temperature under this pressure can be calculated by MATLAB software to further determine the design parameters of the whole set. By writing the vortex tube formula and the mixer formula to MATLAB, the optimum temperature range as shown in Figure 3 can be obtained.

![Vortex tube optimal intake temperature selection line chart](image3)
As the temperature of the vortex tube intake (i.e., the mixer outlet) increases, the amount of heat is gradually increased, but the amount of cooling is gradually reduced. In order to meet the condensed water production, the vortex tube cooling capacity is required to be greater than $1.5 \times 10^5$ kJ, that is, the intake air temperature should be lower than $320$ K; to meet the preheater heating capacity, the eddy current regulation heat is required to be greater than $7 \times 10^4$ KJ, that is, the intake air temperature should be higher than $310$ K. Therefore, we chose $310$ K ($37^\circ$C) ~ $320$ K ($47^\circ$C) as the optimum inlet temperature range of the vortex tube.

For the temperature separation effect that can be generated by the vortex tube, according to the turbulent characteristics of the high-pressure flow field in the vortex tube, the Fluent simulation is performed on the vortex tube by using the RNG-$k$-$\sigma$ turbulence equation of state, and the inlet pressure is set by simulating the vortex tube. The phenomenon of cold and heat separation under temperature conditions, and the lowest total temperature and maximum total temperature respectively achieved by the cold and hot ends, and compared with the measured data to verify the rationality, and then extended to the seawater under actual conditions. The preheating calculation and the steam condensation calculation are performed to obtain the results as shown in FIG. The inlet boundary conditions were set to 0.6 MPa (total pressure) and the temperature was $313$ K (40°C). The cold end air temperature is calculated to be as low as $251.1$ K ($-21.9^\circ$C) and the hot end is up to $374.4$ K ($101.4^\circ$C).

2.2.2. Eddy current tube experimental verification. In this project, the Fluent simulation and experimental verification of the vortex tube were carried out under the same conditions, and the error analysis method was compared to judge the correctness of the temperature simulation results of the vortex tube under the design conditions.

The Fluent simulation was performed on the vortex tube according to the method in 2.2.1, and the inlet boundary condition was set to 0.35 MPa (total pressure) and the temperature was $283.65$ K (10.5°C). The cold end air temperature is calculated to be as low as $263.44$ K ($-9.71^\circ$C) and the hot end temperature is up to $337.65$ K (64.5°C).

| Project Name          | Inlet Pressure / Temperature | Hot End Temperature | Cold End Temperature |
|-----------------------|------------------------------|---------------------|----------------------|
| Fluent simulation     | 0.5MPa/15°C                  | 64.6°C              | -9.6°C               |
| Experimental verification | 0.47MPa/14.9°C               | 64.7°C              | 11.1°C               |

In order to verify the actual effect, the vortex tube was tested experimentally (see Appendix V for the experimental report). We experimented with a vortex tube using an inlet air temperature of $14.9^\circ$C.
and a pressure of 0.47 MPa as the intake air. The cold end air temperature is -11.1°C and the hot end temperature is 64.7°C. The data is shown in Table 2. The cold junction temperature and simulation error are 15.6%, and the hot end error is 0.15%. Therefore, within a certain error range, the experimental results are consistent with the theoretical simulation.

2.3. Mixer design
The mixer is designed as a venturi mixer that allows the exhaust from the evaporator to be efficiently mixed with the compressed air. The basic principle of the Venturi mixer is that when the compressed air enters the zoom nozzle, a negative pressure is formed at the throat, the smallest section of the pipe, and the exhaust air enters the pipe due to the pressure difference. The use of the Venturi effect is beneficial to reduce the exhaust back pressure of the diesel engine and improve the working efficiency of the diesel engine. The negative pressure test of the mixer was carried out. The experimental results show that under the pressure of 0.3MPa air compressor, the pressure at the inlet of the air mixture is reduced by the sudden decrease of the pressure generated by the sudden change of the venturi mixer speed. -0.03MPa, its negative pressure condition causes the adsorption force at the inlet, and the experimental results prove the correctness of the design within the system error allowed by the experiment. In actual use, the mixer acts to promote exhaust. The mixer schematic is shown in Figure 5.

![Figure 5. Mixer schematic](image)

According to the requirements of the vortex tube, the optimum pressure of the air outlet of the mixer is about 0.6 MPa, and the optimum temperature is 40 °C. By designing the compressed air flow, it is possible to control the state of the air after the compressed air and the exhaust air are mixed. According to the calculation, the mass ratio of exhaust air to compressed air is: \( \frac{m_1}{m_2} = 0.37 \), the known exhaust air mass flow rate is 1350 kg/h, and the mixer outlet flow rate is:

\[
M = 1350 \text{kg/h} \times 1.37/0.37 = 5000 \text{kg/h}
\]  (1)

2.4. Heat exchanger design

2.4.1. Vacuum evaporator design. The evaporator is designed as a rising film evaporator. It consists of an internal hollow heat exchange tube and a plurality of evaporation tubes running through the heat exchange tubes, and the inside is a vacuum environment (20 kPa). At work, the exhaust enters the evaporator and transfers heat to the seawater. The seawater absorbs heat and evaporates. The structure of the evaporator is shown in Fig. 6.
We used the ship with a tonnage of 150 tons and a crew of 6 people as an example to design the parameters of the evaporator. To maximize the use of exhaust heat, we established a mathematical model of seawater evaporation as shown in Figure 7, and used MATLAB for calculations.

According to the law of conservation of energy and conservation of mass, the basic equation for obtaining heat transfer from an evaporator is:

\[ Q = KA\Delta t_m, \quad \Delta t_m = \frac{\Delta t_{\text{max}} - \Delta t_{\text{min}}}{\ln \Delta t_{\text{max}} - \ln \Delta t_{\text{min}}} \]  \hspace{2cm} (2)

Where K is the total heat transfer coefficient, W / (m²·°C); A—the total heat transfer area of the heat exchanger, m²; \( \Delta t_m \) the logarithmic mean temperature difference between the two fluids undergoing heat exchange°C.

According to the survey and statistics, the relevant data are obtained: the power of the 150-ton ship diesel engine is 260kW, the exhaust air mass flow is about 1350 kg/h, the exhaust air temperature is about 350°C, and the preheated seawater is about 50°C.

The design of the vacuum evaporator has a heat transfer coefficient of \( K=3000 \) W/(m²·K), a working pressure of 20 kPa, and the exhaust air enters the evaporator at 350°C, and leaves the evaporator at 80°C after heat exchange. The set parameters are taken into equation (2) for calculation to obtain the heat transfer area of the evaporator and the steam production:
\[ A = \frac{Q}{K\Delta t_m} = 0.55m^2 \]

\[ M_v = \frac{Q \times \eta - M_{b, in} \times Cp_{b} \times (t_{b, out} - t_{b, in})}{h} = 149.76\text{kg/h} \quad (3) \]

2.4.2. Preheater design. The preheater uses a plate heat exchanger. The hot end of the vortex tube flows into the preheater, and is fully mixed with the normal temperature seawater to heat the seawater. According to the heat transfer seawater flow and actual use conditions of the device, the temperature of the seawater entering the preheater is 20°C, and the temperature is raised to 50°C after preheating; the heat flow temperature of the vortex tube is 90°C, and the temperature after heat exchange is 70°C. After establishing the mathematical model of the preheater heat transfer, the calculated heat transfer area is 0.242 m².

2.4.3. Condenser design. The condenser uses an air-cooled condenser to reduce corrosion of the device by seawater in the water-cooled condenser. The steam generated by the evaporator enters the condenser and exchanges heat with the cold-end flow of the vortex tube to flow into the storage tank, and the cold air is discharged from the exhaust port. The temperature of the steam entering the condenser was 60°C; the temperature of the cold end of the vortex tube was -10°C, and the temperature after heat exchange by the condenser was 40°C. After establishing the mathematical model of condenser heat transfer, the heat transfer area of the condenser was calculated to be 0.597 m², and the yield of condensed water was 61.5 kg/h.

3. Device experimental test and analysis

To verify the correctness of the design process, a verification experiment was designed. The hot air gun is used to generate high temperature air to simulate diesel exhaust. The specific parameters are: air flow rate is 300L/min; air temperature is 190–220°C; exhaust pressure is 0.1MPa. The evaporator was simulated by a heat exchanger, and the heat exchange area was 0.915 m²; the condenser was simulated by a serpentine condenser. The hot air gun heat is introduced into the heat exchanger to allow the seawater to evaporate and then enter the mixer to mix with the compressed air. The mixed air enters the vortex tube to achieve hot and cold separation. The cold end air of the vortex tube enters the condenser, condensing the incoming steam into fresh water. Prepare the equipment, link the pipeline, and carry out experimental research on the device pressure drop and water production effect.

3.1. Device pressure drop verification

Whether the exhaust of the diesel engine is smooth or not determines its performance. According to the survey, the exhaust back pressure of the diesel engine should not exceed 0.05 MPa. In order to verify that the device does not affect the normal exhaust of the diesel engine, we measured the vacuum of the device inlet after the device was introduced with high pressure air.

The vacuum at the inlet of the evaporator was zero at the beginning of the experiment, indicating that the pressure inside and outside the device was equal before the introduction of the compressed air. When the system starts to work, the mixer is supplied with compressed air, and the degree of vacuum is displayed as -0.03 MPa, forming a negative pressure environment. Therefore, the device can reduce the exhaust back pressure of the diesel engine and promote the exhaust of the diesel engine.

3.2. Device water production efficiency verification

In order to verify the correctness of the mathematical model of the heat transfer, we designed the water production experiment under the experimental conditions. The experimental conditions are shown in Table 3.
Table 3. Experimental data table of tail air cold and heat separation method

|                   | Temperature    | 16.3°C |
|-------------------|----------------|--------|
| Sea water         |                |        |
| Compressed air    | Flow rate      | 7.8kg/10min |
|                   | Temperature    | 18.2°C |
| Heat exchanger    | Inlet air temperature | 201°C |
|                   | Intake flow rate | 2.9kg/10min |
|                   | Outlet temperature | 87.9°C |
| Vortex tube       | Intake air temperature | 37.2°C |
|                   | Intake flow rate | 10.7kg/10min |
| Condenser         | Intake air temperature | 5.3°C |
|                   | Outlet temperature | 15.6°C |

The device can obtain 23.5g of fresh water in 10min. The experimental condition parameters are brought into the calculation formula of the evaporator and the condenser to obtain the theoretical water production (see the annex for the specific calculation process), and the theoretical calculation of the water production under the experimental conditions can be obtained: 26 g of fresh water is produced within 10 min. The error between the fresh water and the theoretical value was 9.62%. Therefore, the heat transfer mathematical model satisfies the design requirements.

4. Analysis of energy saving and emission reduction benefits

4.1. Environmental benefits

Take a 150-ton ship as an example for analysis. The condensate production was 61.5 kg/h, the electric power was 32.2 kW, and the volume of the unit was 1.97 m³. The device is calculated to work for 20 hours per day, and can get 1.23t of fresh water per day. At the same time, the unit water production capacity of the device is:

\[
\frac{61.5\text{kg/h} \times 1\text{h}}{32.2\text{kW}} = \frac{61.5\text{kg/h}}{1.97\text{m}^3} = 31.19\text{kg/m}^3
\]

(4)

According to statistics, the per capita daily fresh water consumption is about 200kg [4]. According to the main technical parameters of the ship, the number of crew members of the 150-ton ship is at least 6 people. The device is calculated to work for 20 hours per day, and 1.23 tons of fresh water can be obtained every day. It can be seen that the fresh water production can meet the requirements. Check the specifications of the existing products; reverse osmosis method to reduce the water yield of 65.5kg / h is 34.5kW, the volume is 1.96m³; the distillation method to reduce the water yield of 68.5kg / h is 55kW, the volume is 3.56m³. According to the calculation method of the formula (3), the water production amount comparison of the three desalination methods shown in Fig. 8 can be obtained.

![Figure 8. Comparison of water production capacity of the device](image)
For the reverse osmosis method and the distillation method, under the condition that the water production per unit time is required, the unit water production of the distillation method is lower, the energy consumption is larger, and the water production per unit volume is lower, which cannot meet the requirements of small and medium-sized ships. The cabin space is in short demand. The main chemical agents used in the reverse osmosis membrane pretreatment include: bactericide, coagulant, scale inhibitor, corrosion inhibitor, defoamer, reducing agent, acid and alkali, etc., and the concentration is 20 mg/L. These agents and their by-products are eventually discharged into the ocean with salt water, seriously damaging the marine environment.

**Table 4. Typical properties of concentrated brines during reverse desalination and distillation desalination**

| Item                        | Distillation method | This device | Reverse osmosis method |
|-----------------------------|---------------------|-------------|------------------------|
| Flocculant                  | None                | None        | Exist                  |
| Coagulant                   | None                | None        | Exist                  |
| Chemical cleaning agent     | Acid solution       | None        | Acid and alkali agent, etc. |

With this device, a 150-ton ship can recover waste heat every year.

6.53×10^5 KW·h, producing fresh water 307.5t.

Compared with the existing distillation desalination device, a 150-ton ship can save 1.14×10^5 kW·h of electricity per year, which is about 9.6t of diesel oil;

By replacing the existing reverse osmosis desalination device with this device, it can reduce chemical emissions by 6.15g per year. In summary, the device can save a lot of electric energy and reduce environmental pollution as compared with the existing seawater desalination device, and the environmental protection benefits are considerable.

4.2. Energy efficiency

The existing diesel engine is equipped with an exhaust air turbocharging system. When the flow rate of the exhaust air is insufficient at a low rotational speed of the diesel engine, the exhaust of the diesel engine is hindered, and the exhaust air pressure is increased, which directly leads to an increase in the fuel consumption rate of the diesel engine, and the economic performance of the diesel engine. Deterioration. According to Wang Jian [6] and others, the torque will gradually decrease with the increase of exhaust back pressure, and the specific fuel consumption will gradually increase. According to the research of Wu Qiwei [7] et al., the vacuum of the mixer varies with the pressure of the compressed air. When the increase gradually increases to about 0.5 MPa, it tends to be stable.

After the evaporator outlet is connected to the mixer, the problem of large exhaust back pressure of the diesel engine can be effectively solved. According to the design of the device, the pressure of the compressed air supplied to the mixer is 0.6 MPa, and a vacuum of 90 kPa can be formed. The exhaust resistance of the evaporator is generally 30 kPa, so the exhaust back pressure of the diesel engine is about - (90-30) = -60 kPa. Under this negative pressure exhaust condition, the diesel engine's specific fuel consumption can save 12g / (kWh). Calculated according to the diesel engine operating 5000h a year, one year can save diesel:

\[
260kW \times 12 \times 10^{-6} t/(kW \cdot h) \times 5000h = 15.6t
\]  

4.3. Economic benefits

4.3.1. System Cost. The cost of this system is mainly divided into two parts: investment cost and operating cost. According to the above structural design, the total area of the heat exchanger is 1.5 m², and the total cost of the system heat exchange device is 225 yuan/year; the investment cost of the power input device is \(J_b=540.225\) yuan/year. The annual working time of the device is about 5000h. The power
of the device is mainly composed of the power input device, and the total power of the system is 24.2kW. After calculation, the operating cost is about $9.68 \times 10^4$ yuan / year. Thus, the annual cost of the system is 296.1 yuan / year.

4.3.2. **Benefit Analysis.** The desalination devices currently used on offshore platforms mainly include reverse osmosis and distillation [6]. According to the calculation, the total cost of the reverse osmosis method is 314.03 yuan / year; the total cost of the distillation method is 365.53 yuan / year. The cost comparison between the system and the existing parts of the existing desalination method is shown in Table 5:

|                      | Reverse osmosis | distillation | The method  |
|----------------------|----------------|--------------|-------------|
| Investment cost (yuan/ton) | 1.94           | 1.34         | 2.32        |
| Operating cost (yuan/ton)    | 312.09         | 364.19       | 293.77      |
| Total cost (yuan/ton)        | 314.03         | 365.53       | 296.09      |

According to the table, a 150-ton ship can save about 5,551.55 yuan per year by using the device, which has huge economic benefits.

5. **Innovation points**

(1) Propose the miniaturization design of seawater desalination device, which is applied to the field of small and medium-sized ships;

(2) Using vortex tube cold and heat separation technology to realize exhaust air cascade utilization;

(3) There is no pretreatment process to reduce the pollution of seawater desalination.

6. **Conclusion**

In this paper, the waste heat energy of diesel exhaust in existing small and medium-sized ships is wasted. The distillation method in marine desalination has high energy consumption, large equipment volume, and serious pollution caused by reverse osmosis. Based on vortex tube effect, the exhaust air from waste heat is used to make light. The mathematical model was established to determine the calculation method. The vortex tube size and heat exchanger size were calculated by MATLAB. The vortex tube effect was analyzed by ANSYS simulation and verified by experiments. A small and medium-sized ship exhaust heat recovery based on the vortex tube cold and heat separation effect was designed. Lightening device. The seawater desalination effect of the works is good, and the effect of effectively utilizing the residual heat of the diesel engine is achieved, and the energy-saving concept of environmental protection, energy saving, quick and efficient is established. The utility model has the advantages of small occupation volume, high lightening efficiency, large fuel saving amount and low cost, and is suitable for islands, offshore platforms and the like, and has good social benefits and broad application prospects.

**References**

[1] C. D. Fulton. Ranque's tube. ASREREfrigerationEngineering, 5, 58, 1950, pp. 473 – 479.
[2] J. S. VanDeemter. On the theory of the Ranque–Hilsch cooleffect. Applied scientific Research (SeriesA), 3, 3, 1952, pp. 174 ~ 196.
[3] AliM. El-Nashar. Economics of small solar-assisted multiple-effect stack distillation plants. Desalination, 3, 130, 2000.
[4] Han Yingyi. Analysis of the change trend of water consumption in Dalian from 2003 to 2016. Northeast Water Conservancy and Hydropower, 01, 37, 2019, pp. 34 - 35.
[5] Yan Yulian, Wu Yunqi, Wu Shuib, Pan Chunyou, Li Lu, Wang Tingting. Analysis of the Potential Advantages of Seawater Desalination in Water Supply Industry. Salt Science and Chemical Engineering, 09, 47, 2018, pp. 16 - 20.
[6] WANG Jian, SUN Yongfu, LIU Shengji, ZHU Daoqing. Study on the Influence of Exhaust Back
Pressure on the Performance of Small Diesel Engine. Journal of Guangxi University (Natural Science Edition), 03, 42, 2017, pp. 897 - 903.

[7] Wu Qiwei. Study on vacuum characteristics of jet vacuum generator. Dalian Maritime University, 2017.