

A Kind of Refrigerant System Design Combined with Knudsen Compressor and Vortex Tube

Xiang Wang¹, Wei Lu^{1,*}, Qianci Mo^{2,3}, Penghao Xing¹, Zhizhou Xu¹

¹College of Mechanical Engineering, Guangxi University, Nanning 530004, China

²School of Chemistry and Chemical Engineering, Guangxi University, Nanning 530004, China

³Guangxi Special Equipment Inspection and Research Institute, Nanning 530219, China

* Corresponding author: tjluwei@163.com

Abstract.Based on the boost characteristics of the Knudsen compressor and the cooling effect of the vortex tube, a novel refrigeration system combining the Knudsen compressors with the vortex tubes is proposed. The system can be driven by low-grade residual/waste heat and has no moving parts. Then the concrete structure of the novel refrigeration system is design for cooling a 50 m² central control room that needs 19,194KWh of cooling energy per year. The calculated results show the proposed refrigeration system can save 11,132.52 yuan per year. Moreover, the novel system is flexible to meet different cooling requirements by altering the arrangement of the Knudsen compressors and the vortex tubes.

1. Introduction

Refrigeration technology is widely used in commercial, industrial and mining enterprises, residential and public places, and even in cutting-edge scientific fields such as microelectronics technology, optical fiber communication, energy, new raw materials, space development, and bioengineering technology. For example, commercial applications mainly include cold processing, cold storage, and refrigerated transportation of perishable foods to reduce the food consumption in production and distribution, and to ensure reasonable market sales in various seasons. In machinery manufacturing, the cryogenic treatment of steel makes the metallurgical phase. The austenite inside the structure transforms into martensite and improves the properties of the steel. Refrigeration plays an important role in the stable operation of various industrial production processes and in ensuring the quality of products. It is also important for improving labor productivity, protecting human health, and creating a comfortable working and living environment. At present, the commonly used cooling methods at home and abroad are liquid vaporization heat absorption and cooling, which requires energy consumption, and various refrigerants also have a certain impact on the environment, so it is very meaningful to explore a more efficient, energy-saving and environmentally friendly refrigeration technology.

The refrigeration technology based on the combination of the Knudsen compressor and the vortex tube was extended on the basis of the Knudsen [1-2] proposed Knudsen pump. Based on the boost effect of the Knudsen pump, Gupta and An et al [3-4] adopted a micro-machining process to obtain a higher compression ratio. The maximum compression ratio of the Knudsen pump was around 109.



And Gupta et al [5-7] studied the method of increasing the flow rate of the Knudsen pump. In addition, the vortex tube has a cooling effect and can - be driven only with compressed gas. So we can design a new refrigeration system.

2. Design of the novel refrigeration system combining Knudsen compressor with vortex tube

2.1. Principle of the proposed refrigeration system

The Knudsen compressor is composed of a cold chamber, a thermal chamber, and a micro-channel. When the characteristic size of the micro-channel is equal to or smaller than the average free path of the gas molecules, and the tangential temperature gradient exists on the wall, the gas molecules spontaneously move from the cold chamber. The pressure in the hot chamber increases due to the increase of gas molecules, and the pressure in the cold chamber decreases due to the reduction of gas molecules. The pressure difference between the cold cavity and the hot cavity. This phenomenon is called the thermal transpiration. [8] Due to the effect of thermal transpiration, the gas flows from the cold chamber to the hot chamber, and the gas pressure in the hot chamber rises to form a pressure boost effect. The Knudsen compressor uses this principle to compress the gas. The vortex tube is a very simple energy separation device, which is composed of a nozzle, a vortex chamber, a separation orifice, and cold and hot ends. During operation, the compressed gas expands in the nozzle and then enters the vortex tube in a tangential direction at a very high speed. When the air flow rotates at high speed in the vortex tube, it is separated into two partial air flows with unequal total temperatures after vortex flow transformation. The temperature of the air flow in the central part is low, and the temperature of the air flow in the outer part is high, and the ratio of cooling heat flow can be adjusted to obtain the maximum cooling effect or heating effect. Since the Knudsen compressor has a boost effect and the vortex tube has a cooling effect, a new refrigeration system is designed by combining the characteristics of both.

2.2. Construction of the proposed refrigeration system

2.2.1. The entire system layout

The novel refrigeration system consists of two parts, namely, the Knudsen compressor subsystem and the vortex tube subsystem. The system layout is shown in Fig.1.

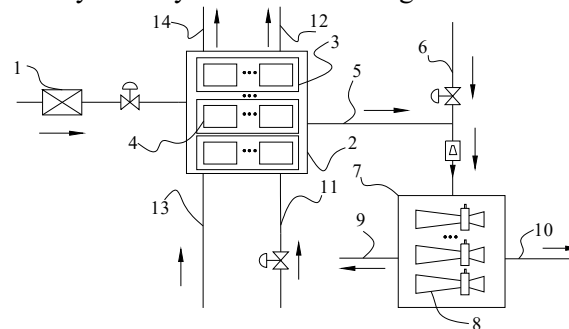


Fig. 1. Sketch of system layout

The work process of the system is as follows: Gas enters into the Knudsen compressor device 2 through the gas filter 1, and the gas is boosted by the Knudsen compressor device 2. The single micro-channel feature size of a Knudsen compressor is not greater than the molecular mean free path of the gas. The Knudsen compressor device 2 is stepwise stepped up by the thermal transpiration, and the boosted gas is input from the gas output pipe 5 to the vortex tube device 7, and the high pressure gas is divided into a cold fluid and a hot fluid by the vortex tube. The cold fluid is made of cold gas. Output through tube 10. The hot fluid flows out through the hot gas outlet pipe 9, and the hot gas can be used where needed in industrial production. The number of the Knudsen compressor sets 3 and the number of the Knudsen compressors 4 in each of the Knudsen compressor sets 3 and the number of the vortex tubes 8 are determined and adjusted based on actual usage. The hot fluid flows into the pipe 11 from

the hot fluid inflow and flows out of the hot fluid outflow pipe 12 after the heat exchange. The cold fluid flows into the pipe from the cold fluid inflow pipe 13, and flows out of the system from the cold fluid outflow pipe 14 after the heat exchange. Each flow is regulated by the flow regulating valve in the system, and the flow rate detection is completed by the flow meter. Since the gas entering the Knudsen compressor device 2 is filtered in advance, the content of impurities in the gas is reduced, so that the gas is relatively pure, and the service life of each Knudsen compressor 3 is extended.

2.2.2. The Knudsen compressor structure

The schematic diagram of the Knudsen compressor is shown in Fig. 2. By placing the heat exchanger in the cold and hot chambers, the chamber is subjected to heat exchange so as to maintain the temperature difference between the cold chamber and the hot chamber. The meanings of numbers in Fig.2 are as follows: 21-cold chamber, 22-thermal chamber, 23-micro-channel, 24-connecting channel, 25-cold chamber heat exchanger, 26-thermal chamber heat exchanger

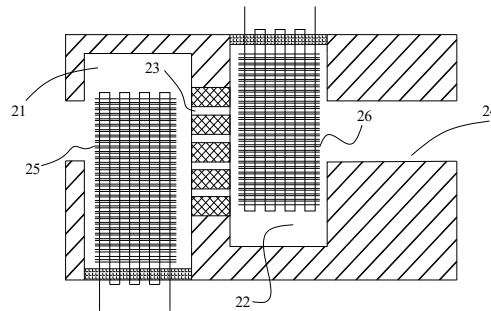


Fig. 2.The structure of the Knudsen compressor

2.3. Energy analysis of the proposed refrigeration system

According to the system analysis, the heat Q required by the Knudsen compressor is defined in [9]

$$Q = \sum_i^n (Q_{b,i} + Q_{c,i} + Q_{h,i} + Q_{d,i}) \quad (1)$$

Where: Q_b is the amount of heat required to maintain the micro-channels and the connecting channels, Q_c is the loss of cold in the cold chamber, Q_h is the loss of heat in the thermal chamber, and Q_d is the loss of heat in the micro-channel.

Defining the unit energy consumption of the Knudsen compressor is

$$\dot{Q} = \frac{Q}{\sum_i^n V_i} \quad (2)$$

Where: V is the Knudsen compressor flow, m^3/min .

The use of heat energy has an efficiency problem and defines the thermal efficiency of the Knudsen compressor as

$$\eta = \frac{R}{C_p} \left(\frac{M_c - M_h}{M_c + M_h + \frac{2L_w \mu}{C_w C_p} \frac{Q_b}{\Delta T}} \right) \quad (3)$$

Where: $R=8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$, which is the gas constant; C_p is the specific heat of constant pressure gas, $\text{kJ} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$; M_c is the mass flow rate from the cold chamber to the hot chamber, kg/s ; M_h is the mass flow from the hot chamber to the cold chamber, kg/s ; C_w is the gas conductance, $\text{L} \cdot \text{s}^{-1}$.

When comprehensively considering the entire system, the system is required to be highly efficient and energy-saving. Therefore, the thermal efficiency of the Knudsen compressor is required to be

maximized during the design of this system. When the required flow rate V of the vortex tube is satisfied, the unit energy consumption of the Knudsen compressor is required to be minimized.

Therefore, we can establish the following minimum energy model

$$\begin{cases} \min \dot{Q} \\ \max \eta \\ V \geq V' \end{cases} \quad (4)$$

Where: V' is the actual required flow.

3. The application of the novel refrigeration system combining Knudsen compressor with vortex tube

Taking a chemical plant as an example, we select a 50m² central control room in the factory as an application object and conduct a preliminary example analysis of the system.

3.1. System parameters setting

There are multiple control devices in the central control room to control the operation status of the equipment and process, adjust the parameters in time, and ensure the product quality. so the cooling capacity is needed to maintain the central control room in a suitable temperature range. According to the characteristics of chemical plant production, the chemical plant is set to run for 350 days a year, and the central control room needs to be on duty 24 hours a day. In combination with reality, in order to meet environmental requirements, a separate floor-standing room air conditioner is required. The relevant parameters are shown in Table 1:

Table 1. Air conditioner performance parameters

Brand	CHIGO	
Performance parameter	EER	3.15W/W
	COP	3.30W/W
	refrigerating capacity	7200W
	Maximum input power	5000w
	Rated refrigerating power	2285W

According to the air conditioner performance parameters, we can calculate the 50m² central control room cooling demand. This part of the cooling capacity comes from the vortex tube system in the system. After matching, choose VAIR vortex tube, vortex tube flow series operating parameters are shown in Table 2.

Table 2. Working parameters of vair vortex tube flow series

100CFM		
Inlet gas pressure		
PSIG	MPa	Bar
100	0.7	7

Maximum air intake		
CFM	L/min	m ³ /min
100	2830	2.83
Maximum cooling capacity		
Watts	Kcal/Hr	BTU/Hr
2031	1746	6930

At present, the total waste heat resources of various industries account for about 17%-67% of the total fuel consumption. These waste heat are mainly in the form of hot water. The temperature of these hot water is general-ly 30°C-60°C. Therefore, the water temperature is 60°C, and the deep well water is used for the cooling water. The summer temperature is generally about 22°C. There-fore, set the temperature of the hot chamber to 50°C and the temperature of the cold chamber to 25°C.

3.2. System design

Based on the system parameters that have been set, we designed the Knudsen compressor. The Knudsen compr-essor is required to provide a compressed gas with a pressure of 0.7 MPa and a gas flow rate of 2.83 m³/min. Through calculation, we get the series number and pressure distribution of the Knudsen compressor, as shown in Table 3:

Table 3.Series connection and pressure distribution

Stages	Pressure	Stages	Pressure
1	1.00E+05	26	2.74E+05
2	1.04E+05	27	2.85E+05
3	1.08E+05	28	2.97E+05
4	1.13E+05	29	3.09E+05
5	1.17E+05	30	3.22E+05
6	1.22E+05	31	3.35E+05
7	1.27E+05	32	3.49E+05
8	1.33E+05	33	3.63E+05
9	1.38E+05	34	3.78E+05
10	1.44E+05	35	3.93E+05
11	1.50E+05	36	4.10E+05
12	1.56E+05	37	4.26E+05
13	1.62E+05	38	4.44E+05
14	1.69E+05	39	4.62E+05

15	1.76E+05	40	4.81E+05
16	1.83E+05	41	5.01E+05
17	1.90E+05	42	5.21E+05
18	1.98E+05	43	5.43E+05
19	2.06E+05	44	5.65E+05
20	2.15E+05	45	5.88E+05
21	2.24E+05	46	6.13E+05
22	2.33E+05	47	6.38E+05
23	2.43E+05	48	6.64E+05
24	2.53E+05	49	6.91E+05
25	2.63E+05	50	7.20E+05

Through analysis and calculation, we can see that in order to meet the temperature requirements of the central control room, we need a Knudsen compressor to provide compressed gas at a pressure of 0.7 MPa, and the required gas flow rate is $2.83\text{m}^3/\text{min}$. At this time, we need to connect 50 series of Knudsen compressors to meet the requirements. According to calculations, the 50m^2 central control room of the chemical plant needs 19,194 kWh of cooling energy per year. If the cooling requirement is met by the proposed refrigeration system, the calculation based on an average electricity price of 0.58 yuan/KWh indicates the saving 11,132.52 yuan per year.

4. Conclusion

The proposed refrigeration system combining the Knudsen compressor with the vortex tube is a brand new refrigeration method, which fully utilizes the advantages of the Knudsen compressor and the vortex tube, and its cooling effect and application occasions can be very wide. When the system is used in the control room of a chemical plant, the system uses the characteristics of the plant generating a large amount of waste heat, and uses the heat of low-grade residual/waste to drive the Knudsen compressor. The compressed gas produced by the Knudsen compressor is directly used for the vortex tube. After the cooling effect of the vortex tube, we get the cooling capacity we need. The entire system has no moving parts and does not need to consume extra electric energy. Through calculations, a 50m^2 central control room needs 19194KWh of cooling capacity per year, and 11132.52 yuan per year, and chemical plants usually have multiple central control rooms. Using this system, we can save this cost. In addition, through the series and parallel connection of the Knudsen compressor and the vortex tube, we can use more low-grade residual/waste heat, get more cooling capacity, and apply it to more places.

The proposal of a refrigeration system that combines the Knudsen compressor and the vortex tube provides a new idea for energy saving and consumption reduction.

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