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DEVELOPMENT OF UNI-FLOW VORTEX TUBE

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Abstract

In this study, a uni-flow vortex tube is designed and fabricated. Energy separation characteristics have been investigated with a protocol uni-flow vortex tube through a series of tests. The effects of energy separation characteristics by changing the gap between tubes and gap between throttle valve and tube are analyzed. Energy separation and throttle valve are significant parameters in the performance of a uni-flow vortex. Further, the positions of the separation tube and throttle valve are found to control the air flow at the hot side as well as at the cold side. Test results have been expressed as dimensionless temperature and heat transfer rate. When the discharge flow is the same at the hot side and the cold side, the energy separation efficiency has been found to be highest.

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1. Introduction

A vortex tube is also called a *Ranque-Hilsch vortex tube*. It generates a strong vortex by spraying a high-pressure gas into a tube. With this strong vortex, gas is not only separated into low temperature and high temperature gases but particle-shaped substances are also separated [1, 2]. This vortex tube has merits of getting low temperature air as well as high temperature air without using a separate power source if it is used in the place where high-pressure gas is used. Its operation is easy and its response is fast. However, cold air flow shows inferior performance compared with existing cooling devices [3].

The energy separation effect by vortex tube has not been fully elucidated, yet generally energy separation effect is explained with energy transfer theory as in Figure 1 [4]. A gas which enters by compression generates a strong vortex while going through a tangential nozzle part at the vortex generator and progresses toward the hot air exit. The spiral rotatory flow inside the tube can be broadly categorized into a forced vortex and a free vortex. At the center of the tube, a forced vortex of almost forced rotation is formed. Meanwhile, a free vortex is generated by forced vortex at the wall of tube. At this time, it is known that a free vortex accompanies another vortex inside the free vortex due to friction between the flow at axis direction and wall surface. Therefore, the speed of a free vortex becomes abruptly increased. The strength of vortex becomes decreased as it passes some distance towards the axis direction of a vortex tube; thus, a reverse flow towards low temperature exit is generated from the center portion of a tube. At this time, a stagnation point is generated at the center of a tube where flow is stopped for some moment. Reverse flow is generated towards cold exit from this stagnation point as an apex. A bell-shaped surface centering from this stagnation point would act as an interface where exchange between energy transfer and momentum transfer takes place. Since the momentum transfer at interface is larger than the energy transfer, the temperature of the fluid is increased and the temperature at the tube center portion becomes further dropped, which in turn makes energy separated. A momentum transfer is taken place from the center of the tube to the wall direction due to speed difference inside the vortex tube. Heat moves thereby toward the center of the tube. However, since momentum transfer is larger than heat transfer, gas temperature near the wall is increased and the gas at the center of the tube becomes cooled down.

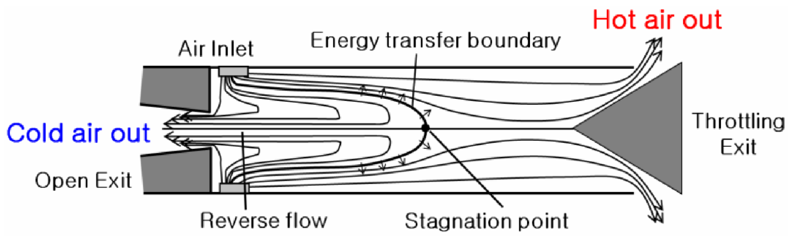


Figure 1. Energy separation theory in the vortex tube.

A vortex tube is largely divided into a counterflow type and a uni-flow type depending on the flow type. A counterflow type means a vortex tube where the hot air out and cold air out are set at opposite directions to each other. A uni-flow type refers to the vortex tube in which hot air exit and cold air exit are facing the same direction [5, 6].

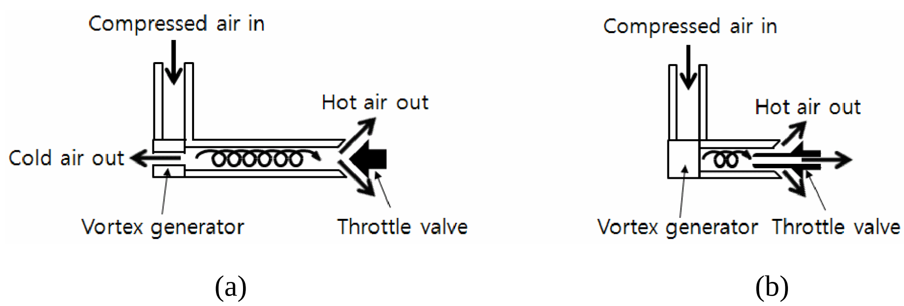


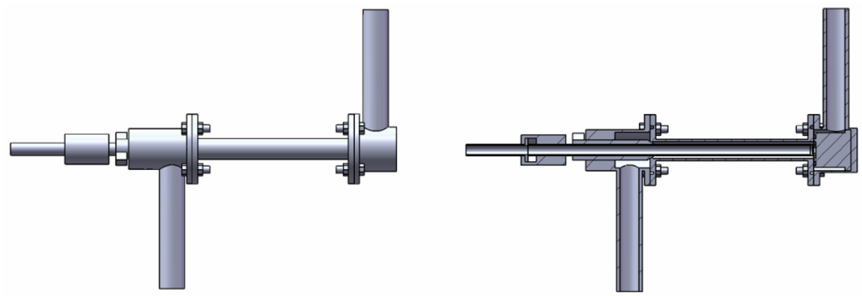
Figure 2. Classification by the type of a vortex tube: (a) Counterflow vortex tube and (b) Uni-flow vortex tube.

Generally, since counterflow vortex tube is superior in the efficiency as well as energy separation aspects, there have been many researches about counterflow vortex. However, there is rare literature about a uni-flow vortex tube and the research results are difficult to find. Nonetheless, since a uni-flow vortex tube has a small size and hot air and low air flow that are formed toward the same direction, it is beneficial to use in a limited space like automobiles. In this study, therefore, a uni-flow vortex tube is designed and fabricated to analyze the energy separation characteristics of a uni-flow vortex tube. A basic performance of uni-flow tube is, thus, performed.

2. Main Text

2.1. Design and fabrication of vortex tube

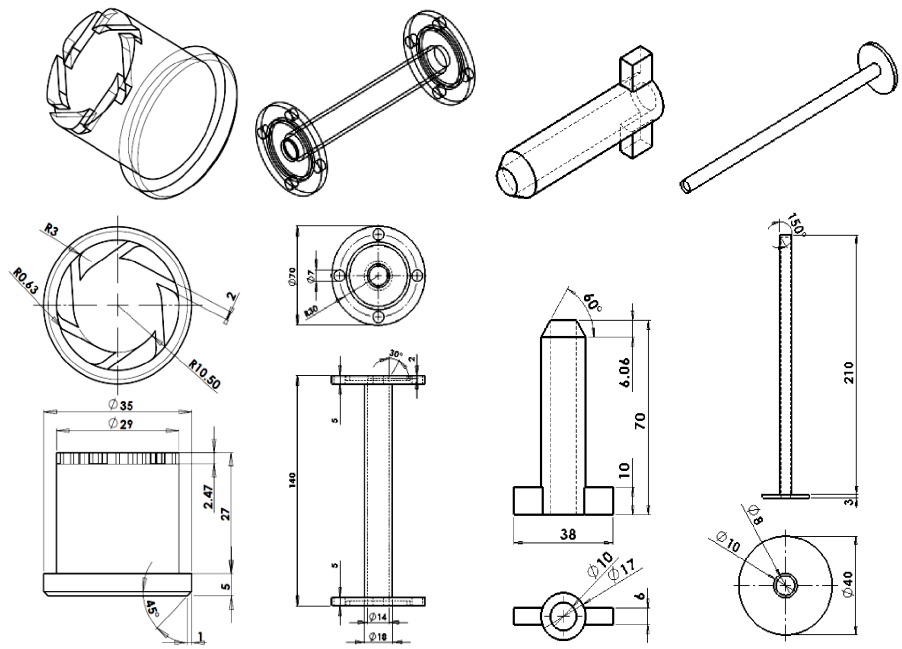
The vortex tube as a subject of this study is a uni-flow type vortex tube. Design and fabrication are performed by specifying the basic form of uni-flow vortex tube and range of the design parameter based on the performance parameter of counterflow vortex tube which has been extensively studied so far [5]. Figure 3 shows the designed uni-flow vortex tube. The key design item of uni-flow vortex tube is shown in Figure 4.



(a) (b)

Figure 3. Uni-flow type vortex tube: (a) Assembly view and (b) Sectional view.

Figure 4(a) shows a vortex generator which generates vortex with tangential nozzle; Figure 4(b) shows a tube having cold exit and hot exit; Figure 4(c) shows a throttle valve which regulates flow; and Figure 4(d) shows a separation tube to separate the high temperature gas and low temperature gas. A throttle valve is arranged at the hot exit and machined to move 1mm each per one rotation by the machining thread on the surface. Meanwhile, the separation tube is inserted inside the throttle tube. It is machined to move 1mm each per one rotation inside the throttle valve with the help of a machined screw thread. The tube, vortex generator, throttle valve, and separation tube are made of SUS304.



(a) (b) (c) (d)

Figure 4. Each elements part of vortex tube: (a) Vortex generator, (b) Tube, (c) Throttle valve and (d) Separation tube.

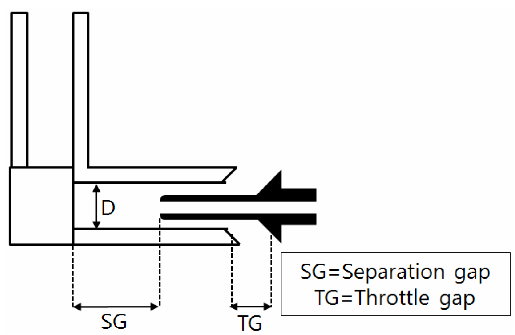
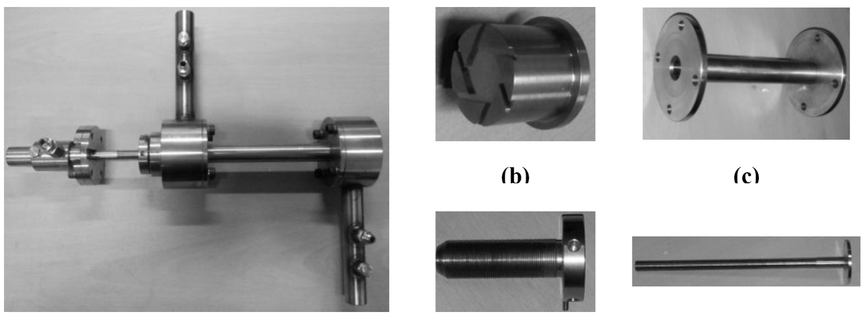


Figure 5. Definition of separation gap and throttle gap.

Figure 5 shows the tube diameter, separation gap, and throttle gap which are the key performance parameters of the vortex tube. The diameter of the tube is marked as D, separation gap as SG, and throttle gap as TG. SG is the distance from the generator to tube while TG indicates the distance from tube to throttle valve. Designing and fabrication are done so that TG and SG are varied to draw the optimized design parameter of a uni-flow vortex tube.

Figure 6 shows the fabricated uni-flow vortex tube per design. Figure 6(a) shows a uni-flow vortex tube, Figure 6(b) shows a vortex generator, Figure 6(c) shows a tube comprising a cold exit and a hot exit, Figure 6(d) shows a throttle valve to adjust the flow, and Figure 6(e) shows a separation tube to separate the high temperature gas and low temperature gas.

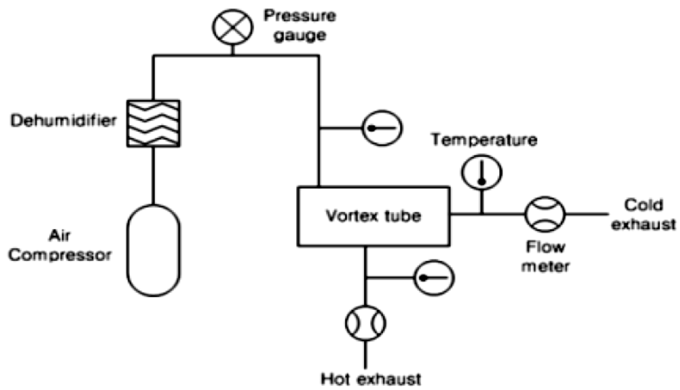


(a) (d) (e)

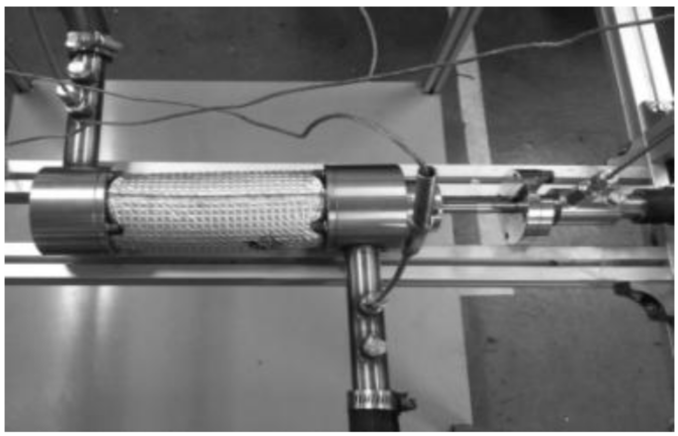
Figure 6. Uni-flow vortex tube and each compositional part: (a) Uni-flow vortex tube, (b) Generator, (c) Tube, (d) Throttle and (e) Separation tube.

2.2. Construction and method of testing apparatus for the vortex tube

A testing apparatus is constructed (Figure 7) to test the energy separation effect of a vortex tube. Figure 7(a) illustrates a brief diagram of a testing apparatus and Figure 7(b) presents a photo of the installation of a uni-flow vortex into the testing apparatus. As can be seen from Figure 7, temperature sensors are installed at air pressure entry and corresponding exit to measure the temperature. Insulation is arranged on the tube to shorten the time to reach the temperature equilibrium stage. Compressed air inflows by connecting the air flow with 20hp compressor and 3,000 liters capacity air tank. Constant air is maintained to feed 200kPa air pressure using a pressure regulator. Testing parameters are set as TG and SG. The range of TG is set from 0mm to 1.5mm, while SG varies from 3mm to 10mm.



(a)



(b)

Figure 7. Brief diagram of testing rig and vortex testing apparatus: (a) Schematic diagram and (b) Testing apparatus.

3. Test Results

Test results are expressed as a graph in terms of temperature ratio, flow ratio, and heat transfer rate. The values expressing each axis of graph are defined below:

$$L_{TG} = \frac{TG}{D}, \tag{1}$$

$$L_{SG} = \frac{SG}{D}, \quad (2)$$

$$R_T = \frac{T_{out} - T_{in}}{T_{in}}, \quad (3)$$

$$R_m = \frac{Flow\ rate\ of\ cold\ exit}{Flow\ rate\ of\ inlet}, \quad (4)$$

$$\dot{Q} = \dot{m} C_p \Delta T. \quad (5)$$

Figure 8 is the testing result for the temperature ratio when the SG of vortex tube is fixed as 10mm and TG is changed. The test results show that as TG is increased, temperature ratios at both the hot side and the cold side are decreased. This tendency implies that the temperature separation effect is decreased from the hot side, while temperature separation effect is increased at the cold side. It means there is no difference in the amount of energy transfer of gases at the hot side and the cold side. However, as TG increases, the flow rate at the hot side is increased to make air flow difference between the cold side and the hot side; thereby, the temperature separation effect at the hot side is decreased while this effect is increased at the cold side.

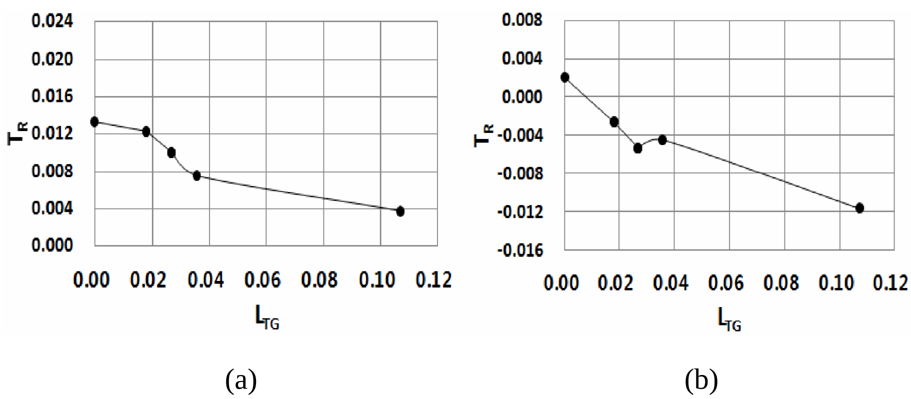
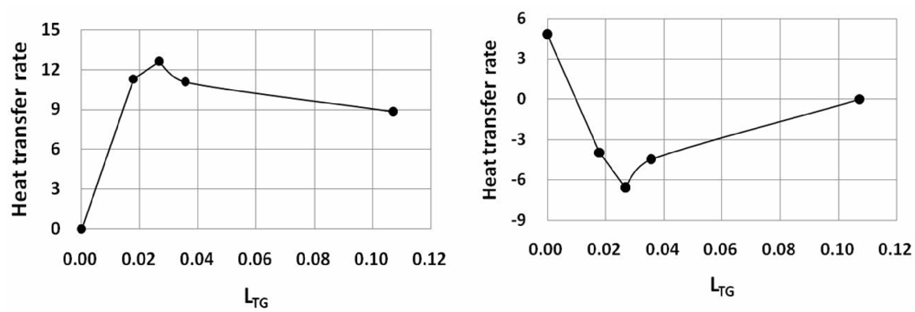


Figure 8. Changes in the temperature ratio following L_{TG} changes (SG = 10mm): (a) Hot exit and (b) Cold exit.

However, since the temperature ratio does not reflect only the mass flow ratio, it is needed to confirm the heat transfer rate. Figure 9 shows the test result for the heat transfer rate under the condition shown in Figure 8. Here, the heat transfer rate shows a different result from the temperature ratio. The mass flow rate of air is reflected in the heat transfer rate (equation (5)). The best effect is found from around $L_{TG} = 0.027$ at low side as well as the hot side. Figure 10 shows a mass flow rate of air at the hot side and at the cold side. The maximum heat transfer rate occurs at the point where flow rates at the cold side as well as at the hot side become the same. The same phenomenon is observed from the counterflow vortex tube [3].



(a) (b)

Figure 9. Changes in the heat transfer rate by L_{TG} (SG = 10mm): (a) Heat transfer rate at the hot side and (b) Heat transfer rate at the cold side.

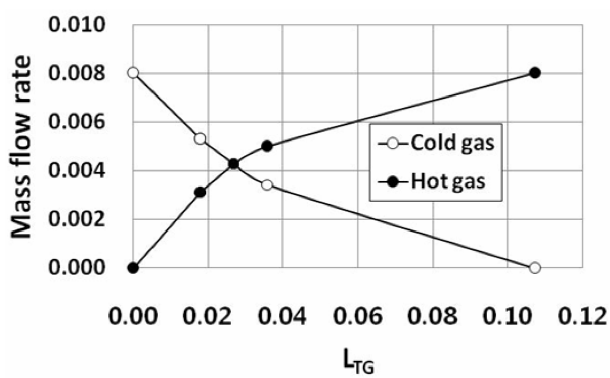
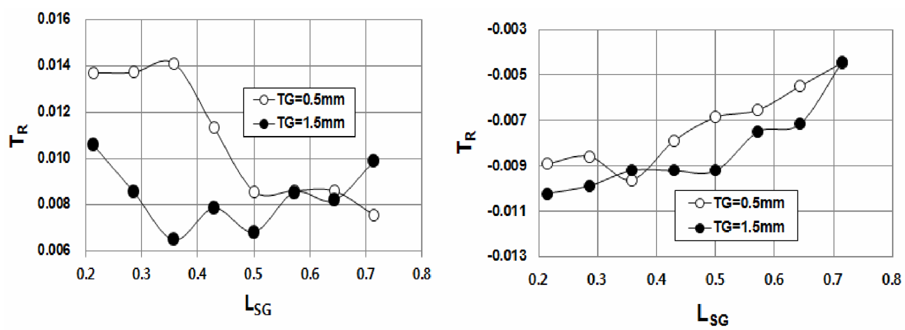


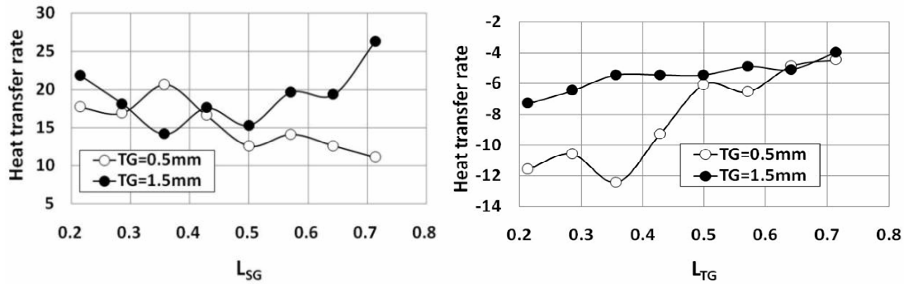
Figure 10. Changes in the mass flow rate by L_{TG} (SG = 10mm).

Figure 11 shows the testing result when TG is fixed as 0.5mm and 1.5mm while changing SG values. From the hot side, higher temperature separation effect is observed when TG is at 0.5mm compared with TG at 1.5mm. In addition, energy separation effect is in decreasing trends as L_{SG} is increased. At the cold side, on the other hand, a 1.5mm TG shows a higher energy separation effect compared with TG at 0.5mm in reverse tendency from the hot side. The energy separation effect could be confirmed as L_{SG} is increased. However, the heat transfer rate in Figure 12 shows different trends from temperature ratio. At the hot side, the higher energy separation effect is observed when TG is at 1.5mm compared to TG at 0.5mm. Also, with increase in L_{SG}, the energy separation effect under 1.5mm TG is increased, while the energy separation effect under 0.5mm TG is decreased. The same tendency is found from the cold side where a higher energy separation is observed under 0.5mm TG compared with 1.5mm TG, which is different from the phenomenon occurring at the temperature ratio. The reason why a higher energy separation effect than 1.5mm TG is observed under 0.5mm TG might be due to a similar flow rate at the hot side as well as at the cold side as can be seen from Figure 13.



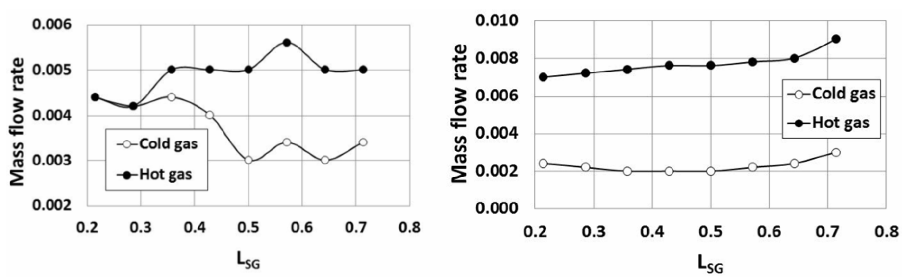
(a) (b)

Figure 11. Changes in the temperature ratio by L_{SG} (SG: 3~10mm): (a) Temperature difference at the hot side and (b) Temperature difference at the cold side.



(a) (b)

Figure 12. Changes in the heat transfer ratio by L_{SG} (SG: 3~10mm): (a) Heat transfer rate at the hot side and (b) Heat transfer rate at the cold side.



(a) (b)

Figure 13. Changes in the mass flow rate by L_{SG} (SG: 3~10mm): (a) TG = 0.5mm and (b) TG = 1.5mm.

4. Conclusion

The energy separation characteristics of the uni-flow vortex tube have been tested and the results below are obtained:

(1) A uni-flow vortex tube is designed and fabricated to carry out tests under various conditions. The vortex tube protocol is designed in such a way that SG gap and TG gap could be adjusted. The basic performance test is carried out with fabricated protocol uni-flow type vortex tube. The energy separation effect of vortex tube is, thus, investigated.

(2) When the SG is fixed at 10mm, the temperature ratio is decreased as L_{TG} is increased. However, the heat transfer rate is highest near L_{TG} = 0.027 due to the effect of flow rate. The point near $L_{TG} = 0.027$ which shows the best energy separation effect is the point where air flow at the hot side as well as at the cold side becomes the same.

(3) When L_{SG} is changed while L_{TG} is fixed at some scale, the excellent energy separation effect is obtained with a smaller difference in the air flow at the hot side and at the cold side.

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