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Progress of Pulse Tube Cryocooler

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Abstract-- **The pulse tube cooler as an alternative of Stirling, G-M or VM cooler to overcome the requirement from the various application fields is described. The necessity of the object oriented cooler development is explained to realize the cryocooler of more energy-efficient, more reliable, more compact and less expensive than what is currently available commercially.**

1. INTRODUCTION

Cryogenic technology, including cryocoolers, is a crucial supporting technology for superconductor applications, without exception. In general, if the existing room temperature technology is replaced with the superconducting technology, the extra work required for the cooling system becomes a sort of penalty. Therefore the development of efficient cryocooler becomes essential issue. The request from the application fields, however, is not only the efficiency but also reliability, low cost, compactness and applicability (easy to use).

The key technical aspects that must be taken into consideration are the different specifications required for various applications. Generally, for power applications, the most important application issues are reliability and redundancy problems; for electronics applications, reliability, cost and, possibly, temperature stability are critical issues. Cryocoolers might be used in various temperature regions in the future, depending on their applications; at present, operation temperatures of 4.2 K, 20 K and 77 K (based on the liquid temperature of Helium, Hydrogen and Nitrogen) are standard.

Cryocoolers are categorized by the thermodynamic operating cycle, such as; Brayton, Joul-Thomson, Stirling and Gifford-McMahon (G-M) cycle. Former two are based on the circulating gas and the latter two are based on the oscillating gas. Pulse tube cooler (PTC) as an alternative of Stirling cooler or G-M cooler, which also uses the oscillating gas, is noted as a cooling system to overcome the request from the wide application fields described above. Pulse tube coolers might be a promising solution for some power and electronics applications. The cooling temperatures obtained from each cryogen described above are completely covered by pulse tube coolers. Fundamental thermodynamics of PTC is described to find the direction of future development of the cooling system for each application fields.

2. CLASSIFICATION OF PTC

2.1. Critical components of PTC

Most characteristic merit of the pulse tube cooler is that it has no mechanical moving components at the cold part of the cooling device without the sacrifice of thermodynamic efficiency. From the view point of thermodynamic aspect, pulse tube cooler will be divided into five critical components.

Fig. 1 shows the basic arrangement of each component; pressure wave generator, regenerator, pulse tube, heat exchanger and the work receiver section. The simplest configuration of the pressure wave generator will be represented by a piston control volume with heat exchanger. Similarly, the work receiver part will be represented by a reservoir with an orifice as shown in the doted area respectively. The regenerator, in typically, is made by a stack of fine metallic mesh (normally ~300 mesh) within the thin tube to have good heat transfer with the gas, when the gas passing through in the void volume of the mesh. The pulse tube is a simple hollow tube with no heat transfer surface in it. Therefore the pulse tube is act as an adiabatic tube. In this example of Fig. 1, the mechanical moving

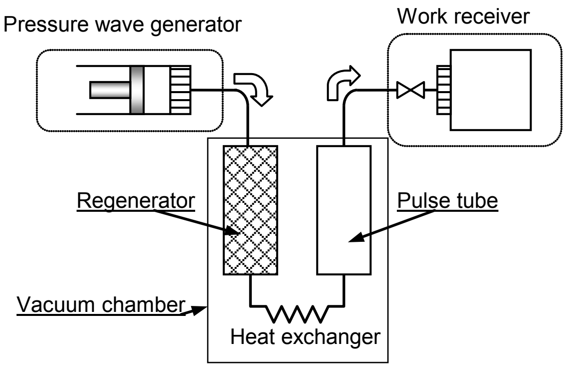

Fig. 1. Fundamental arrangement of the pulse tube cooler divided into five critical components. White arrow indicates the work flow direction to generate the cooling effect at the heat exchanger between the regenerator and the pulse tube.

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component is only the piston located at the room temperature. Input the external energy to the piston, then it produces the work flow directed to the regenerator as shown by the white arrow on the figure.

This work flows through the pulse tube and dissipated at the orifice within the work receiver section. According to the pressure oscillation, the gas temperature at the heat exchanger is lower when the gas flows from the pulse tube to the regenerator than that of the reversed flow. This gives the cooling effect at the heat exchanger and the minimum cooling temperature is given when this cooling effect balanced with the heat load.

Traditional expression of the cooling effect is due to the gas expansion occurred near the expansion piston head. In the case of the pulse tube, there is no solid expansion piston; however, the part of the gas column, which is oscillating within the pulse tube will act as a gas piston. Therefore the heat exchanger temperature decreases and has some cooling capacity at the appropriate cooling temperature without any moving parts at the low temperature region inside of the vacuum chamber. This unique structure leads the design flexibility of the cooling system and it expands the further application fields. Following section introduces the various pressure wave generators and the work receivers to understand the mechanism of keeping high efficiency of the pulse tube cooler.

2.2. Historical background

Three different types of pressure wave generator are given in Fig. 2. Type (a) is called as valve less compressor or Stirling type because it is same as the gas compression part used in Stirling cycle. Type (b) consists of circulating gas compressor with a heat exchanger (generally called as after cooler), and a set of switching valve to generate the oscillating flow. This type is called as valved compressor or G-M type because it is same as the gas compression part used in Gifford-McMahon cycle. Type (c) is called as thermo-acoustic or Vuillemier type because it is same as the gas compression part of Vuillemier (VM) cycle. If the displacer used in the VM cycle replaced to a gas column, then it becomes thermo-acoustic engine.

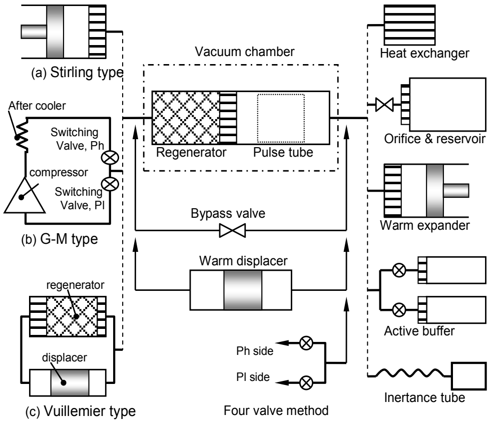

Fig. 2. Schematic comparison of the pressure wave generators (left side of dashed line) and the work receivers (right side of dashed line) for a common regenerator and the pulse tube. Additional phase sifters are shown by arrows below the vacuum chamber.

One of the pressure wave generators is connected to the regenerator side and one of the work receivers is connected to the pulse tube side to complete the pulse tube cooler. Three additional components shown by arrows below the vacuum chamber are act as the phase shift mechanism.

The efficiency of the pulse tube cooler keeps improving by changing the work receiver since the first pulse tube cooler was reported by W. E. Gifford and R. C. Longsworth in 1964 [1]. They choose the work receiver of simple heat exchanger. This type is now called as Basic pulse tube cooler. Second important improvement has been done by E. I. Mikulin in 1984 [2]. Instead of the simple heat exchanger, an orifice and the reservoir is added to receive the work more actively. This type is called as Orifice pulse tube cooler.

A bypass valve between the regenerator warm end and the pulse tube warm end, as shown in middle part of Fig. 2, was added to the orifice pulse tube by S. Zhu in 1990 and is called as Double inlet pulse tube [3]. Cooling performance of this type improved further than Orifice type and is classified as 3rd generation corresponding to 2nd generation of Orifice type and 1st generation of Basic type. All other work receivers shown in Fig. 2 are proposed since 1988 to improve the performance of the pulse tube cooler and are corresponding to 3rd generation [4-6]. The warm displacer can be used instead of warm expander. If this solid displacer is replaced to simple gas column then it becomes thermo-acoustic cooler. Two valves in the Active buffer type connected to each buffer must be well controlled with main valves of GM type pressure wave

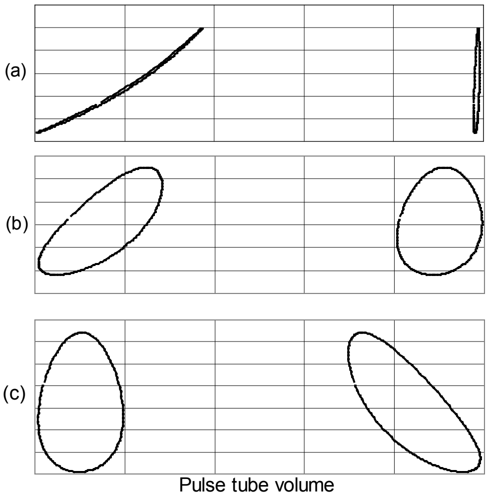

Fig. 3. Equivalent PV diagrams within the pulse tube.
(a) Basic pulse tube, (b) Orifice pulse tube, (c) Double inlet or any other 3rd generation pulse tube. Y-axis is the pressure, X-axis is the pulse tube volume, left end is the low temperature side and the right end is the room temperature side.

generator. If these two buffers are eliminated and connected to the main compressor high and low pressure side respectively, then it becomes four-valve method. The reason of the necessity of these developments will be explained by PV diagram as shown in Fig. 3.

In the case of Basic pulse tube, warm end of the tube (right side) is closed by a heat exchanger. Therefore the oscillating gas near the end does not move and no work is dissipated. So the PV diagram is almost vertical line. Because of the large volume of the tube, the gas at the cold end (left side) is moving with the pressure oscillation. The pressure increases when the gas flows in from the regenerator and decreases when the gas flows out from the pulse tube. Therefore the PV diagram at this end becomes a shape as shown in (a). Pressure increasing process is slightly left side and decreasing process is slightly right side due to the heat transfer between the gas and the tube wall or heat exchanger at the warm end of the tube. The area of this PV diagram represents the work and the flow direction of the work is from the left to the right because the trajectory of the PV diagram is clockwise.

In the case of Orifice pulse tube, the gas movement near the warm end is delayed by 90 degrees from the pressure wave if the reservoir volume is large enough to keep the mean oscillating pressure. Trajectory of the gas movement is given by the gas piston within the pulse tube as shown by doted line in Fig. 2, which part of the gas is always oscillating within the pulse tube and never flow out from the pulse tube. The work of this PV diagram (called as PV work) is dissipated by the gas flow at the orifice. Therefore much larger PV work can generates without help of the heat transfer effect. The phase delay at the cold end of the pulse tube, however, is also decreased by the existence of the pulse tube volume.

To realize the higher thermodynamic efficiency similar to the well developed Stirling cooler or G-M cooler, the phase of the PV diagram at the cold end of the pulse tube must be larger than 90degrees as shown in Fig. 3 (c). PV work at the cold end represents the maximum cooling capacity in the case of no thermal losses. The most significant thermal loss is the loss due to the enthalpy flow through the regenerator. Therefore minimize the enthalpy flow, which proportional to the mass flow becomes the most important issue. To realize the minimum mass flow without reducing the PV work, the phase delay should be larger than 90 degrees, which never be realized by the Orifice pulse tube. Because of this phase shift limit, the Orifice type is categorized by 2nd generation. Any other methods, which realize the phase delay of over 90 degrees at the pulse tube warm end, are categorized as 3rd generation. Consequently, the Basic type is categorized by 1st generation because the phase delay near the pulse tube warm end is almost zero.

Warm expander method and warm displacer method can realize any phase over 90 degrees by means of mechanical or electrical linkage with the compressor piston; however, it requires another moving part. Double inlet method can realize the PV diagrams shown in (c), but it may have the possibility of instability due to the circulating flow through the bypass valve. A four-valve method does not require the reservoir, so it makes compact but the problem of the circulating flow is still remains. Active buffer method and the Inertance tube method have no such closed loop as a source of instability, however, the former requires extra buffer volume and the latter is not applicable to GM type or low frequency pulse tube cooler. Improvement by use of Inertance tube is not significant for the small scale coolers.

Even though, the merit of no moving part at low temperature region of these pulse tube coolers still attractive for the various application fields if the appropriate work receiver method is selected.

Comparison study of different work receivers has been done by the pulse tube of 19 mm inner diameter and 237 mm length with the regenerator (stack of 300 mesh) of 36 mm diameter and 123 mm length. By use of pressure amplitude of 1.1 to 2.2 MPa at the oscillating frequency of 1.75 Hz of the G-M type pressure wave generator, the minimum attainable temperatures were 170 K by Basic model, 58 K by Orifice model, 32 K by Double inlet model and 30 K by four-valve model respectively [7]. These results clearly explain the importance of phase between the pressure and the gas movement at the pulse tube.

3. STATE OF THE ART PULSE TUBE COOLERS

3.1. Pulse tube design

Pulse tube cooler can be designed according to the object requirement. Basic configurations are shown in Fig. 4.

In-line type is the most efficient configuration to minimize the viscous loss. Therefore the oscillating frequency can be increased up to 50 Hz or more to make the cooler compact with minimum loss due to the pressure drop. Flow distribution to the radial direction could also be minimized. If the efficiency is the first priority, the In-line type should be selected. However, the limited application will be caused by the fact of that the cold heat exchanger is located at the middle of the cooling head.

U-shape type is commonly used in relatively low frequency G-M type PTC (1 or 2 Hz) because the loss at the connecting tube between the regenerator and the pulse tube is not so significant. Most of the multi-staged PTC is based

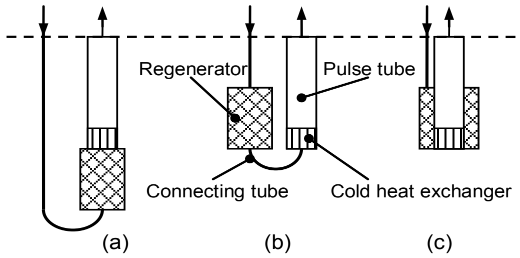

Fig. 4. Basic configuration of the cold head. (a):In-line type, (b):U-shape type, (c):Co-axial type. Below the dashed line is the vacuum environment. Downward arrow means work flow into the regenerator from PWG and upward arrow means work flow out from the pulse tube to work receiver.

on this type because of its fabrication simplicity.

Co-axial type is the most compact cooler design. In general, the pulse tube is located in middle surrounded by regenerator to minimize the radial surface of the pulse tube wall. This is important to minimize the shuttle heat transfer loss along the pulse tube wall especially it has large temperature gradient.

In general, the optimum regenerator length is depends on the required cooling temperature and the operating frequency and not the cooling capacity. For the cooling temperature of 30 to 80 K, optimum regenerator length is 50 to 150 mm in the case of G-M type and 30 to 100 mm for Stirling type.

Minimum attainable temperature of single stage PTC is around 30 K for Stirling type and about 10 K for G-M type. Therefore if the required cooling temperature is below 30 to 10 K or higher thermodynamic efficiency around 30 K is required, then multi-staging PTC as shown in Fig. 5 is used.

Series pulse tube method (a) is the most compact design and it has been used 1st and 2nd generation PTC. Warm end of the 2nd stage pulse tube is thermally connected to the 1st stage pulse tube cold end. Work flow through the 2nd stage pulse tube is converted to the heat and dissipated at the 1st stage cold end by consuming the 1st stage cooling power. Therefore this method is not commonly used except the special requirement of this arrangement necessity is exist.

Parallel pulse tube method (b) is widely applied to the most of 3rd generation PTC. Several examples are given in the following section.

Thermally coupled method (c) has many options; couple of 1st stage Stirling type and 2nd stage G-M type: Working gas of He4 for 1st stage and He3 for 2nd stage: Couple of G-M type and VM type: Use of different charge pressure and driving frequency for each pulse tube unit.

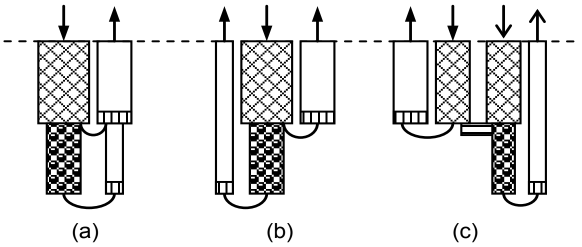

Fig. 5. Three different type of multi-staging method, shown by two-staged example. (a); Series regenerator with series pulse tube, (b); series regenerator with parallel pulse tube, (c); thermally coupled regenerator with separate pulse tube. Meaning of each pattern is the same with Fig. 4.

3.2. Stirling type pulse tube cooler

Small scale Stirling cooler has been developed in the field of Military and Space science because of its compactness and relatively high efficiency. However the limited operating time and the mechanical vibration due to the crank mechanism for convert the rotary motion to reciprocal motion had to be improved. Since the introduction of the flexure bearing by G. Davey in 1999 [8], problems of mechanical vibration and the short operating time was solved. This technology was successfully applied to the pulse tube cooler as shown in Fig. 6.

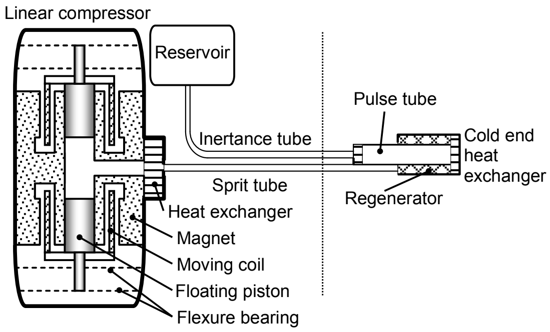

Fig. 6. Split Stirling type pulse tube cooler.

The piston is supported by dual flexure bearing so as to reciprocate the piston without solid friction to the cylinder. The cold head, which consist of the regenerator, heat exchanger and the pulse tube within the vacuum chamber, can be separate from the compressor unit by means of a sprit tube. The orifice, which is a needle valve or simple nozzle, could be replaced by an inertance tube to separate the large reservoir from the cold head. As the results, installation of the cooling object becomes more flexible.

Mid scale Stirling type pulse tube cooler is developed by use of the flexure bearing linear compressor driven by the moving magnet method. Fig. 7 shows the example of 146 watts at 80 K with input power of 3.3 kW. Regenerator is 80 mm in diameter and 80 mm in length. Driving frequency is 50 Hz and charge pressure is 2 MPa. Pulse tube is 39 mm in diameter and 120 mm in length. Inertance tube is 10.7 mm in diameter and 1.7 m in length.

Face to face arrangement of the piston is required to eliminate the mechanical vibration. This type of the pressure wave generator is called as linear compressor.

Large scale Stirling type PTC having 20 kW input and the expected cooling capacity of 1kW at 80 K is under development. In such a large cooling capacity, the pulse tube and the regenerator diameters become too large to

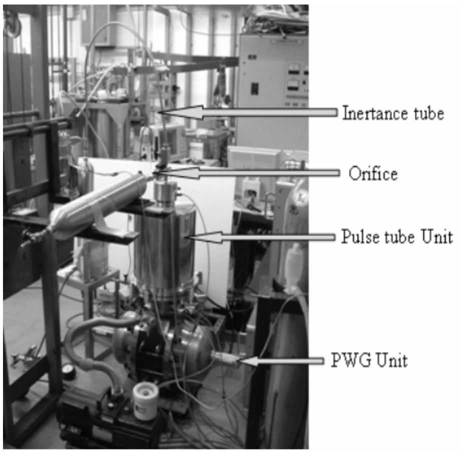

Fig. 7. Experimental set up of integral Stirling type pulse tube cooler.

maintain the stable temperature distribution to the radial direction. To overcome this unexpected effect, multiple down sized cold heads for a single compressor unit has been used [9].

Low temperature down to 4 K level is not easy by multi-staged Stirling type PTC, because of relatively high oscillating frequency, which induce the regenerator enthalpy loss associated with large pressure drop. Minimum temperature of 2-stage PTC is only 10 to 20 K. Further study is required to improve the thermodynamic performance below 10 K.

3.3. G-M type pulse tube cooler

G-M cooler is already well developed from the small scale, several watts at 80 K to large scale, several handled watts at 80 K. Wide temperature range down to 2 K is also available by using double expansion stage. G-M type pulse tube cooler is now replaceable in all of this cooling capacity range and the temperature range. Fig. 8 shows an example of single stage inline pulse tube cooler [10], which cold heat exchanger is located at middle in the vacuum chamber.

Pulse tube diameter is 49 mm, length 239 mm, regenerator is made by 49 mm diameter stainless steel 300 mesh stacked 108 mm in length, connecting tube is 6 mm inner diameter with the length of 1 meter to the switching valve.

Cooling performance obtained by four valve method is shown in Fig. 9. Double inlet and active buffer method are also examined. Results are almost same and the cooling capacity at 80 K is 160 watts by use of 6 kW compressor. The maximum thermodynamic efficiency is 8 % Carnot at 50 K; however, the much higher efficiency above 80 K has been given by use of smaller compressor 1.7 kW input power. Therefore the optimum combination of compressor unit and the cold head will be exist depend on the requirement from the applications.

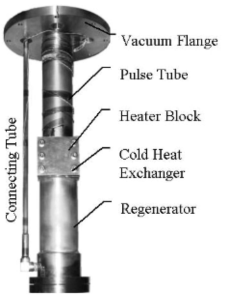

Fig. 8. G-M type PTC of In-line arrangement.

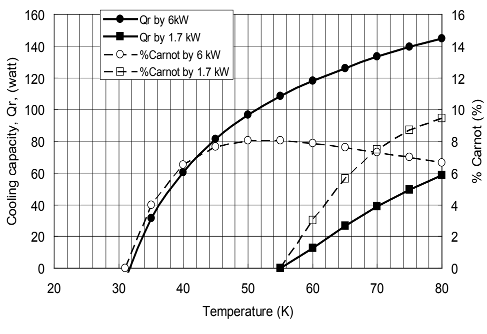

Fig. 9. Cooling performance of GM type PTC with different compressor unit.

Largest G-M type pulse tube cooler is developed for the cooling system of the superconducting transformer. The cooling capacity at 65 K is 1 kW. Target of the thermodynamic efficiency of this system is 18.1 %Carnot. By use of active buffer method, 13.4 %Carnot has already been obtained [11].

When the pulse tube cooler is installed to the cooling object, orientation of the pulse tube must be careful especially for G-M type. To minimize the loss due to the natural convection due to the gravity, pulse tube cold end should be located at the bottom and the vertical layout should be adopted.

Minimum attainable temperature of PTC is obtained as; 2.07 K 2-staged LN2 pre-cooled PTC using He4 [12], 1.7 K by 3-staged parallel PTC using He3 as the working gas [13]; 1.4 K by thermally coupled 2-stage PTC [14].

3.4. Vuilleumier type pulse tube cooler

Vuilleumier (VM) cycle was proposed by R. Vuilleumier in 1918 [15]. The basic structure is a couple of Stirling engine and the Stirling cooler. Therefore the required input energy is not the electric power to drive the piston but the heat source to the heat exchanger. Pressure wave required for the cooling section is given by the movement of the displacer. Small scale VM cooler of 2 watts at 77 K was first reported in 1969 [16]. Input heat of 185 watts at 1000 K is used but the electrical input power to drive the motor for displacer is only 5 watts. Farther development of VM cooler is not so significant; however, since the performance of the multi-staged pulse tube improved, replacement of the mechanical compressor to the heating part of VM cycle has been proposed to minimize the amount of He3 [17]. Thermally coupled 2stage PTC is also reported [18].

The introduction of the thermo acoustic pressure wave generator, which consist of compliance, resonance tube and inertance passage instead of the solid displacer, becomes an attractive cooling system. Fig 10 shows an example of the pulse tube cooler having totally no moving parts. Natural gas liquefaction plant using this type of PTC is fabricated, which has a liquefaction capacity of 10,000 gallon/day [19].

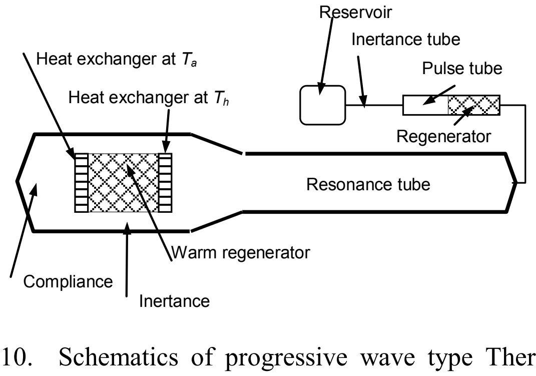

Fig. 10. Schematics of progressive wave type Thermo acoustic pressure wave generator coupled with Inertance type pulse tube cooler.

4. OBJECT ORIENTED PULSE TUBE DESIGN

4.1. Integrated current lead

G-M type PTC has been developed to apply for the current lead system of the Superconducting Magnetic Energy Storage (SMES) as shown in Fig. 11.

The co-axial PTC has been selected because the compactness is a key to apply a relatively simple high voltage tolerance technique which withstands more than 15 kV. The cooler unit can be floated from the electrical potential by use of the plastic tubes for the connecting tube to the switching valve unit. To make the best use of this characteristic, the cooler was designed as which becomes to the current lead itself. With this configuration, all of the thermal conduction loss through the regenerator and tube walls will not be the loss and it becomes to the part of current lead materials effectively.

The cooling capacity of the first test cooler was designed as 40 watts at 65 K, which corresponding to the heat load of 1 kA current from the room temperature. The regenerator is located at the pulse tube surrounding coaxially. The pulse tube diameter is 40 mm and its length is 230 mm. An additional copper rod is inserted at the center of the pulse tube to optimize the electrical conductivity. Pulse tube cold head is controlled by four-valve method as its phase shift mechanism. Oscillating frequency of 1.5 Hz has been tested under the mean driving pressure of 1.5 MPa. This test cooler successfully demonstrate the PTC as the current lead [20]. Up to 3 kA model with 2nd stage down to 30 K for cooling the HTC current lead is also fabricated and tested [21].

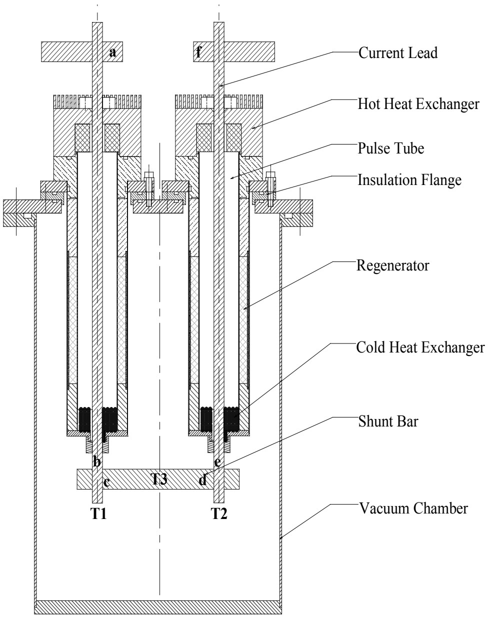

Fig. 11. A couple of PTC worked as a current lead for the superconducting magnet.

4.2. Future prospect of object oriented PTC

Most of PTC already developed is an alternative cooler from the existing G-M or Stirling coolers. The merit of PTC is mainly the higher reliability and lower cost in scarify of increased size for same cooling capacity. To expand the further application field, the merit of no moving part at the cold head should be found out more aggressively.

In the case of U-shape type, regenerator and the pulse tube can be separate by use of long connecting tube. This gives a distributed cooling method. For example, conduction cooling of large object, such as superconducting coil, could be effectively performed as shown in Fig. 12 (a).

If the object to be cooled to cryogenic temperature is heavy in weight, the conduction and radiation loss through the supporting rod becomes major thermal loss. These supporting rods can be replaced by regenerator tube to compensate the thermal loss by the cooling effect of the PTC as shown in Fig. 12 (b). So the PTC becomes an active supporting rod.

In the case of G-M or Stirling cooler, increase the number of expansion stage to get lower temperature is make the cold head complicate. Therefore it decreases the reliability and increase the production cost. In the case of PTC, however, increase the stage number is not accompanying such undesired problems because there are no mechanical moving components. Application to multi-radiation system as shown in Fig. 13 could be a most effective use of PTC to increase the total system performance.

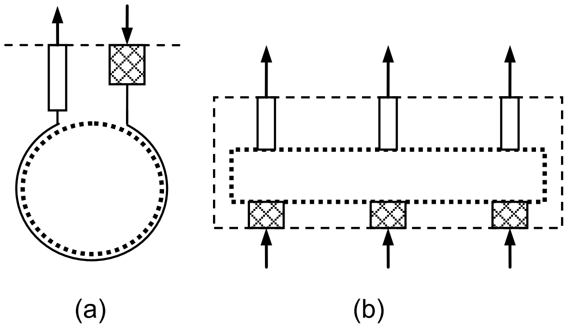

Fig. 12. Schematically example of object oriented PTC. (a); conduction cooling method of the large object, (b); decentralizing cooling method of large and heavy object. Doted line means the object to be cooled. Below or inside of the dashed line means vacuum area. Other patterns are same with Fig. 4.

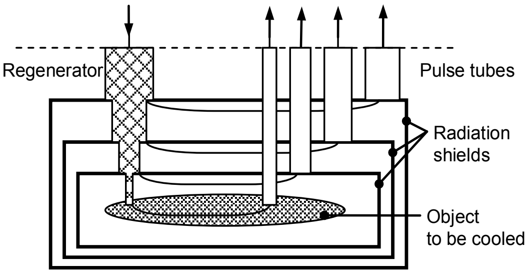

Fig. 13. Schematics of multiple floating radiation shield cooled by multi-staged PTC.

5. SUMMARY

The most important issue to meet the requirements from the various applications is to select the optimum type of the pulse tube cooler categorized in Fig.2 for each application.

In the case of Cryopump, the item demanded by priority is to lower the cost without the sacrifice of efficiency. To overcome this requirement, two staged Stirling type pulse tube cooler could be replaceable to G-M cooler now mainly used, because the required temperature of 1st and 2nd stage are just fit for Stirling type PTC. Mass production is necessary to improve the cost performance.

Much quiet 4K G-M cooler is requested for MRI, NMR or MEG. Multi-staged G-M type pulse tube cooler could be replaced for this purpose because of its lower acoustic noise and more maintenance free. Improvement of the switching valve mechanism, which is a source of acoustic noise, should be desired.

Some of the HTC application requires the cooling capacity of up to 1kW at 70 K level. Multiple parallel G-M cooler has been used, but it will be changed to high power G-M type pulse tube cooler. Stirling type pulse tube cooler could be replaced, however, the progress of these cooler seems not sufficient.

Much larger scale Stirling coolers are now used for power applications such like Power cable, SMES or current limiter. These coolers could be replaced by Stirling type pulse tube coolers in near future.

Requirement from the power application field is increasing. If the temperature requirement is below 20 K, two stage cooler is necessary. In this case, G-M type should be selected because the progress of multi-staged high power Stirling type is not sufficient so far.

Commercialization cannot occur without customers' confidence. In the course of demonstration programs, technical and operational problems for commercialization can also be clarified, enabling technological and managerial measures to be taken in future commercialization efforts.

Efforts should be focused on developing a family of cryocoolers, suitable for both electronic (small scale) and power applications (large scale) that are more energy -efficient, more reliable, more compact and less expensive than what is currently available commercially.

The concept of establishing an international consortium to accelerate the development and maturing of cryogenic technology that will meet the needs of the superconducting community should be discussed. The results of such a consortium would eventually be made available to the superconducting community and cryocooler venders.

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