Oscillating Flow Characteristics of a Regenerator under Low Temperature Conditions

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ABSTRACT

An experimental system was designed and constructed to investigate oscillating flow characteristics of a regenerator under low temperatures. Experimental data of the pressure drops of the regenerator in the oscillating flow under low temperature conditions are obtained. It is found that the value of the cycle-averaged pressure drop of the oscillating flow in the regenerator under liquid nitrogen temperatures is 5~6 times higher than that of a steady flow at the same Reynolds number based on the cross-sectional mean velocity. The correlation equation of the friction factor is obtained in the liquid nitrogen temperatures, a comparison with that in the ambient temperatures is discussed. The test conditions are very close to the operating conditions of the practical high frequency cryocoolers, resulting the experimental data are useful for the performance prediction and practical design of cryogenic regenerators.

INTRODUCTION

The ability to accurately predict pressure drops in the regenerator subject to an oscillating flow is of crucial importance in the optimum design of cryocoolers. In the past, the regenerator was normally taken to be a kind of high efficiency heat exchanger, which may be close to the actual performance for unidirectional steady flow or very low frequency regenerator. The correlation equation of the friction factor given by Kays and London[1] has been widely used. There are also some correlations with pressure drop in regenerators[2, 3], but most of them are based on a unidirectional steady flow through packed screens. Considering the fact that most regenerative cryocoolers operate under periodically reversing flow conditions, it is evident that the correlation equations based on the steady flow cannot accurately predict the pressure drops and phase shifts in the regenerator under the oscillating flow. Zhao and Cheng[4] and Helvensteijin et al.[5] found a higher friction factor in the regenerator under oscillating flow than that under the steady flow at the same Reynolds number based on the cross-sectional mean velocity. Since 1996, we have been working on the experimental study of the flow resistance characteristics of the regenerators under the oscillating flow conditions. We reported detailed experimental data of the pressure drops and predicted that the oscillating flow characteristics of the regenerator demonstrate not only pressure drops but also phase shifts[6-8]. However, all of the above works were focused on the flow characteristics of the regenerator under ambient temperature conditions.

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The regenerator in a practical cryocooler operates under low temperature conditions, and there exists a large temperature gradient along the regenerator length. Therefore, it is necessary to study the oscillating flow characteristics of the regenerator under low temperatures. In this paper, we will focus on the effects of low temperatures on the oscillating flow characteristics of the regenerator.

EXPERIMENTAL SYSTEM

A hot wire anemometer was used in the experiments for the velocity measurements. However, the hot wire anemometer must be calibrated firstly when used under low temperatures. A calibration system was set up to calibrate the hot wire anemometer under liquid nitrogen temperatures. Fig.1 shows the calibration data, which is fitted by:

$$E^2 = 2.216 + 2.622 \times U^{0.25} \qquad (1)$$

here, E is the voltage output of the hot wire and U is the velocity of the working fluid.

The schematic diagram of the experimental apparatus is given in Fig. 2. The test section of the regenerator consists of a thin wall stainless steel tube (48 mm in length and 9 mm inner diameter) packed with stainless steel screens. A linear compressor is connected to one end of the test section by the velocity straightener (21 mm in length and 8 mm inner diameter) to provide desirable oscillating flow. The swept volume of the compressor is about 2cc, and its operating frequency can be adjusted from 20 to 80 Hz. A reservoir with an adjustable needle orifice valve is connected to the other end of the test section through a U-shaped tube. To maintain the low temperature, the test section is immersed into a tank filled with liquid nitrogen.

Three small quartz differential pressure transducers (KISTLER, Type 601A), connected to a charge amplifier (KISTLER, Type 5011) having a high natural frequency (150 kHz), are used to measure the transient gas pressure wave. They are placed at the outlet of the velocity straightener, at the inlet of the U-shaped tube and at the reservoir, as shown in Fig. 1. A hot wire anemometer (DANTEC, Model 90N10) is used to measure the instantaneous cross-sectional mean velocity. Two small hot wire probes (DANTEC, Model 55P11) are placed at both ends of the test section of the regenerator, details of the principle of the hot wire anemometer was given in Ref. [7]. Analog-to-digital conversions are carried out by an A/D conversion board (KEITHLEY, DAS 1610), which is plugged into a 486 personal computer. A 4-channel simultaneous sample and hold front ends are employed to ensure that both the dynamic pressures and the velocity voltage signals are sampled simultaneously. An oscilloscope (HP 5402B) is also employed to simultaneously observe the pressure wave signals.

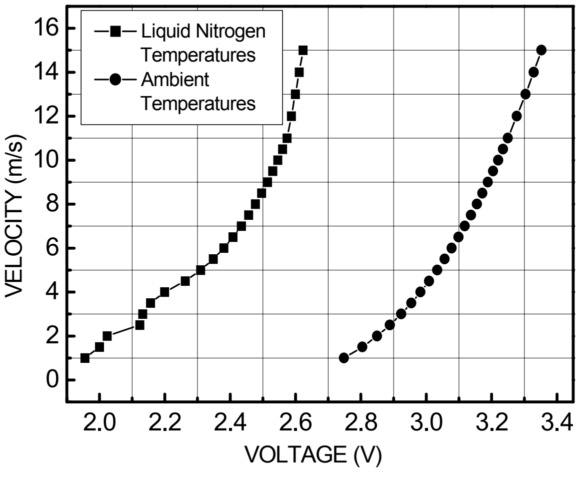


Figure 1. Calibration results of the hot wire anemometer under liquid nitrogen temperatures.

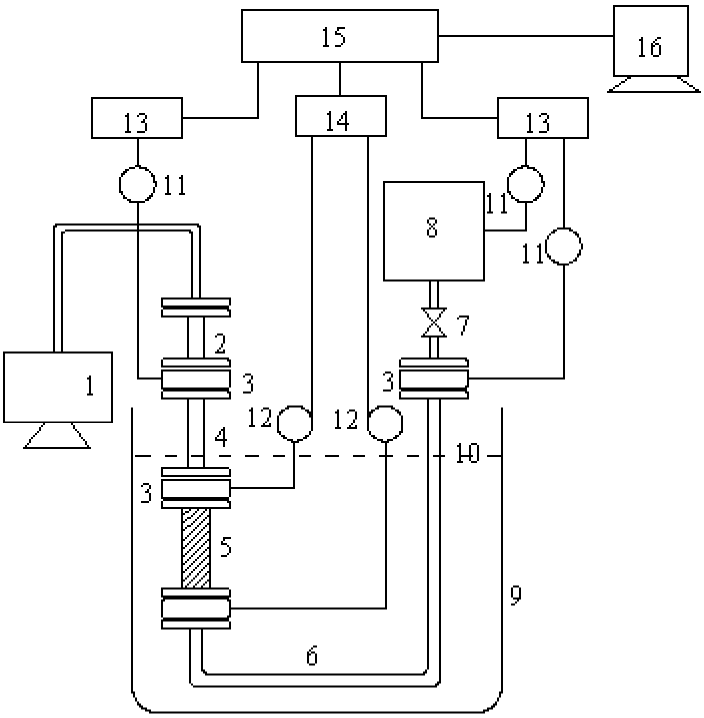


Figure 2. Schematic diagram of the experimental apparatus.

1. compressor; 2. velocity straightener; 3. measurement connector; 4. connection tube; 5. regenerator; 6. U-shaped tube; 7. orifice valve; 8. reservoir; 9. tank; 10. surface of liquid nitrogen; 11. pressure transducer; 12. hot wire probe; 13. charge amplifier; 14.hot-wire anemometer; 15. A/D conversion board; 16. 486 computer.

Table 1. Properties of stainless-steel screens

Mesh size	Number of screens n	Wire diameter D_w (mm)	Porosity φ	Mesh distance β (mm)	Hydraulic diameter D_h (mm)
150	550	0.061	0.6993	0.120	0.1418
250	650	0.041	0.6582	0.100	0.0788
300	700	0.031	0.6938	0.087	0.0704

EXPERIMENTAL CONDITIONS

In the present experiment, the stainless steel screens with three different mesh sizes are tested under various working conditions. The properties of the number of screens n, wire diameters D_w, mesh distance β, porosity φ and hydraulic diameter D_h for the three mesh sizes of the wire screens are listed in Table 1. Among of the parameters, the wire diameter D_w, the pitch λ and the mesh distance β are provided by the manufacturer, respectively. The hydraulic diameter D_h and the porosity φ of the regenerator are determined from the equations given below. The working medium is helium gas. The operating frequency is 50 Hz and the system mean pressure varies from 0.5 to 2.0 MPa.

The raw measured experimental data include: (1) the pressures at the inlet and outlet of the regenerator, and at the reservoir, (2) the temperatures at the inlet and outlet of the regenerator, and at the reservoir. Due to operating difficulties of using the hot wire anemometer in the liquid nitrogen temperatures, the velocity of the working gas at the outlet of the regenerator is obtained by measuring the instantaneous pressure oscillation at the reservoir. Assuming $P = P_0 + P_1 e^{j\omega t}$, the relationship between the gas mass of helium and the pressure in the reservoir is given by [9, 10]:

$$\frac{dm}{dt} = \frac{V}{\gamma R T_{res}} \frac{dP}{dt} \tag{2}$$

here, P is the pressure oscillation in the reservoir, P_0 and $P_1 e^{j\omega t}$ are the steady and oscillating part of the pressure in the reservoir, respectively. Both the pressure ratio and the oscillation amplitude of the temperature are so small in the reservoir during the experiments that the temperature T_{res} in the reservoir can be approximated as the environmental temperature T. Thus the mass flux into the reservoir can be rewritten as:

$$\frac{dm}{dt} = A_m \rho u = \frac{V}{c^2} \frac{dP}{dt} \tag{3}$$

here, $c = \sqrt{\gamma R T}$ is the local sound speed. With $dP = dP_1 e^{j\omega t}$, the velocity of the helium at the outlet of the regenerator can be simply expressed as:

$$u_{mean} = \frac{P_1 V \omega}{A \rho c^2} e^{j\left(\omega t + \frac{\pi}{2}\right)} \tag{4}$$

The averaged relative deviation between the velocity obtained by the hot wire anemometer and Eq. (4) is about 3.35%.

RESULTS AND DISCUSSIONS

Pressure drop

Performance predictions of the cryocoolers involve estimating pressure drops to determine regenerator efficiency under oscillating flow condition. Therefore, it is important to know the correlation to calculate pressure drops and pressure drop factor. We have obtained the experimental data for the pressure drops across the regenerator subjected to oscillating flow under different experimental conditions. To compare the pressure drops over the regenerator in oscillating flow with those in steady flow, we use the following correlation equation for predicting the friction factor of a steady flow through a stack of wire screen[1]:

$$f_{st} = \frac{33.6}{\mathrm{Re}_\beta} + 0.337 \tag{5}$$

where

$$f_{st} = \frac{\Delta P_{st} / n}{\frac{1}{2} \rho u_{st}^2} \tag{6}$$

$$\mathrm{Re}_\beta = \frac{u_{st} \beta}{\nu} \tag{7}$$

where ΔP_{st} and u_{st} is the pressure drop and cross-sectional fluid velocity in the packed column under steady flow; n is the number of screens; β is the distance between meshes, and Re_β is the Reynolds number based on β and u_{st}.

We use the cycle-averaged velocity u_{mean} instead of u_{st} and equations (5), (6) and (7) to predict the steady flow pressure drops. To predict the pressure drop across the regenerator under the oscillating flow, the maximum friction factor is defined as follows[6]:

$$f_{\max} = \frac{\Delta P_{\max} D_h}{\frac{1}{2} \rho (u_{\max})_p^2 L} \tag{8}$$

and the cycle-averaged friction factor is

$$f_{mean} = \frac{\Delta \overline{P}_{mean} D_h}{\frac{1}{2}\rho (u_{\max})_p^2 L} \tag{9}$$

Defining the Reynolds number:

$$\mathrm{Re} = \frac{u_{\max} D_h}{\nu} \tag{10}$$

where $\Delta P_{\max}$ is the maximum pressure drop in one cycle, $\Delta \overline{P}_{mean}$ is the cycle-averaged pressure drop, $u_{\max}$ is the maximum cross-sectional mean fluid velocity in the regenerator, L is the length of the regenerator, and D_h is the hydraulic diameter of the screen, which is defined as follows^6

$$D_h = \frac{\varphi D_w}{1-\varphi} \tag{11}$$

with φ being the screen porosity which is defined as:

$$\varphi = 1 - \frac{\pi D_w \sqrt{\lambda^2 + D_w^2}}{4\lambda^2} \tag{12}$$

We also define the dimensionless distance as:

$$X = \frac{1}{2}\frac{u_{\max}}{D_h \omega} \tag{13}$$

Based on the experimental data, the cycle-averaged friction factor f_{mean} is evaluated according to Eq. (9). Fig. 3 represents the experimental data of oscillating flow of 50 Hz, which is obtained in the liquid nitrogen temperatures. It is shown that the experimental data are well fitted by the following correlation equation:

$$f_{mean} = \frac{1}{X}\left(3.81\times 10^2 + \frac{1.08\times 10^2}{\mathrm{Re}}\right) \tag{14}$$

This equation can be used to predict the 50 Hz oscillating flow pressure drop in the liquid nitrogen temperatures.

Table 2 is the comparison of the pressure drops of steady flow and oscillating flow with operating frequency of 50 Hz at ambient temperatures and liquid nitrogen temperatures. It shows that the ratio of $\Delta \overline{P}_{mean}$ to ΔP_{st} increases with decreasing temperature. It was of 2~3 at ambient temperatures ^{7}, while in present work, we find that the ratio is of 5~6 at the liquid nitrogen temperatures. We conclude that the lower the temperature is, the larger the ratio of $\Delta \overline{P}_{mean}$ to ΔP_{st} is. The effect of the temperature on the pressure drop of the oscillating flow is useful to evaluate and design the regenerator.

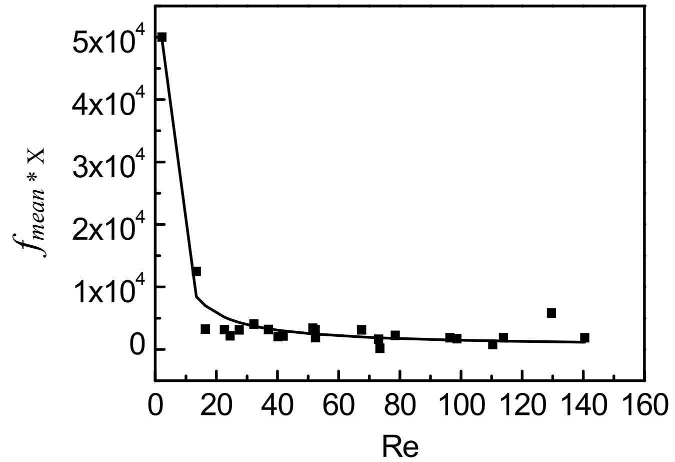
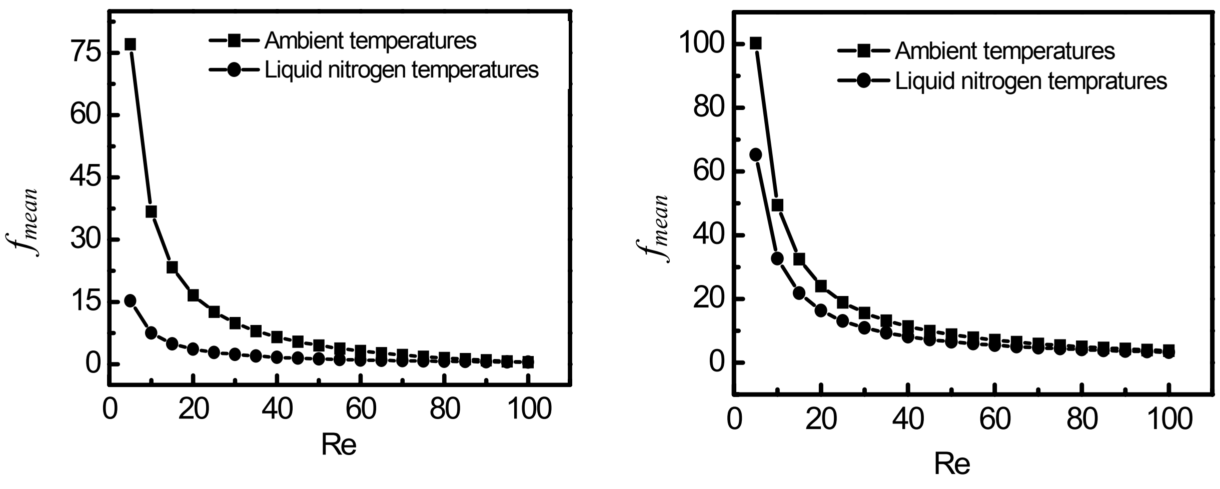
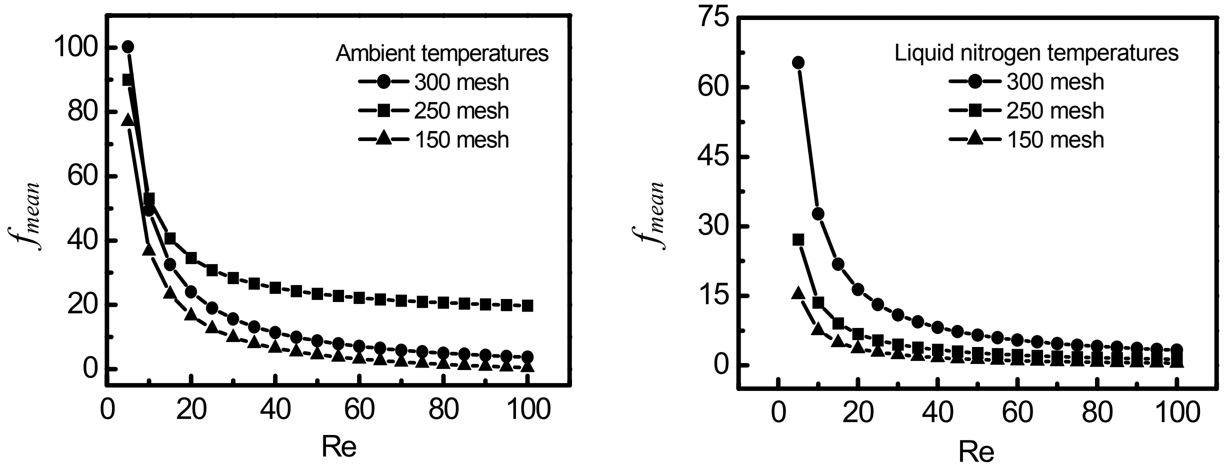


Figure 3. Correlation equation of the cycle-averaged friction factor in terms of Re and X .



(a) (b)

Figure 4. Comparison of the friction factors. (a) 150 mesh; (b) 300 mesh.



(a) (b)

Figure 5. Relationship between the cycle-averaged friction factor and the mesh size. (a) at ambient temperatures; (b) at liquid nitrogen temperatures.

Table 2. Pressure drops of oscillating flow compared with those of steady flow

Temperaturs	Mesh size	Re_β	$\Delta\overline{P}_{mean}$ (kPa)	ΔP_{st} (kPa)	$\Delta\overline{P}_{mean} / \Delta P_{st}$
Ambient	150	5.57	12.67	5.98	2.28
	250	5.17	17.21	7.42	2.32
	300	5.09	20.44	8.69	2.35
Liquid nitrogen	150	302.6	238.8	38.95	6.130
	250	262.5	289.7	52.59	5.508
	300	220.9	369.3	59.52	6.205

Friction factor

In this section, we compare the cycle–averaged friction factor f_{mean} under the liquid nitrogen temperatures with which under the ambient temperatures. Fig.4 illustrates the comparison results with different mesh sizes. We can see clearly that the friction factors f_{mean} have similar tendency under different temperature range with the Reynolds number in the range of 5-100. They decrease with increasing Reynolds number and reach a constant value ultimately. The cycle-averaged friction factor f_{mean} under the liquid nitrogen temperatures is less than that at ambient temperatures. It means that the oscillating flow resistance in low temperatures is smaller than that in ambient temperatures.

Fig. 5 demonstrates the influence of the mesh size on the cycle-averaged friction factor f_{mean}. At ambient temperatures [7], the cycle-averaged friction factor f_{mean} with 250 mesh size has the largest value. However, at liquid nitrogen temperatures, the cycle-averaged friction factor f_{mean} increases with increasing mesh size. Under the condition of ambient temperatures and small Reynolds number, the effect of mesh size on the friction factor is smaller, while the effect increases with increasing Reynolds number. However, the effect of mesh size on the friction factor under the liquid nitrogen temperatures decreases with increasing Reynolds number. Therefore, the friction factor is nearly independent of the mesh size under the condition of large Reynolds number and liquid nitrogen temperatures.

CONCLUSIONS

Experimental measurements on the oscillating flow characteristic of the regenerator under low temperatures have been carried out in this paper. The experimental data have been compared with that under ambient temperatures. Correlation equations for the maximum and cycle-averaged friction factors in terms of Reynolds number and dimensionless distance X are obtained. It is found that the value of the cycle-averaged pressure drop of the oscillating flow in the regenerator under the liquid nitrogen temperatures is 5~6 times higher than that of a steady flow at the same Reynolds number based on the cross-sectional mean velocity. The friction factor decreases with decreasing temperature.

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