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Effects of Tube Materials and Cooling Media on the Energy Separation in Vortex Tubes

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Key words: Vortex tube, Energy separation, Tube conductivity, Cooling modes

Abstract

The phenomena of energy separation in vortex tubes was investigated experimentally to see the subsidiary effect of the conductivity of tube material and cooling conditions around the outer surface of the tube. The experiment was carried out with pyrex, stainless steel and copper tubes, and the heat transfer conditions of the tubes were with insulation, without insulation and water cooling modes respectively. The results were obtained that the hot exit fluid temperature was highly affected by a change of conductivity of a tube when the outer surface was cooled by the water, while the working fluid through the tubes was air. However, the cold exit temperature was little affected by the heat transfer modes on the outer surface of the vortex tube.

Nomenclature

P : Pressure [MPa]

ΔT : Difference of air temperature between at the inlet and at the outlets [℃]

$\Delta\overline{T_a}$: Mean value of ΔT at the insulated tube surface [℃]

$\Delta\overline{T_p}$: Mean value of ΔT when Pyrex tube is used [℃]

ΔT_{I} : Temperature difference between $\Delta\overline{T}$ and $\Delta\overline{T_a}$ [℃]

ΔT_{II} : Temperature difference between $\Delta\overline{T}$ and $\Delta\overline{T_p}$ [℃]

y : Mass fraction at the cold exit to the total air

Greek symbols

η : Energy separation efficiency of vortex tube

χ : Specific heat ratio

Subscripts

c : at cold exit

h : at hot exit

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in : at inlet

1. Introduction

Since a vortex tube was invented by Ranque,(1) a French metallurgist, in 1932, it was used for liquefying gases in early times and gradually researched due to the feature of no moving parts and its simplest form. The vortex tube is a piece of tubing closed towards one end by a plug or an orifice, and provided with a tangential inlet nozzle near to the plug. A gas stream is led into the tube through the jet from compressed gas source to get cold and/or hot streams. Nowadays, it is applied in various fields, such as local cooling and cooling jacket to remove the heat produced at machine tools or electronic components.

Hilsch(2) researched systematically on the basis of Ranque's result(1) and made up a foundation for the analysis of energy separation mechanism through a vortex tube. As a realistic approach, Suzuki(3) did the experiments and the theoretical analysis to reveal gas velocities and temperature distribution occurred in a vortex tube.

For a counterflow vortex tube, which has a better performance than does a uniflow one, both ends of the tube are opened and flow rates are controled by closing the throttle valve partly at the far end of the tube. As the flow enters tangentially into the tube and moves along the tube, vortex flows are produced as illustrated in Figure 1. On account of the friction between gas and tube inner surface, the angular velocity becomes low in the outer annular region of flow and high in the inner region, so that the free vortex are formed by the law of constant angular momentum. In the center core, however, the flow is changed to the forced vortex, because it has a tendency to have a uniform velocity distribution due to viscous effect between adjacent layers. Also, the flow in the center core is reversed because of the inversed pressure gradient near to the throttle valve.

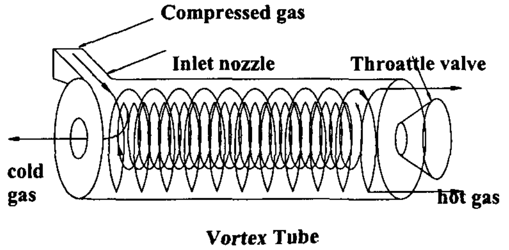


Fig. 1 Folw pattern through a counterflow vortex tube.(4)

Owing to such a vortex and viscous effect, the hot stream flows along the tube wall and out the throttle valve. Meanwhile, the cold stream moves along the center core and out the orifice.

Martynovskii and Alekseev(5) carried out the work on the energy separation performance affected by the geometry of vortex tube. They proposed optimum geometric ratios of vortex generating nozzle and cold-end orifice to the tube diameter. Furthermore, the effects of vortex tube components and working fluids were investigated by Metenin,(6) Takahama,(7) Riu,(8,9) Negm.(10) Stephan et al.(11) revealed that Görtler vortex brought about the energy separation in a vortex tube and that the insulation of the tube outer surface improved energy separation as well as Görtler vortex.

To improve the energy separation efficiency, however, more research is necessary to evaluate the subsidiary effect of tube cooling and thermal conductivity of tube material with the reference of an adiabatic condition on the tube surface. Meanwhile, a vortex tube can be applied as an expansion device in a vapor-compression refrigeration system, so that its possible application is needed to obtain a reasonable performance of the system. Therefore, the effect of thermal conditions around a tube on the energy separation has been investigated prior to carrying out the work on a refrigeration system with a vortex tube.

2. Experiment

The experimental apparatus used in this work is schematically shown in Figure 2. It consists of mainly air supply part, an experimental vortex tube and data acquisition part.

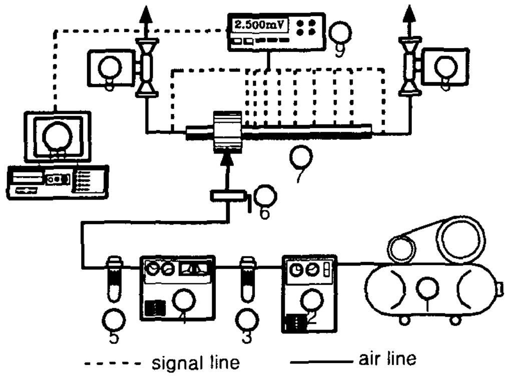
The supply air was pressurized by a compressor (①), and it was forced toward an after-cooler (②) to drop down its temperature. Subsequently, the compressed air was filtered to remove impurities (③, ⑤), and dehydrated to extract moisture (④) that might affect the system performance. The air pressure was controlled by a regulator (⑥).

The air mass flow rates are measured at the cold and hot exits respectively (⑧). The temperature at the tube wall were measured by thermocouples installed at 8 points. Figure 3 is showing the location of thermocouples and the cross-sectional view of the vortex tube including a detail of vortex generating nozzle and a water jacket which is used for tube cooling.

The experimental vortex tube has been made of a commercial one, Vortec model 208, as shown in Figure 3. It consists of a vortex generator with a cold-end orifice, a throttle valve for hot exit, a tube and connectors. Among them, the tube was replaced with Pyrex, stainless steel and copper tubes for

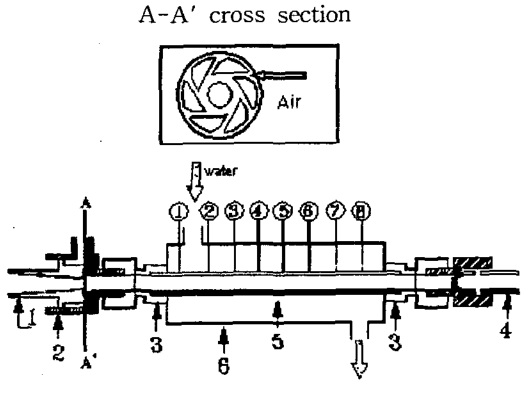
Table 1 Dimension of vortex tube and experimental conditions

Classification		Size
Dimension	Tube inner diameter	10.0 mm
	Tube length	340.0 mm
	Tube wall thickness	1.0 mm
	Cold exit diameter	3.8 mm
	Nozzle area	4.0 mm^2
Tube material (conductivity)	Pyrex (1.09 W/mK) Stainless steel (15 W/mK) Copper (380 W/mK)	
Working conditions	Working fluid : Air Ambient temperature : 25℃ Inlet air temperature : 27℃ Inlet air pressure : 0.7 MPa Cold air mass fraction : 0.1~0.9	
Cooling modes of tube surface (cooling water velocity)	With insulation of tubes Without insulation in the air With water cooling (0.03 cm/s) With water cooling (0.05 cm/s) With water cooling (0.11 cm/s)	



① Air compressor
② After cooler
③ Main filter
④ Air dryer
⑤ Pre filter
⑥ Pressure regulator
⑦ Vortex tube
⑧ Flow meter
⑨ Data aquisition
⑩ Personal computer

Fig. 2 Schematic diagram of experimental apparatus.



1. Vortex gernerator
2. Generator housing
3. Nylon connector
4. Throttle valve
5. Tube
6. Water jacker

①~⑧ : Thermocouples

Fig. 3 Detailed cross-section of vortex tube system with thermocouple location.

testing the effect of material thermal conductivity. In addition to that, a water jacket was made of an acrylic tube whose inner diameter was 5.6 cm, and installed outside the vortex tube. To cool the vortex tube outer surface, water was circulated with the average velocities of 0.03, 0.05 and 0.11 cm/s respectively. The water temperature was 25℃, which was the same as the ambient temperature. Meanwhile, the compressed air temperature was set to 27℃ at the vortex tube inlet and the pressure was maintained with 0.7 MPa by adjusting a pressure regulator. On the other hand, the cold air mass fraction was varied from 0.1 to 0.9 by controlling the throttle valve at the hot exit.

The dimensions of tested vortex tubes, experimental conditions and heat transfer modes on the tube surface are summarized in Table 1.

3. Results and discussion

Figures 4 and 5 show the differences between the hot and cold air temperatures and the temperature at the inlet of vortex tube ($\triangle T_h$, $\triangle T_c$) at varying mass fraction of the cold air. Hence, three vortex tubes, which have the same dimension with different thermal conductivities, were tested at various cooling modes on the tube surface.

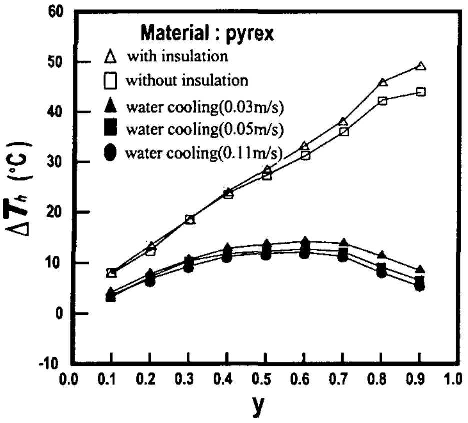
To compare the temperature differences quantitatively, the mean temperature differences at the hot and cold exits ($\triangle T_h$, $\triangle T_c$) are presented in Table 2 according to the tube material and the cooling modes of the tube surface. The mean temperature differences from the adiabatic condition ($\triangle T_{\mathrm{I},h}$, $\triangle T_{\mathrm{I},c}$) are shown in Table 3, and the mean temperature differences from Pyrex tube ($\triangle T_{\mathrm{II},h}$, $\triangle T_{\mathrm{II},c}$) are in Table 4 respectively.

When the tube surface are insulated and exposed in the air, the temperature differences at the hot exit ($\triangle T_h$) increase linearly as the cold air mass fraction (y) increases as shown in Figure 4, that is the same tendency as the result of Kim.(12) Although the mean hot temperature difference ($\triangle \overline{T_h}$) with the insulation condition is a little higher than that without the insulation, the difference is less than 1℃, as tabulated in Table 2. Also, noticeable difference cannot be found even though the tube materials are varied.

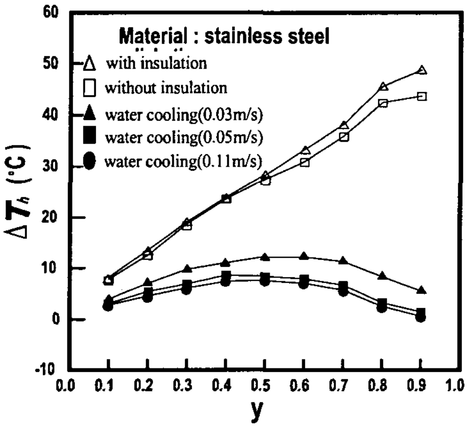
In case of the water cooling condition, however, the hot temperature difference becomes high as the cold air fraction becomes large and it reaches the maximum at y=0.6, but it decreases gradually when the cold air mass fraction is more than 0.6. As the cold air fraction is small with wide flow area at the hot exit, a large quantity of air moves through the throttle valve directly, so that the vortex flow may not be vigorous to make the energy separation in full.

When the cold air fraction is more than 0.6 with the reduced flow area at the hot exit, however, a large amount of air is reversed in the center core and the remainder, which is relatively less, moves towards the throttle valve along the tube inner wall. Thus, the hot temperature difference is to be lower in case of the forced convection with water. As shown in Table 2, the mean hot temperature difference ($\triangle \overline{T_h}$) in the water cooling condition is about 25~45% of those with the insulation and without the insulation condition. The maximum difference between at the water cooling and at the insulation condition ($\triangle T_{\mathrm{I},h}$) is 20.73℃ in Table 3, when the tube material is copper and the water velocity is 0.11 cm/s which is the highest in the experiment. In comparison with the Pyrex tube in Table 4, the maximum difference ($\triangle T_{\mathrm{II},h}$) is 4.71℃. It means that the hot air temperature decreases as the thermal conductivity of tube is high.

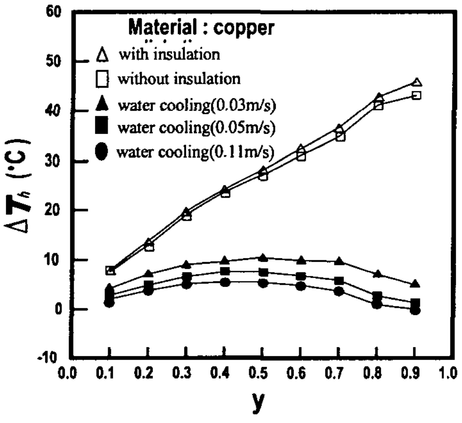
The reason is that the conductive heat flux becomes large from the inner wall to the outer



(a) Pyrex

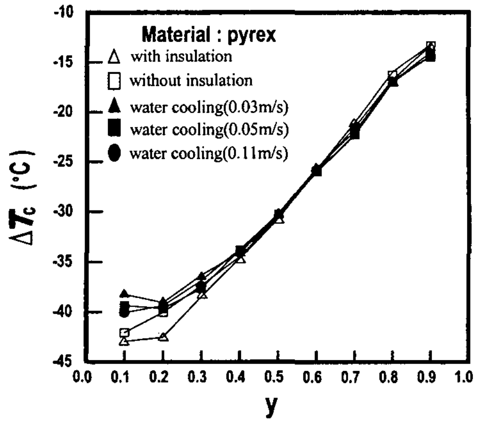


(b) Stainless steel

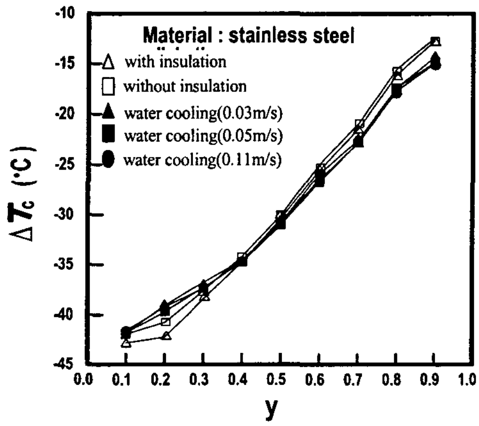


(c) Copper

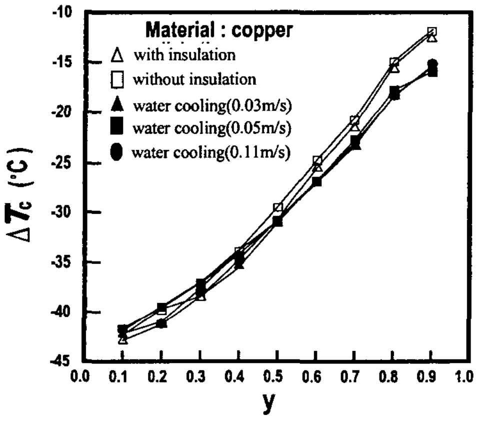
Fig. 4 Hot exit temperature differences versus cold air mass fraction for different cooling modes and tube materials.



(a) Pyrex



(b) Stainless steel



(c) Copper

Fig. 5 Cold exit temperature differences versus cold air mass fraction for different cooling modes and tube materials.

Table 2 Mean temperature differences of hot exit and cold exit at different cooling modes and tube materials

Conditions	Tubes (conductivity)	Pyrex ($\Delta \overline{T_p}$) (1.09 W/mK)	Stainless steel (15.0 W/mK)	Copper (380.0 W/mK)
$\Delta \overline{T_h}$ (Hot exit)	With insulation of the tube ($\Delta \overline{T_a}$)	28.95	28.54	27.96
	Without insulation in the air	28.28	28.02	27.78
	With water cooling (0.03 cm/s)	12.55	10.12	8.01
	With water cooling (0.05 cm/s)	12.25	9.85	7.68
	With water cooling (0.11 cm/s)	11.94	9.38	7.23
$\Delta \overline{T_c}$ (Cold exit)	With insulation of the tube ($\Delta \overline{T_a}$)	−29.89	−28.62	−28.31
	Without insulation in the air	−28.72	−28.52	−27.82
	With water cooling (0.03 cm/s)	−28.34	−28.51	−28.55
	With water cooling (0.05 cm/s)	−28.46	−28.73	−28.83
	With water cooling (0.11 cm/s)	−28.56	−28.92	−29.12

Table 3 Temperature differences $\Delta T_{\mathrm{I}}(=\Delta \overline{T}-\Delta \overline{T_a})$ to the reference cooling mode of insulation condition (▲ : increase, ▼ : decrease) (Unit : ℃)

Conditions	Heat transfer modes	With insulation of the tube	Without Insulation in the air	Water Cooling (0.03 cm/s)	Water Cooling (0.05 cm/s)	Water Cooling (0.11 cm/s)
$\Delta T_{\mathrm{I},h}$ (Hot exit)	Pyrex	-	▼ 0.67	▼ 16.40	▼ 16.70	▼ 17.01
	Stainless steel	-	▼ 0.52	▼ 18.42	▼ 18.69	▼ 19.16
	Copper	-	▼ 0.18	▼ 19.95	▼ 20.28	▼ 20.73
$\Delta T_{\mathrm{I},c}$ (Cold exit)	Pyrex	-	▲ 1.17	▲ 0.55	▲ 1.43	▲ 1.33
	Stainless steel	-	▲ 0.10	▲ 0.11	▼ 0.11	▼ 0.30
	Copper	-	▲ 0.49	▼ 0.24	▼ 0.52	▼ 0.81

Table 4 Temperature differences $\Delta T_{\mathrm{II}}(=\Delta \overline{T}-\Delta \overline{T_p})$ to the reference material of Pyrex tube (▲ : increase, ▼ : decrease) (Unit : ℃)

Conditions	Tubes (conductivity)	Pyrex (1.09 W/mK)	Stainless steel (15.0 W/mK)	Copper (380.0 W/mK)
$\Delta T_{\mathrm{II},h}$ (Hot exit)	With insulation ot the tube	-	▼ 0.41	▼ 0.99
	Without insulation in the air	-	▼ 0.26	▼ 0.50
	With water cooling (0.03 cm/s)	-	▼ 2.43	▼ 4.54
	With water cooling (0.05 cm/s)	-	▼ 2.40	▼ 4.57
	With water cooling (0.11 cm/s)	-	▼ 2.56	▼ 4.71
$\Delta T_{\mathrm{II},c}$ (Cold exit)	Adiabatic condition	-	▲ 1.27	▲ 1.58
	Natural convection (air)	-	▲ 0.32	▲ 0.35
	With water cooling (0.03 cm/s)	-	▼ 0.17	▼ 0.21
	With water cooling (0.05 cm/s)	-	▼ 0.27	▼ 0.37
	With water cooling (0.11 cm/s)	-	▼ 0.36	▼ 0.56

wall of the tube due to higher thermal conductivity of tube material, and subsequently, more heat is transferred to the water as the water velocity is getting higher.

To use the hot air only, the insulation of the vortex tube surface is desired without much difference in tube materials. However, the cold air temperature and its fraction should be considered simultaneously to apply a vortex tube in a refrigeration system.

Unlike the tendency of hot air temperature, the variation of cold air temperature is similar in all cases, as shown in Figure 4, although the cold temperature in the water cooling condition is a little higher than that in the insulation condition, when the cold air fraction (y) is less than 0.4. It may result from the weakened strength of Görtler vortex as the heat loss the tube surface is increased.(11) However, the cold temperature in the forced convection is lower when y is more than 0.4, because the hot air temperature drops down with the reduced amount of the hot air. Consequently, the overall operating temperature in the vortex tube becomes low in the water cooling condition.

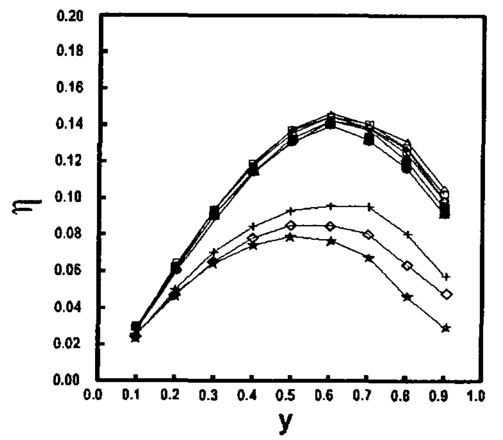
The mean cold temperature difference is slightly low when the thermal conductivity of tube is low, as shown in Tables 3 and 4. It results from the conductive heat transfer along the tube wall. Sine the vortex tube itself has a temperature gradient, at which one side on a reference to the vortex generator housing (right hand side in Figures 1 and 3) is hot and the other side is cold, more heat can be conducted with higher thermal conductivity.

Nevertheless, the mean cold temperature difference is in the order of 1℃, so that the thermal condition on the tube surface does not affect the cold air temperature so much and the cold air can be used in the same degree for wide application.

Figure 6 represents the vortex tube efficiency according to the cold air mass fraction, when the cooling conditions on the tube surface are varied with insulation, without insulation in the air and with water cooling (0.11 cm/s) and also the tube materials are changed respectively. To consider the hot temperature and the cold temperatures together, the efficiency (η) was calculated by Equation (1), which was proposed by Takahama,(7) as the ratio of the actual energy difference to the maximum energy difference attainable through the ideal adiabatic expansion process between the inlet and outlet air streams.

$$\eta = \frac{y(T_{\text{in}} - T_c) + (1-y)(T_h - T_{\text{in}})}{T_{\text{in}}\left\{\left(\frac{P_{\text{in}}}{P_c}\right)^{\frac{\kappa-1}{\kappa}} - 1\right\}} \quad (1)$$

The vortex tube efficiency increases until the cold air fraction goes up to 0.6. After it reaches the maximum around there, it decreases again with more fraction of the cold air. In the whole range, the insulation case



Material	With insulation	Without insulation	Water cooling (0.11cm/s)
Pyrex	△	▲	+ .
Stainless steel	□	■	◇
Copper	○	●	☆

Fig. 6 Efficiency of vortex tubes versus cold air flow ratio for different tube materials and heat trandfer moodes.

Table 5 Temperature differences at the maximum cooling efficiency of vortex tube (y=0.6)

(Unit : ℃)

Conditions	Tubes (conductivity)	Pyrex (1.09 W/mK)	Stainless steel (15.0 W/mK)	Copper (380.0 W/mK)
$\triangle T_h$ (Hot exit)	With insulation of the tube	34.2	33.5	32.6
	Without insulation in the air	33.8	33.7	31.9
	With water cooling (0.03 cm/s)	16.1	33.5	11.2
	With water cooling (0.05 cm/s)	15.9	13.1	10.3
	With water cooling (0.11 cm/s)	15.6	12.7	10.1
$\triangle T_c$ (Cold exit)	With insulation of the tube	−27.3	−26.5	−26.3
	Without insulation in the air	−26.3	−26.0	−25.8
	With water cooling (0.03 cm/s)	−23.8	−24.1	−24.9
	With water cooling (0.05 cm/s)	−24.6	−24.8	−25.1
	With water cooling (0.11 cm/s)	−25.3	−25.4	−25.5

shows the best efficiency, but the water cooling cases give the worst.

In case of the water cooling condition, the temperature of the hot air stream does not rise as much as those in the other cooling modes, but the cold temperature is similar to the others, as shown in Figures 4 and 5. Thus, the decrease in the efficiency is caused by the heat loss to the cooling water through the tube wall, and it becomes lower if the thermal conductivity of tube material is high.

The temperature differences at the hot and cold exits are tabulated in Table 5 according to the thermal conditions and the tube materials, when the cold air fraction is 0.6, at which the maximum efficiency might be obtained.

If the vortex tube is concerned by itself for the best performance, the Pyrex tube, which has the lowest thermal conductivity, gives 34.2 ℃ and −27.3℃ as the highest hot temperature difference and the lowest one respectively. However, to apply a vortex tube into a refrigeration system, cooling the hot gas is necessary, whether it is done through the tube wall or after the exit. Therefore, further study on a refrigeration system with a vortex tube is necessary while the cold gas fraction is varied from 0.4 to 0.6, at which the best efficiency can be achieved in the forced convection with water.

4. Conclusions

The experiments has demonstrated the characteristics of energy separation through a vortex tube, when the cooling modes on the tube surface are varied with different tube materials. Although further experiments should be recommended to apply a vortex tube as a expansion device in a refrigeration system, the following results could give some guidelines for the application.

(1) The working gas temperatures at the hot exit of a vortex tube are similar, when the case with the insulation around the tube surface is compared to the one without the insulation in the air. However, in the water cooling condition, the hot gas temperature is much lower than those in other cases, although it reaches its maximum when the cold gas fraction is around 0.6.

(2) On the other hand, the cold gas temperature does not affected significantly by the tube conductivity and the cooling modes. It is slightly lower in the case of water cooling, when the cold gas fraction is larger than 0.4.

(3) The energy separation efficiency is the

best, when the cold gas fraction is about 0.6 in the cases with the insulation of tubes and without the insulation in the air. However, it does not affected so much by the tube material. When the tube surface is cooled with water, the efficiency is lower those in the other cases. Although the efficiency decreases as the conductivity of tube material becomes high, the overall operation temperature of working gas goes down as well when the cold gas fraction is in the range of 0.5 to 0.7.

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