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Review:

Temperature inhomogeneity in high capacity pulse tube cryocoolers[*]

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Abstract: High power pulse tube cryocoolers are expected to be a very promising candidate for high temperature superconductors (HTS) cooling. Unfortunately there are still some problems significantly deteriorating the performance of these cryocoolers, one of which is temperature inhomogeneity. Several different theories have been proposed to explain the mechanism and many factors have been indicated as contributors to the generation and development of temperature inhomogeneity. However, some relations between these factors are seldom noticed, nor classified. The underlying mechanisms are not yet clear. The paper classifies, as internal and external, factors leading to temperature inhomogeneity based on their location. We examine some apparently unreasonable assumptions that have been made and difficulties in simulation and measurement. Theoretical and experimental research on the driving mechanism and suppression of temperature inhomogeneity is reviewed, and potential analysis and measurement methods which could be used in future are identified.

Key words: Temperature inhomogeneity, Internal streaming, High capacity, Pulse tube cryocooler
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1 Introduction

Recent developments in high temperature superconducting technology create a great demand for high power cryocoolers. Stirling type pulse tube cryocoolers (SPTC), having the benefit of no moving parts at the cold end, could be more reliable and require lower maintenance than Gifford-McMahon (GM) and Stirling cryocoolers (Li *et al*., 2014; Zhang *et al*., 2014). However, there are still serious unsolved problems in large scale SPTC. Temperature inhomogeneity is one of the most important.

By 'temperature inhomogeneity' we mean that some temperature difference appears around the shell

of the regenerator. This normally happens with inhomogeneous flow and leads to regenerative inefficiency and performance deterioration. There are some typical characteristics as follows:

1. The temperature difference (ΔT) appears around the shell of the regenerator at the same cross section, and ΔT increases dramatically with larger input powers. Also it has been reported that the location of maximum and minimum temperatures could change during an experiment (Dietrich *et al.*, 2007).

2. Normally temperature inhomogeneity occurs in a small length/diameter ratio regenerator (the largest ratio reported is 1.5 so far (Ercolani *et al.*, 2008)), or in some regenerators connected in parallel.

3. The regenerator fillings with high thermal conductivity could suppress temperature inhomogeneity effectively (Gromoll *et al.*, 2006).

4. There is some direct current (DC) flow in the regenerator (Fig. 1).

5. The performance deteriorates significantly, along with the increase of loss and no load cooling

temperature, and the decrease of the coefficient of performance (COP) (Yuan and Maguire, 2004).

Since temperature inhomogeneity was reported for the first time (Kirkconnell, 1999), many researchers worldwide have been attracted to this area. There have been many theoretical and experimental studies exploring the underlying mechanism and to attempt suppression of temperature inhomogeneity. But the generation mechanism is still unclear, and now possible differences between the micro channels, non-uniform flow resistance, as well as natural convection in the regenerator and exterior temperature perturbation are considered to contribute to the temperature inhomogeneity (Gedeon, 2004; Sun *et al.*, 2009a; 2009b; Fang *et al.*, 2012; de Waele *et al.*, 2013).

In this study, the factors leading to temperature inhomogeneity have been classified as interior factors (inside cryocoolers) and exterior factors (out of coolers' physical boundary). We also examine some of the assumptions and difficulties in simulation and measurement. The theoretical and experimental research on underlying mechanisms and suppression of temperature inhomogeneity are explored, and potential analysis and measurement methods that could be used are identified.

2 Generation mechanism

The existing theoretical and experimental results show that many factors could generate temperature inhomogeneity in a regenerator. Interior factors can be further divided into the regenerator factors and variable flow channels factors. Exterior factors include natural convection and exterior temperature perturbation.

2.1 Regenerator factors

Some studies offer several regenerator factors, such as flow resistance distribution, thermal conductivity in the radial direction, pressure behavior at both ends of the regenerator, difference between micro channels, the ratio of energy flow to PV power flow in the axial direction, and the ratio of cold end temperature to the ambient temperature.

Gedeon (2004) studied the correlation of non-uniform layers spacing in the regenerator and flow circulations with temperature inhomogeneity, discussing the contribution of geometry difference between micro-channels in the regenerator to the inhomogeneity. A formulation of gas velocity in the micro-channel was derived based on Darcy's law:

$$u = -\frac{G^2}{12\mu}\frac{\partial P}{\partial x},\qquad(1)$$

where u refers to the section mean flow velocity, μ is the gas viscosity, $\partial P/\partial x$ is the pressure loss per length in x direction, and G refers to the channel width in parallel regenerators A and B.

Substituting the pressure variation equation, the ratio equation of DC flow to the whole AC flow of the
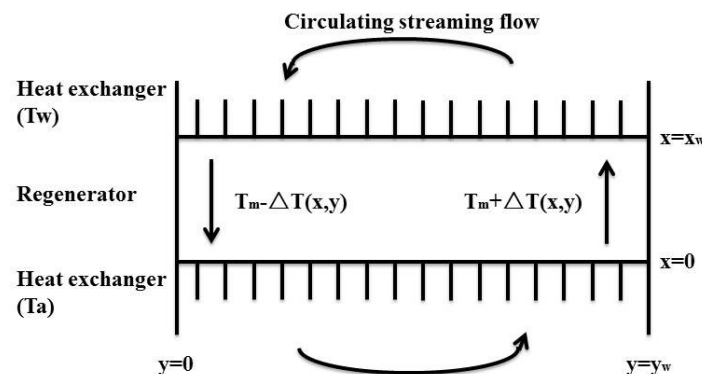

Fig. 1 Temperature inhomogeneity caused by DC flow in a single regenerator. Reprinted from (So *et al.*, 2006), Copyright 2006, with permission from American Institute of Physics
T_w refers to the working end temperature, T_a refers to the ambient end temperature, T_m refers to the average temperature of the middle cross section of regenerator, and ΔT refers to the temperature variation

regenerator was obtained:

$$\frac{(\rho u)_{dc}}{(\rho u)_1} \approx \frac{\gamma P_m \Delta P_1 T_w^{1.4}}{48(\gamma-1)Nuk_w \mu_w L} \frac{\partial T}{\partial x}\left[\frac{G^4}{T_{cen}^{3.4}}\right]_B^A, \quad (2)$$

where ρ means density, γ means ratio of specific heat, T means temperature, k means gas conductivity, and L means regenerator length. The subscript dc means DC flow, w means working end, 1 means amplitude, and cen means central point of the regenerator.

Eqs. (1) and (2) indicate that the geometry of micro-channels in the regenerator could generate the DC flow and inhomogeneity directly. Using the software SAGE, Gedeon (2004) built a parallel regenerators model and reproduced the inhomogeneity caused by different channels between two regenerators (Fig. 2).
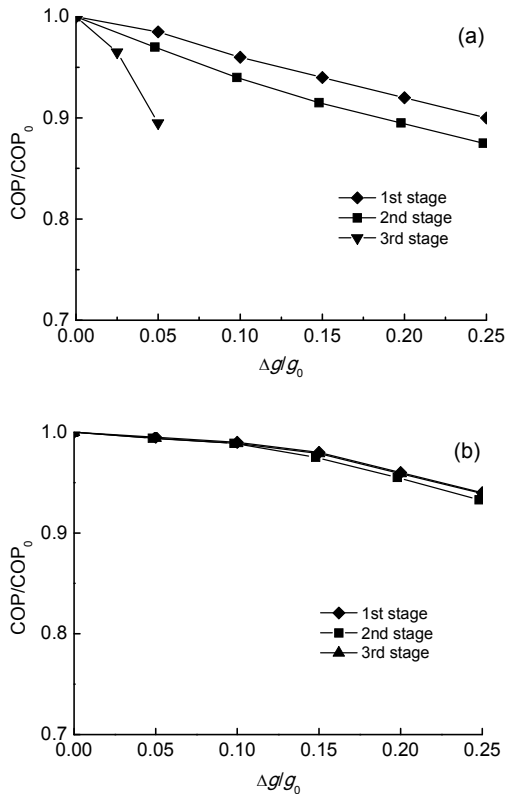

Fig. 2 Degradation in cryocooler COP (heat/PV power) as a function of gap variations between two foil-type regenerator parts. Δg/g₀ may be thought of as the amplitude of the gap variation between the two regenerator parts: (a) COP vs. gas variation, no thermal connection; (b) COP vs. gas variation, good thermal connection. Reprinted from (Gedeon, 2004), Copyright 2004, with permission from Springer Science+Business Media

Focusing on the non-uniform flow resistance, we built a 2D regenerator model by the computational fluid dynamics (CFD) method (Fang *et al.*, 2012). The regenerator was divided into five zones with different porosities to produce temperature inhomogeneity. The results showed that when the porosities of zones of the same cross section are different, two net mass flows with opposite direction appeared (such as in the cross section of both Zones 1 and 3, shown in Figs. 3 and 4), which meant there was a DC flow circulating between Zones 1 and 3, and temperature inhomogeneity was generated. It proved the contribution made by non-uniform porosity.
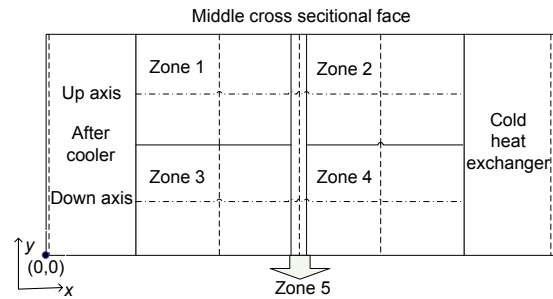

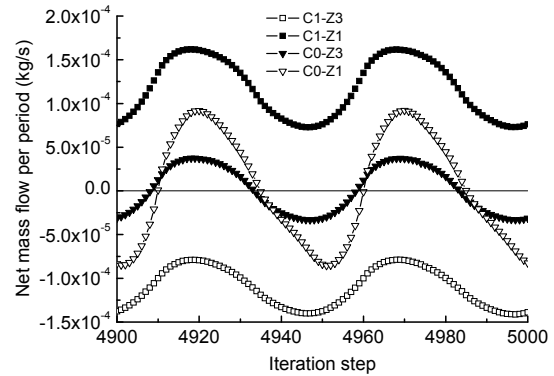Fig. 3 Non-uniform porosity model structure (Fang *et al.*, 2012)

Fig. 4 Average mass flow rate on middle face of Zones 1 and 3 (Fang *et al.*, 2012)
C1 and C0 mean Cases 1 and 0 in (Fang *et al.*, 2012); Z1 and Z3 mean Zones 1 and 3, respectively

Non-uniform flow resistance at the same cross section is not the only factor. Dietrich *et al.* (2007) reported that during some experiments with the same operating conditions, the location of maximum and minimum temperature points around the middle cross section of the regenerator were moving, and the

structure of their cryocooler is shown in Fig. 5. If the temperature inhomogeneity was only caused by the non-uniform flow resistance, the temperature profile around the regenerator should be stable if there were no change of operating conditions when the cryocooler reached the steady state. This experiment indicated that the mechanism of temperature inhomogeneity was more complicated than the contribution of non-uniform flow resistance. Imura *et al.* (2008) verified this conclusion. They changed the azimuthal connection angle of the compressor and the heat exchanger to the regenerator, compared the former temperature distributions around the regenerator and found that temperature distribution was not rotated with the regenerator's rotation.

Dietrich *et al.* (2007) reported simulation of the temperature inhomogeneity. A model with two parallel regenerators was built with SAGE. To investigate the effect of radial conductivity on the temperature inhomogeneity, two parallel regenerators were connected by some thermal-bridges in the radial direction (Fig. 6, where $Q_{trans} \sim \Delta T$ refers to the heat transferred along the radial direction with temperature difference ΔT). With different initial temperatures of two regenerators, the temperature inhomogeneity was reproduced. The temperature difference decreased when the thermal conductivity of the thermal-bridges increased, as shown in Fig 7. These results proved in theory that temperature perturbation from outside could generate temperature inhomogeneity, and high radial thermal connection in the regenerator may suppress it effectively (Fig. 8).

Andersen *et al.* (2007) reported analysis and simulation results of temperature inhomogeneity generation, focusing on the shape and phase of pressure waves at hot and cold ends of the regenerator.
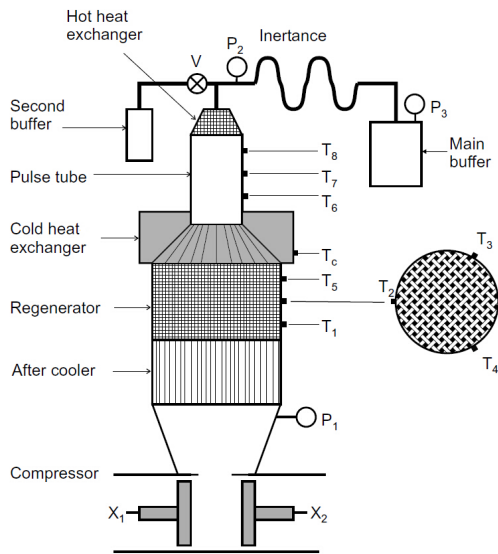

Fig. 5 Schematic of the inline pulse tube cryocooler with linear compressor
T means thermometer, P means pressure sensor, X means displacement sensor, and V is the valve
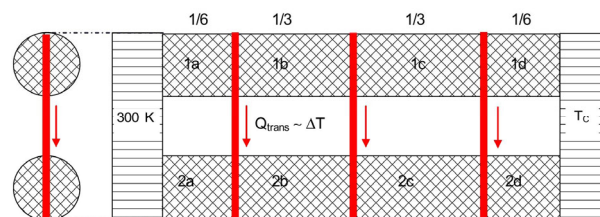

Fig. 6 Schematic of the model of two parallel regenerators with variable transverse thermal coupling
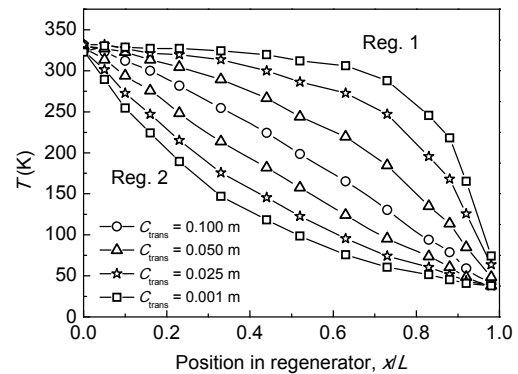

Fig. 7 Calculated axial temperature profiles in the two regenerators (Reg. 1 and Reg. 2) for different transverse thermal coupling factors (C_{trans})
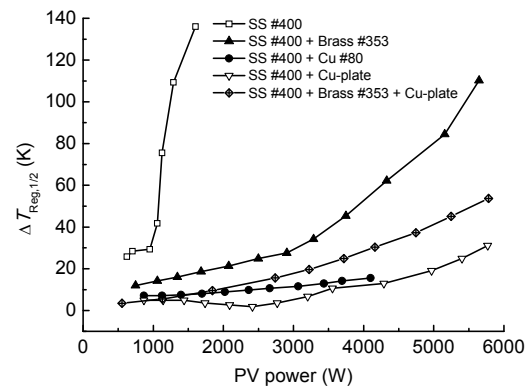

Fig. 8 Measured maximum azimuthal temperature variation $\Delta T_{reg,1/2}$ for the five tested regenerator matrices
Figs. 5–8 are reprinted from (Dietrich *et al.*, 2007), Copyright 2007, with permission from Elsevier

Based on the Euler method, a single regenerator model and a whole pulse tube cryocooler model were built. The cryocooler model contains two parallel regenerators, without any radial mass and thermal connection between them. To find generating mechanisms of temperature inhomogeneity, the models were kept in steady state, and a temperature perturbation was introduced when $f \cdot t = 0$ (f means frequency and t means time) at the middle position of the regenerators. Andersen *et al.* (2007) monitored the change of temperature distribution around the regenerators. Although the temperature perturbation was eliminated in the cryocooler model, the inhomogeneity was produced in the single regenerator model (Figs. 9 and 10).
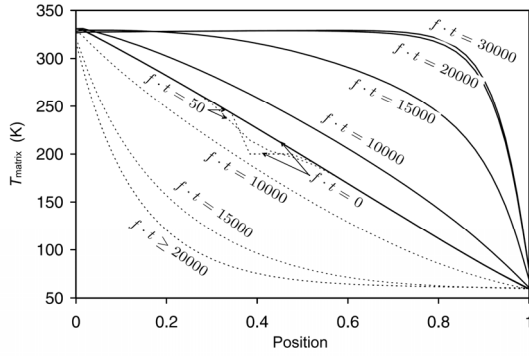

Fig. 9 Evolution in time of the asymmetry in the temperature profiles in the two regenerator channels. At $f \cdot t = 0$ a notch is introduced in the temperature profile of one channel. Reprinted from (Andersen *et al.*, 2007), Copyright 2007, with permission from Elsevier
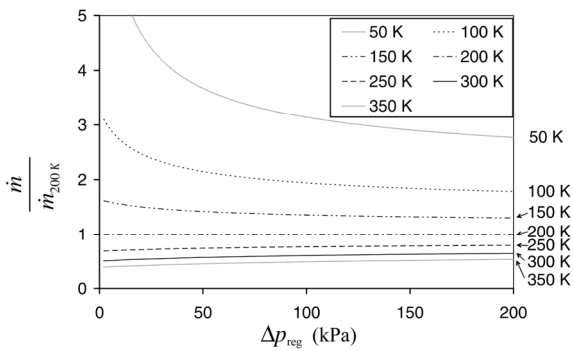

Fig. 10 Regenerator instantaneous mass flow rate ($\dot{m}$) relative to regenerator instantaneous mass flow rate at 200 K ($\dot{m}_{200 K}$) as a function of the pressure difference (Δp_{reg}) between the ends of the regenerator. Reprinted from (Andersen *et al.*, 2007), Copyright 2007, with permission from Elsevier

Andersen *et al.* (2007) pointed out that the temperature inhomogeneity was caused by two factors: one was the shape of the pressure difference wave, and the other was the dependence of the instantaneous mass flow rate on the instantaneous pressure difference and on the temperature in the regenerator. The oscillation of temperature in the regenerator amplified the DC flow, and the variation of average pressure could weaken it.

Furthermore, Andersen *et al.* (2007) summarized the inhibiting factors for temperature inhomogeneity: thermal conduction in mesh, gas and radial thermal conduction enhanced by turbulence, and cross flow caused by the temperature distribution around the regenerator. The gas viscosity's effect is not only because of its correlation with the temperature. Even when the gas viscosity was constant, the inhomogeneity would be amplified because of the gas temperature difference when gas flows through the regenerator over a period.

Gedeon (1997) reported on the DC flow in a pulse tube cryocooler, discussing the contribution of the thermal boundary difference between microchannels in the regenerator. With the assumption of isothermal and adiabatic channels, the mass flow rate in each channel was derived (Eq. (3)). Finally it was concluded that DC flow could be generated in the channels with different boundary conditions (isothermal and adiabatic) when they formed a closed loop.

$$\{\rho u\}_{is} = C \frac{\rho_m \Delta P_1^2}{8 P_m} \left(1 - \frac{1}{\gamma}\right),$$
$$\{\rho u\}_{ad} = C \frac{\rho_m \Delta P_1^2}{8 P_m} \left(\frac{1}{\gamma} - 1\right),$$

(3)

where C means geometrical constant, the subscript is means isothermal, subscript m refers to mean value, and subscript ad means adiabatic.

2.2 Variable flow channels factors

Normally there are some flow channels with different diameters in a pulse tube cryocooler, where gas parcels with different velocities would mix, which leads to non-uniform flow, such as the jet flow. It has been found that this kind of non-uniform flow would generate a temperature inhomogeneity.

Garaway *et al.* (2009a) from National Institute of Standards and Technology (NIST), USA showed pictures of the temperature inhomogeneity in the regenerator. With infrared imaging equipment, the evident jet flow from the inertance tube was photographed and a more than 30 K temperature difference was monitored around the middle regenerator and the pulse tube (Fig. 11). After the optimization of flow straighteners at the exit of the inertance tube, both the jet flow and temperature inhomogeneity were significantly reduced.

Garaway *et al.* (2009b) proved that the jet flow caused by the variation of channels could generate a temperature inhomogeneity. Compared with traditional temperature measurement, infrared imaging equipment may give a more detailed temperature distribution of the regenerator, and could be a valuable alternative measurement method.

2.3 Natural convection

de Waele *et al.* (2013) reported on the influence of natural convection on the temperature inhomogeneity generation. The natural convection was introduced into the regenerator and the results led to a better understanding of the temperature inhomogeneity mechanism. They established a 1D perpendicular regenerator model with the hot end upside. The pressure head of gas in the regenerator is related to its density (Eq. (4)). Because of the temperature difference between the two ends of the regenerator, the densities are different in the hot and cold areas, which leads to a pressure difference between those ends, and a net mass flow is generated.

The calculation showed the relationship between the DC molar flux and the gravity. Eq. (5) explained the molar flux driven by the pressure head difference between the ambient end and cold end of the regenerator, and Eq. (6) showed the axial temperature profile of the regenerator.

$$P_w = \rho g L_r, \tag{4}$$

$$j_g = \frac{(\rho_w - \rho_a)gp}{\mu_w z_r R T_w}, \tag{5}$$

$$T = T_a - (T_a - T_w)\frac{1 - \exp(\lambda_{dc} l / L_r)}{1 - \exp \lambda_{dc}}, \tag{6}$$

where g is the gravity, j is molar flux, and λ refers to a dimensionless parameter, which determines the impact of the DC flow on the temperature profile. The subscript g means gas, r means regenerator, and a means ambient end. Different λ_{dc} will lead to different temperatures at the same section of the regenerator, which reproduces the temperature inhomogeneity. It should be pointed that the result also indicated that the DC flow is independent on the sign of temperature difference between the two ends of the regenerator, which means that whether the cold end is above or under the hot end on the regenerator, the temperature inhomogeneity can appear because of natural convection.

The effect of the flow resistance variation on the temperature inhomogeneity was also discussed. For an extreme assumption (porosity=0), the relation between the DC flow and pressure loss in the regenerator is presented:
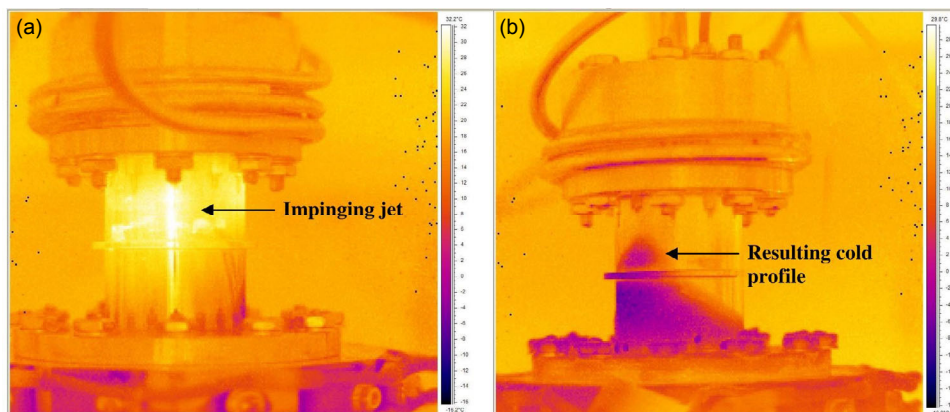

Fig. 11 Infrared images of the buffer tube: (a) northeast face showing impinging jet; (b) southwest face showing the resulting flow instability (Garaway *et al.*, 2009a)

$$\overline{\Delta P^2} = Z_r R(1+b)\frac{\mu_a}{\beta_a} C_p T' j_1'^2 L_r, \tag{7}$$

$$Z_r R(1+b)\frac{\mu_a}{\beta_a} C_p T' j_1'^2 L_r = 2\mu_a Z_r R T_a j_{dc} L_r, \tag{8}$$

where Z is the flow resistance, R is the specific gas constant, β is the volume heat exchange factor, b is a constant parameter, and C_p is a constant (pressure heat capacity).

2.4 Exterior temperature perturbation

Dietrich *et al.* (2007) performed a theoretical study on the effect of outside temperature perturbation on the temperature inhomogeneity. Sun *et al.* (2009a) reported on the experimental results from the University of Giessen, Germany and Zhejiang University, China.

In their two stage U-shape pulse tube cryocooler with thermal coupling of the stages, the thermal bridge used for precooling created a 13 K temperature difference at the connection area of the second stage regenerator (middle part) due to the non-uniform thermal conduction, which was amplified to a difference of 30–40 K at the cold end of the regenerator.

Sun *et al.* (2009b) tried to suppress the temperature inhomogeneity by inserting 80# and 11# copper screens. The temperature difference at the cold end of the regenerator was reduced, but copper screens had little effect on the temperature difference at the middle of the regenerator (Table 1).

3 Driving mechanism

Several theories on the mechanism driving the temperature inhomogeneity have been raised since its first observation. One widely supported view, both by theory and experiment, was that the dependence of viscosity on the temperature creates a positive feedback loop in the flow resistance and temperature of the regenerator.

3.1 Feedback loop between the flow resistance and the temperature

Kirkconnell (1999) reported on experiments results on a cryocooler composed of three regenerators and four pulse tubes. A 10 K temperature difference was measured between the middle cross sections of three regenerators (Figs. 12 and 13).

Kirkconnell (1999) explained that because of slight differences in the tubes, the efficiencies could be different in these regenerators, and the temperature of the most efficient regenerator could be lower, resulting in a lower pressure drop and more gas flow in it. More mass flow will lead to a lower temperature in the regenerator and so a positive feedback loop is formed.
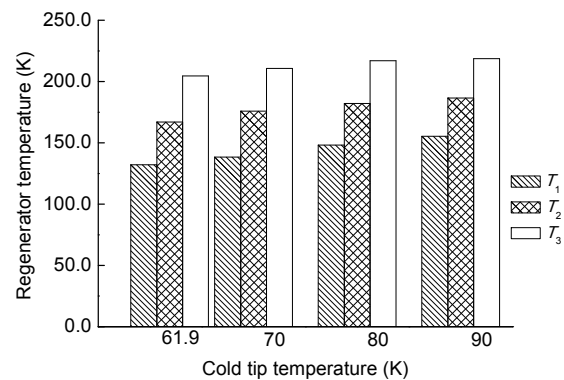
Fig. 12 Regenerator temperature vs. cold tip temperature for baseline expander configuration. Reprinted from (Kirkconnell, 1999), Copyright 1999, with permission from Springer Science+Business Media

Table 1 Radial temperature difference with different filling matrixes in middle heat exchanger

Matrix	Number of copper screens		Radial ΔT in middle heat exchanger (K)	Circumferential ΔT in lower part of regenerator (K)
	80#	11#		
1	4	1	12.02	7.25
2	24	1	11.59	13.43
3	8	4	11.54	8.12
4	8	2	11.65	9.80

(a) Radial temperature difference (ΔT) in middle heat exchanger is defined as ($T_{RHX2} - T_{RHX1}$); (b) Circumferential temperature difference (ΔT) in regenerator is defined as ($T_{Reg0.25A} - T_{Reg0.25D}$); (c) Working conditions: working pressure is 2.12 MPa, working frequency is 55 Hz, and input PV power is 2.8 kW; (d) Wire diameters of 80# and 11# copper screens are 0.14 mm and 1 mm, respectively. Reprinted from (Sun *et al.*, 2009b), Copyright 2009, with permission from Springer
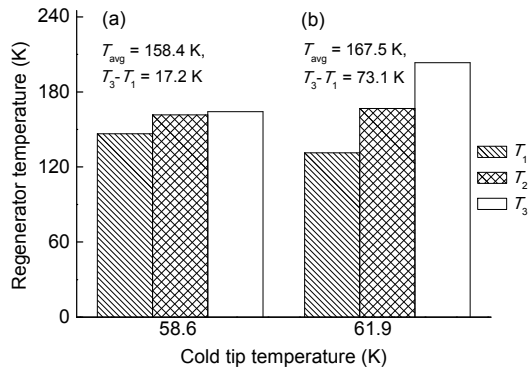
Fig. 13 Comparison of regenerator temperatures: (a) no-load with thermal strap; (b) no-load without thermal straps. Reprinted from (Kirkconnell, 1999), Copyright 1999, with permission from Springer Science+Business Media

Kirkconnell (1999) also indicated that the temperature distribution could be suppressed by enhancing the thermal connection between regenerators. The experimental results agreed well with Gedeon (1997)'s conclusion, and proved that high radial thermal conductivity would be efficient in reducing temperature inhomogeneity.

Martin and Martin (2002) measured the temperature inhomogeneity in a single regenerator for the first time in pulse tube cryocoolers, and the temperature difference between four points on the middle shell of the regenerator was 15 K.

A feedback loop of temperature and flow resistance was also employed to explain the driving mechanism of temperature inhomogeneity. Different from Kirkconnell (1999)'s viewpoint, Martin and Martin (2002) mainly focused on the effect of gas viscosity on temperature inhomogeneity. Due to the positive correlation of temperature, viscosity, and flow resistance, a low temperature leads to a small flow resistance, which causes the cold area to become colder and the hot area hotter in the regenerator, and a temperature inhomogeneity appears. This theory is becoming well accepted.

3.2 Other characteristic effects

Besides the temperature and flow resistance feedback loop, So *et al.* (2006) reported other characteristic parameters contributing to the development of temperature inhomogeneity, including the ratio of cold end temperature to the ambient temperature, the ratio of energy flow to the PV power in the regenerator, thermal conductivity of the screen, as well as flow resistance.

Based on thermoacoustic theory, a 2D regenerator model was built to get the mass and temperature distribution at a steady state in a coaxial regenerator. With the assumption of no radial pressure gradient, and no radial temperature gradient or phase shift between pressure and velocity, an equation for the perturbation growth rate was derived:

$$
\begin{aligned}
& \frac{x_{\mathrm{w}} y_{\mathrm{w}} z_{\mathrm{w}}(1-\phi) \rho_{\mathrm{s}} c_{\mathrm{s}} T_{\mathrm{a}}}{\pi^2 E_{\mathrm{a}}} \varepsilon \\
& = -\frac{H / E_{\mathrm{a}}}{1-\tau} - n^2 \frac{k_y T_{\mathrm{a}} z_{\mathrm{w}} x_{\mathrm{w}} / y_{\mathrm{w}}}{E_{\mathrm{a}}} \\
& \quad + \frac{\gamma}{\gamma-1} \frac{1-\tau}{2\pi} \left(\frac{\delta u_{1\mathrm{R}}(0)}{u_{1\mathrm{R}}(0)} - \frac{\delta u_{20}(0)}{u_{20}(0)} \right) \frac{1}{f(y)},
\end{aligned} \tag{9}
$$

where z is the short transvers dimension, E is the total acoustic power flux, H is the total energy flux, ϕ is the volume porosity, ε is the growth rate, τ is the temperature ratio of working end to ambient end, and n is the regenerator geometry, which is $n=2$ for annular regenerator, and $n=1$ for rectangular/circular regenerator. The subscript s means solid, 1R means the first-order part, 20 means the second-order constant part, and y means the radial direction.

So *et al.* (2006) considered that the characteristics in the left side were positive except ε, so the sign depended on the right side of the equation. It was found that the ratio of energy flow to the PV power, radial thermal conductivity, ratio of cold end temperature to the ambient temperature, geometry characteristic, and the passage distribution in the regenerator all contribute to the perturbation growth rate. By comparing characteristics mentioned before in engines and cryocoolers, they explained that the perturbation would be intensified in cryocoolers, but weakened in acoustic engines, even when the regenerators were the same. The experimental results also qualitatively supported this theoretical analysis.

However, note that two assumptions are not reasonable in their paper. The first one is that no radial pressure gradient exists at the ends of the regenerator. Normally the axial flow resistance is much smaller than the radial one in the regenerator, and to form a

flow loop, the DC flow would have to flow in radial direction at the two ends of the regenerator, and this should be driven by the radial pressure gradient. Without such a pressure gradient, the flow loop canot form. The second assumption is that the velocity perturbation is nonzero only parallel to the acoustic axis. But this assumption hinders the DC flow to turn around in the regenerator, so that the flow loop cannot form.

4 Suppressing methods

Many studies have been done to suppress the temperature inhomogeneity since it was found to decrease the performance of cryocoolers. Main methods were the enhancement of radial thermal conductivity and optimization of flow at both ends of the regenerators.

Gromoll *et al.* (2006) reported their work on a 25 K pulse tube refrigerator. A temperature inhomogeneity was noticed, deteriorating the performance of the refrigerator. To find an effective method for improving the performance, they tested four types of sandwich screens and firstly verified that an improved radial conductance in the regenerator leads to a reduced temperature inhomogeneity in conjunction with an improved cooling performance (Figs. 14 and 15). Then Dietrich *et al.* (2007) reported more detailed results on this effective suppressing method.
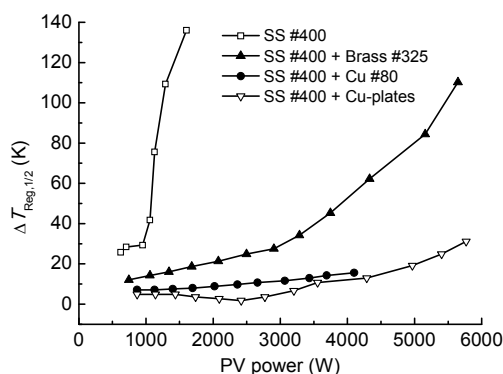

Fig. 14 Maximum temperature variation around the middle plane of the regenerator tube vs. PV power for different regenerator fillings, *f*=52 Hz. Reprinted from (Gromoll *et al.*, 2006), Copyright 2006, with permission from American Institute of Physics
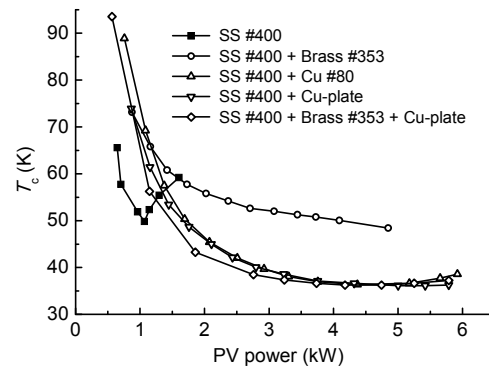

Fig. 15 Measured refrigeration temperature vs. PV power for the five tested regenerator matrices: *f*=50 Hz for matrix SS #400, otherwise 52 Hz. Reprinted from (Dietrich *et al.*, 2007), Copyright 2007, with permission from Elsevier

Imura *et al.* (2006; 2008) from Nihon University reported on a high power pulse tube cryocooler. Temperature inhomogeneity was measured as large as 150 K. They followed the idea of the University of Giessen (Gromoll *et al.*, 2006) and inserted 60# copper screen mesh into the regenerator. The temperature difference decreased to 40 K, and the performance was improved (Figs. 16 and 17).

Other researchers from Air Liquid (Ercolani *et al.*, 2008), Praxair (Lynch, 2003), Clever Fellows Innovation Consortium (CFIC) (Spoor, 2012), Eindhoven University of Technology (Daniel, 2007), and Zhejiang University (Sun *et al.*, 2011; 2012; Liu *et al.*, 2011) obtained evidence that high thermal conductivity mesh could suppress temperature inhomogeneity. As mentioned above, the optimization of flow straighteners has also been proven to be effective for reducing the temperature inhomogeneity (reports from NIST (Garaway *et al.*, 2009a; 2009b; Lewis *et al.*, 2009; 2010), University of Wisconsin-Madison (Potratz *et al.*, 2006; Potratz, 2007), Air Liquid (Tanchon *et al.*, 2006; 2007; Ercolani *et al.*, 2008), and Praxair (Zia, 2007; Chen *et al.*, 2010)).

Another method to avoid temperature inhomogeneity is to use several cold heads with increased length/diameter (L/D) ratio of the regenerators instead of a single cold head with one regenerator with low L/D ratio. The University of Giessen has reported on such a cryocooler assembly and demonstrated its effectiveness in reducing the temperature inhomogeneity (Dietrich and Thummes, 2010).
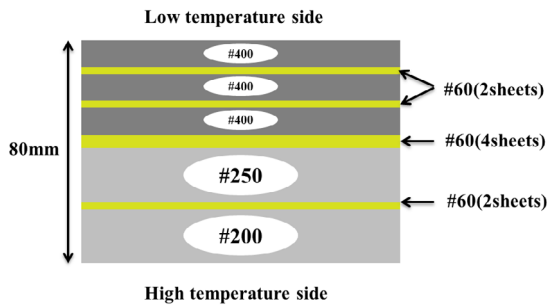
Fig. 16 Schematic insertion of copper #60 meshes. Reprinted from (Imura *et al.*, 2008), Copyright 2008, with permission from Elsevier
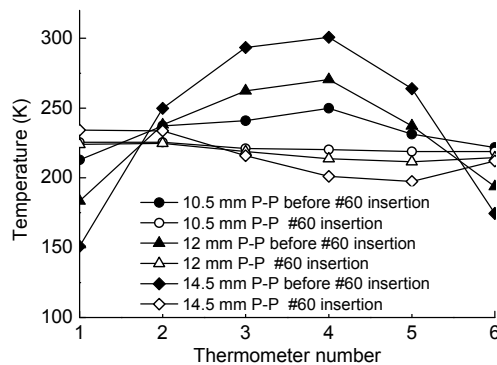

Fig. 17 Temperature distribution in a circumference of the regenerator center. Reprinted from (Imura *et al.*, 2008), Copyright 2008, with permission from Elsevier

5 Conclusions

As a main limitation to the performance improvement of high power pulse tube cryocoolers, temperature inhomogeneity has attracted much attention. Studies on the generation mechanism are mainly on the interior/internal factors (such as those to do with the regenerator and variation channel) and exterior/external factors influencing this effect (such as natural convection and temperature perturbation). It has been shown that the generation of temperature inhomogeneity is the result of several factors acting together, and the positive feedback loop between the flow resistance and the temperature is the main driving mechanism. Other characteristics make some contribution, such as the ratio of energy flow to the PV power, radial thermal conductivity, the ratio of cold end temperature to the ambient temperature, geometry characteristic, and the passage distribution

in the regenerator. The main suppressing methods are enhancement of the radial thermal conductivity of the regenerator and optimization of flow straighteners.

At present, traditional thermodynamic analysis, numerical simulation, and experiment are the main research methods for temperature inhomogeneity. The traditional thermodynamic analysis also can be classified as two kinds: the micro-channel model analysis and the whole regenerator model analysis. Normally traditional thermodynamic analysis is 1D, and has difficulties in describing the radial flow and heat transfer even when some unreasonable/ unrealistic assumptions are made. But the CFD method has the advantage of solving complex and diverse equations, being able to reproduce more accurately the phenomenon and analyze the weight of different factors. Thus, this has gradually become the mainstream method.

There are two points to make about current difficulties in theoretical research, simulation, and experiment: one is that an accurate 3D model for flow and heat transfer in a porous volume is hard to build up, the other is that temperatures in the regenerator are hard to measure. Future development for temperature inhomogeneity study will move towards 3D simulation and experimental measurements. For theoretical study, the generation process of inhomogeneity will possibly be reproduced in 3D models by the CFD method, which is expected to explain the generation and driving mechanism reasonably well. Then the temperature contour could be displayed as a frost line on the shell of the regenerator, which visualizes temperature inhomogeneity (Spoor, 2013). In the future, more advanced measurement methods, such as the particle image velocimetry method and infrared observation, will give more accurate results.

References

Andersen, S.K., Dietrich, M., Carlsen, H., *et al.*, 2007. Numerical study on transverse asymmetry in the temperature profile of a regenerator in a pulse tube cooler. *International Journal of Heat and Mass Transfer*, **50**(13-14): 2795-2804. [doi:10.1016/j.ijheatmasstransfer.2006.10.054]

Chen, R.L., Henzler, G.W., Royal, J.H., *et al.*, 2010. Reliability test of a 1 kW pulse tube cryocooler for HTS cable application. Cryogenics Engineering Conference, Tucson, Arizona, USA, p.727-735.

Daniel, W.J.W., 2007. High-Power Cryocooling. PhD Thesis,

Eindhoven University, the Netherlands.

de Waele, A.T.A.M., Sun, D.M., Fang, K., 2013. Stability of high aspect ratio cryocooler regenerators. International Conference of Cryogenics and Refrigeration, Hangzhou, China, p.A2-42.

Dietrich, M., Thummes, G., 2010. Two-stage high frequency pulse tube cooler for refrigeration at 25 K. *Cryogenics*, **50**(4):281-286. [doi:10.1016/j.cryogenics.2010.01.010]

Dietrich, M., Yang, L.W., Thummes, G., 2007. High-power Stirling-type pulse tube cryocooler: observation and reduction of regenerator temperature-inhomogeneities. *Cryogenics*, **47**(5-6):306-314. [doi:10.1016/j.cryogenics.2007.03.009]

Ercolani, E., Poncet, J.M., Charles, I., *et al.*, 2008. Design and prototyping of a large capacity high frequency pulse tube. *Cryogenics*, **48**(9-10):439-447. [doi:10.1016/j.cryogenics.2008.06.003]

Fang, K., Qiu, L.M., Liu, D.H., *et al.*, 2012. Effect of non-uniform porosity on temperature inhomogeneity in the regenerator of high power Stirling type pulse tube cryocoolers. 24th International Cryogenic Engineering Conference, Fukuoka, Japan, p.347-350.

Garaway, I., Taylor, R., Lewis, M., *et al.*, 2009a. Infrared imaging as a means of characterizing flow and temperature instabilities within pulse tube cryocoolers. 15th International Cryocooler Conference, Long Beach, California, USA, p.1-9.

Garaway, I., Taylor, R., Lewis, M., *et al.*, 2009b. Characterizing flow and temperature instabilities within pulse tube cryocoolers using infrared imaging. 15th International Cryocooler Conference, Long Beach, California, USA, p.233-240.

Gedeon, D., 1997. DC gas flow in Stirling and pules tube cryocoolers. 9th International Cryocooler Conference, Waterville Valley, New Hampshire, USA, p.385-392.

Gedeon, D., 2004. Flow circulations in foil-type regenerators produced by non-uniform layer spacing. 13th International Cryocooler Conference, New Orleans, USA, p.421-430.

Gromoll, B., Huber, N., Dietrich, M., *et al.*, 2006. Development of a 25 K pulse tube refrigerator for future HTS-series products in power engineering. 22nd Cryogenic Engineering Conference, Keystone, Colorado, USA, p.643-652.

Imura, J., Shinoki, S., Sato, T., *et al.*, 2006. Development of high capacity Stirling type pulse tube cryocooler. 19th International Symposium on Superconductivity, Nagoya, Japan, p.1369-1371.

Imura, J., Iwata, N., Yamamoto, H., *et al.*, 2008. Optimization of regenerator in high capacity Stirling type pulse tube cryocooler. 20th International Symposium on Superconductivity, Tsukuba, Japan, p.2178-2180.

Kirkconnell, C.S., 1999. Experimental investigation of a unique pulse tube expander design. 10th International Cryocooler Conference, Monterey, California, USA, p.239-247.

Lewis, M.A., Taylor, R.P., Bradley, P.E., *et al.*, 2009. Pulse tube cryocooler for rapid cool down of a superconducting magnet. 15th International Cryocooler Conference, Long Beach, California, USA, p.167-176.

Lewis, M.A., Taylor, R.P., Radebaugh, R., *et al.*, 2010. Investigation of flow nonuniformities in a large 50 K pulse tube cryocooler. Cryogenic Engineering Conference, Tucson, Tennessee, USA, p.68-75.

Li, Z.P., Jiang, Y.L., Gan, Z.H., *et al.*, 2014. Performance of a precooled 4 K Stirling type high frequency pulse tube cryocooler with Gd$_2$O$_2$S. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, **15**(7): 508-516. [doi:10.1631/jzus.A1400052]

Liu, D.H., Qiu, L.M., Gan, Z.H., *et al.*, 2011. Study on temperature inhomogeneity in regenerator of high-power Stirling-type pulse tube cryocoolers based on two parallel regenerator model. *Cryogenics*, (6):4-8 (in Chinese).

Lynch, N., 2003. Large scale cryocooler development for superconducting electric power application. 21st Cryogenic Engineering Conference, Anchorage, Alaska, USA, p.173-176.

Martin, J.L., Martin, C.M., 2002. Pulse tube cryocoolers for industrial applications. 19th Cryogenic Engineering Conference, Madison, Wisconsin, USA, p.662-669.

Potratz, S.A., 2007. Design and Test of a High Capacity Pulse Tube. PhD Thesis, University of Wisconsin-Madison, USA.

Potratz, S.A., Nellis, G.F., Maddocks, J.R., *et al.*, 2006. Development of a large-capacity, Stirling-type pulse tube refrigerator. 22nd Cryogenic Engineering Conference, Keystone, Colorado, USA, p.3-10.

So, J.H., Swift, G.W., Backhaus, S., 2006. An internal streaming instability in regenerators. *Journal of the Acoustical Society of America*, **120**(4):1898-1909. [doi:10.1121/1.2259776]

Spoor, P.S., 2012. Preliminary results on a large acoustic-Stirling ("pulse tube") cooler designed for 800 W at 70 K. 17th International Cryocooler Conference, Los Angeles, USA, p.121-127.

Spoor, P.S., 2013. Anomalous temperature and amplitude-dependent performance characteristic of a 1000W/80K coldfinger. Cryogenic Engineering Conference, Anchorage, Alaska, USA, p.1405-1409. [doi:10.1063/1.4860871]

Sun, D.M., Dietrich, M., Thummes, G., 2009a. High power Stirling type pulse tube cooler working below 30 K. *Cryogenics*, **49**(9):457-462. [doi:10.1016/j.cryogenics.2009.06.006]

Sun, D.M., Dietrich, M., Thummes, G., *et al.*, 2009b. Investigation on regenerator temperature inhomogeneity in Stirling-type pulse tube cooler. *Chinese Science Bulletin*, **54**(6):986-991. [doi:10.1007/s11434-009-0123-5]

Sun, J.C., Qiu, L.M., Fang, K., *et al*., 2011. Theoretical and experimental investigation on high frequency large power pulse tube cryocooler. Cryogenic Engineering Conference of China, Wuhan, China, p.109-114 (in Chinese).

Sun, J.C., Qiu, L.M., Gan, Z.H., *et al*., 2012. Simulation and experimental investigation of single stage high power Stirling-type pulse tube cryocooler. *Journal of Engineering Thermophysics*, **33**(8):1283-1286 (in Chinese).

Tanchon, J., Ercolani, E., Trollier, T., 2006. Design of a very large pulse tube cryocooler for HTS cable application. 22nd Cryogenic Engineering Conference, Keystone, Colorado, USA, p.661-668.

Tanchon, J., Trollier, T., Ravex, A., *et al*., 2007. Prototyping a large capacity high frequency pulse tube cryocooler. 14th International Cryocooler Conference, Annapolis, Mariland, USA, p.133-139.

Yuan, J., Maguire, J., 2004. Development of a single stage pulse tube refrigerator with linear compressor. 13th International Cryocooler Conferene, New Orleans, USA, p.157-163.

Zhang, X.B., Chen, J.Y., Yao, L., *et al*., 2014. Research and development of large-scale cryogenic air separation in China. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, **15**(5):309-322. [doi:10.1631/jzus.A1400063]

Zia, J.H., 2007. A pulse tube cryocooler with 300 W refrigeration at 80 K with operating efficiency of 19% Carnot. 14th International Cryocooler Conference, Annapolis, Maryland, USA, p.141-147.

中文概要

题　目：大功率脉管制冷机的温度非均匀性

目　的：大功率脉管制冷机中存在的温度非均匀性问题导致回热器效率低下，严重阻碍制冷机性能的提高。本文回顾回热器非均匀性问题的理论与试验研究，对当前理论与实验的研究结果进行细致的分类与探讨，并展望将来非均匀性研究可能的发展方向。

方　法：1. 当前回热器非均匀性理论与实验研究主要包括形成机理、发展机制和抑制方法三个方面。其中对其形成机理和发展机制的研究以理论为主，抑制方法的研究以实验为主。2. 回热器温度非均匀性的形成机理，按照其诱发因素的来源可划分为内源性与外源性因素，其中内源性因素包括与回热器相关和变径流道等，外源性因素包括自然对流效应及外界温度扰动。3. 发展机制主要认为是气体粘度与温度之间的正向关系导致的回热器内温度与流阻的正反馈效应。4. 抑制方法主要是增加回热器内径向热导率，阻断其发展机制，或增加回热器长径比，抑制其影响范围。

结　论：1. 温度非均匀性形成机制复杂，为多因素耦合作用；2. 气体粘度与温度之间的正向关系导致的回热器内温度与流阻的正反馈效应是导致非均匀性发展的主要因素；3. 增加回热器径向热导率和回热器长径比可有效抑制非均匀性。

关键词：温度非均匀性；内部流；大功率；脉管制冷机