Simulation Analysis of Vortex Tube Parameters for Desalination Device Using Ship Exhaust Heat

Shiji He*, Changqing Zhou, Wenbo Zhang, Bingjin Liu and Yue Cui

Wuhan University of Technology, School of Mechanical and Electrical Engineering, Wuhan, Hubei 430070

*Corresponding author: heshiji0871@whut.edu.cn

Abstract. The waste heat energy of diesel exhaust of current small and medium-sized ships is a big waste, while the distillation method in marine desalination is energy-intensive and its equipment is large, as well as the reverse osmosis method is seriously polluting. In order to solve the above problems, a waste heat desalination device for small and medium-sized ships is designed based on the cold-heat separation effect of vortex tube. In this paper, based on the study of the vortex tube working principle, the parameters of the vortex tube are designed and calculated, and the optimum inlet temperature at a certain pressure is calculated to further determine the design parameters of the whole device. According to the basic laws of thermodynamics, a mathematical model is established to describe the changes in the state of diesel exhaust.

1. Introduction

According to Fulton et al [1~2], the principle of vortex tube effect can be understood: the vortex tube converts the kinetic energy in the high-pressure airflow into thermal energy of the airflow, and separates the airflow from hot and cold. High-pressure airflow in the vortex chamber: Airflow expansion in the inner layer works, losing kinetic energy and lowering the temperature. The outer airflow acquires kinetic energy and converts it into thermal energy during friction with the hot end tube. Eventually the vortex tube shows a temperature difference in the radial direction. The operating principle of the vortex tube is shown in Figure 1.

![Schematic diagram of a vortex tube](image)

Figure 1. Schematic diagram of a vortex tube
2. MATLAB calculation of vortex tube parameters

2.1. Model assumptions
In order to simplify the model and make the problem computationally convenient, without changing its underlying laws and principles, the following assumptions are made in this paper.

1. Adequate mixing of exhaust and compressed gases.
2. The gas is ideal and the specific heat $C_p$ is constant.
3. Ignoring the heat conduction through the wall of the pipe and considering the wall to be insulated from the outside.
4. Exhaust gases and gas mixtures are incompressible fluids.

2.2. Description of symbols
$T_i$, mixer outlet (vortex tube inlet) temperature in K.
$p_i$, mixer outlet (vortex tube inlet) pressure, in pa.
$v_i$, specific volume of the mixer outlet (vortex tube inlet) in m$^3$/kg.
$T_1$, mixer inlet gas temperature in K.
$p_1$, mixer inlet tail gas pressure in pa.
$v_1$, specific volume of mixer inlet tail gas, in m$^3$/kg.
$m_1$, mass of mixer inlet exhaust in kg.
$T_2$, mixer inlet compressed air temperature in K.
$p_2$, mixer inlet pressure, in pa.
$v_2$, specific volume of compressed air inlet to the mixer, in m$^3$/kg.
$m_2$ and the mass of compressed air in kg into the mixer.
$R_g$, the gas constant in units of J/(kg·K).
$k$, specific heat capacity ratio.
$c_v$, specific heat capacity in kJ/(kg·K).
$Q_1$, Exhaust heat emission in kJ.
$Q_2$, Heat absorbed by compressed gas, in kJ.
$Q$, vortex tube cooling capacity in kJ.
$P_0$, vortex tube discharge pressure, in Mpa.
$dT_s$, the theoretical maximum temperature drop in units K.
$dT_c$, the actual temperature drop in units of K.
yita, temperature efficiency.
COP, cooling efficiency.
$miu$, cold flow rate.

2.3. Mathematical model of mixer design
The following fixed parameters are set for model solving.
Mixer outlet (vortex tube inlet) pressure $p_i=600000$Pa; tail gas temperature of the mixer inlet $T_1=353$K; tail gas pressure of the mixer inlet $p_1=2500000$Pa; compressed gas temperature of the mixer inlet $T_2=293$K; compressed gas pressure of the mixer inlet $p_2=800000$Pa; gas constant $R_g=287$J/(kg·K); specific heat capacity ratio=1.29. Specific heat capacity $c_v = 1.003$kJ/(kg·K).

2.3.1. Model analysis. The mixing module is designed as a venturi mixer, and the role of the venturi mixer is to make the exhaust gas coming out of the evaporator and the compressed gas mix efficiently. The use of venturi effect can improve the efficiency of rarefaction, help reduce the exhaust back pressure of diesel engines, thereby reducing the negative impact of the device on the exhaust.
According to the requirements of the vortex tube, the optimum pressure of the mixer's discharge air is about 0.6 MPa and the optimum temperature is 40°C. Control of the gas state after mixing the compressed air with the exhaust gas is achieved by designing the compressed air flow rate.

The exhaust gas leaving the evaporator has a pressure of 0.25 MPa and a temperature of 353 K. According to the equation of state of the gas, the specific volume $v_1$:

$$v_1 = \frac{RgT}{p} = \frac{287 \times 353}{250000} = 0.405 m^3/kg$$  \hspace{1cm} (1)

The compressed gas pressure is 0.8 MPa and the temperature is 293 K. According to the equation of state of the gas, the specific volume $v_2$:

$$v_2 = \frac{RgT}{p} = \frac{287 \times 293}{800000} = 0.105 m^3/kg$$  \hspace{1cm} (2)

The mixture is designed for a pressure of 0.6 MPa and a temperature of 313 K. According to the equation of state of the gas, the specific volume $v_3$:

$$v_3 = \frac{RgT}{p} = \frac{287 \times 313}{600000} = 0.150 m^3/kg$$  \hspace{1cm} (3)

When mixing, the exhaust gas exothermic $Q_1$, compressed gas heat absorption $Q_2$, the two processes are for the multi-variable process, and $Q_1 + Q_2 = 0$.

Exhaust heat.

$$Q_1 = \frac{n-k}{n-1} c_v m_1(T_2 - T_1) = \frac{0.88 - 1.29}{0.88 - 1} \times 1.003 \times m_1(313 - 353) = -137.08 m_kJ$$ \hspace{1cm} (4)

Heat absorbed by compressed gas.

$$Q_2 = \frac{n-k}{n-1} c_v m_2(T_2 - T_1) = \frac{0.81 - 1.29}{0.81 - 1} \times 1.003 \times m_2(313 - 293) = 50.68 m_kJ$$ \hspace{1cm} (5)

$Q_1 + Q_2 = 0$, yielding.

$$m_1/m_2 = 0.37$$ \hspace{1cm} (6)

Knowing that mass flow rate of the tail gas is 1350 kg/h, we can obtain Compressed gas flow.
The flow rate of the mixer outlet is.

\[ M_2 = 1350/0.37 = 3648 \text{ kg/h}, V_2 = M_2v_2 = 3300 \times 0.105 = 383 \text{ m}^3/\text{h} \] (7)

(8)

2.3.2. Modelling. Summarizing the above, the following mathematical model can be obtained to describe the mixing process of exhaust gas and compressed gas.

\[
\begin{align*}
\text{p1} \times v_1^n_1 - 0.5 \times v_i^n_1 &= 0 \\
\text{p2} \times v_1^n_2 - 0.5 \times v_i^n_2 &= 0 \\
Q_1 &= \frac{n - k}{n - 1} c_v m_1 (T_2 - T_1) \\
Q_2 &= \frac{n - k}{n - 1} c_v m_2 (T_2 - T_1) \\
Q_1 + Q_2 &= 0
\end{align*}
\] (9)

2.3.3. Model solving. Solve the effect of the vortex tube inlet temperature on the total cooling capacity of the vortex tube, and the result is shown in Figure 3.

![Figure 3](image)

**Figure 3.** Influence of vortex tube inlet temperature on the total cooling capacity of the vortex tube.

2.4. Mathematical model of vortex tube cooling and heating separation

2.4.1. Model analysis. The gas enters the vortex tube and expands to pressure \( P_0 \) in the vortex chamber, with the cold side outlet airflow pressure \( P_c \) at the cold end and the hot side outlet airflow pressure \( P_h \) at the hot end. The vortex tube can generally be approximated as \( P_c = P_h = P_{out} = 0.12 \text{Mpa} \). The optimum pressure of the inlet airflow of the vortex tube is the optimum inlet temperature under the optimum inlet pressure \( P_{in} = 0.6 \text{Mpa} \) can be calculated, so as to determine the design parameters of the whole device.
2.4.2. Modelling. Combining the above various categories, the following mathematical model can be obtained to describe the cold and hot separation process of vortex tube.

\[
\begin{align*}
    dT_s &= Ti - Ti \times [(Po / Pi)(k - 1) / k] \\
    \mu &= COP \times R_g \times Ti \times \log(Pi/Po)/(C_p \times dT_c) \\
    Q &= \mu \times \mu \times C_p \times dT_c
\end{align*}
\]

(10)

2.4.3. Model solving. To solve the effect of the vortex tube inlet temperature on the cooling capacity per unit of power consumption and the result is shown in Figure 5.

Figure 5. Influence of vortex tube inlet temperature on cooling capacity per unit of electricity consumed.

2.5. Analysis of results
The suitable range of inlet temperature of vortex tube is shown in Fig.6.
According to the analysis, as the inlet temperature of the vortex tube (i.e., outlet temperature of the mixer) increases, the cooling capacity per unit of power consumption of the vortex tube gradually increases, but the total cooling capacity gradually decreases. Based on the calculations, we selected 315 K as the optimum inlet temperature for the vortex tube and used this temperature to design the parameters for the other devices in the system.

3. Report on ansys simulation of 2 vortex tubes

3.1. Research methodology

3.1.1. Simulation Thoughts. Simulate the cold and hot separation phenomenon of vortex tube under the condition of inlet pressure and temperature, and the lowest and highest total temperature that can be reached at the cold and hot ends respectively, and compare them with the measured data to verify their rationality, and then extend them to the seawater preheating calculation and water vapor condensation calculation under actual conditions to obtain reasonable results.

3.1.2. Selection of the calculation model. In this paper, the model $K^\xi$ is used to solve the turbulence problem. The control equations include the continuity equation, the momentum equation, the energy equation and the $\kappa, \varepsilon$ equation and the $\eta_t$ computational formula. Where $\eta_t$ is computed as

$$\eta_t = c_{\mu}^{\prime} \rho k^2 l = (c_{\mu}^{\prime} c_D) \rho k^2 \frac{1}{c_D k^2} = c_{\mu} \rho k^2 \frac{1}{\varepsilon}$$

(11)

3.1.3. Construction of geometric models. This paper is based on the structural parameters of the SKW100 large vortex tube purchased from the experiments of Shengdekai, and with reference to the experimental model of Bruun (1969), the three-dimensional geometric model was built and appropriately simplified using the inventor software.
3.2. **FLUENT simulations and result analysis**

![Figure 9](image9.png)

**Figure 9.** Vortex tube total temperature distribution cloud map and temperature range display (16.9°C inlet)

![Figure 10](image10.png)

**Figure 10.** Vortex tube total temperature distribution cloud map and temperature range display (40°C inlet)
It can be seen from Figure 1 that, under the set boundary conditions and parameters, the hot and cold ends of the vortex tube are separated by the following calculation: the highest total temperature at the hot end is 337.65 K and the lowest total temperature at the cold end is 263.44 K after the 0.4MPa gas of 16.9℃ (290.05 K) enters the vortex tube.

The simulation results are compared with the experimental results, and the simulation and experimental errors are 2% and 0.3% respectively, which shows that the vortex tube simulation is reasonable within the error range.

At the same time, as shown in Figure 5, in the case of mathematical model, material composition, solution settings and other parameters remain unchanged, the maximum total temperature of the hot end of the vortex tube is 366.49 K and the minimum total temperature of the cold end is 245.32 K under the inlet condition of 0.7 MPa and 40 ℃ (313.15 K), which can be obtained by simulation.

Acknowledgments
2020 National University Student Innovation and Entrepreneurship Training Program Project Grant (Project Number: S202010497083).

Reference
[1] C.D.Fulton.Ranque'stube.ASERRefrigerationEngineering,1950,58(5)473–479
[2] J.S.VanDeemter.OnthetheoryoftheRanque–Hilschcooleffect.AppliedscientificResearch(SeriesA),1952,3(3):174–196
[3] AliM.El-Nashar.Economicofsmallsolar-assistedmultiple-effectstackdistillationplants[J].Desalination,2000,130(3).
[4] Han Yingyi. Analysis of water consumption change trend in Dalian from 2003 to 2016 [J]. Northeast water conservancy and hydropower, 2019, 37 (01): 34-35
[5] Yan Yulian, Wu yunqi, Wu Shuibo, pan Chunyou, Li Lu, Wang Tingting. Cost advantage potential analysis of seawater desalination in water supply industry [J]. Salt Science and chemical industry, 2018,47 (09): 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 [J]. Journal of Guangxi University (NATURAL SCIENCE EDITION), 2017,42 (03): 897-903
[7] Wu Qibiao. Research on vacuum characteristics of jet vacuum generator [D]. Dalian Maritime University, 2017