Reduction of convective heat losses in pulse tube refrigerators by additional DC flow

Shiraishi M., Fujisawa Y.*, Murakami M.* and Nakano A.

National Institute of AIST, Tsukuba-East, Namiki 1-2-1, Tsukuba, Ibaraki, 305-8564, Japan
*University of Tsukuba, Tennoudai 1-1-1,Tsukuba, Ibaraki, 305-8573, Japan

The effectiveness of using an additional DC flow to improve cooling performance by reducing convective heat losses caused by gravity-driven secondary flow in inclined orifice pulse tube refrigerators was studied by visualization of flow and by measurement of gas temperatures at the cold and hot ends of the pulse tube. Results revealed that the gas temperature decreased at the cold end and increased at the hot end by decreasing the secondary flow to an optimal level in the core region. An additional DC flow thereby improved the cooling performance (temperature difference between hot and cold ends) by over 10%.

INTRODUCTION

The cooling performance of a pulse tube refrigerator is extremely sensitive to convective heat losses caused by convective secondary flows. Two typical convective secondary flows induced in a pulse tube are acoustic streaming induced by pressure oscillating [1] and gravity-driven secondary flow induced by gravity in inclined pulse tubes [2]. If these secondary flows are induced, convective heat losses occur because the flow from the hot end to the cold end in the core region transports fluid that has a relatively higher temperature compared to the cold-end temperature, and thus the fluid releases heat to the cold end. Decreasing the flow to the cold end should therefore reduce convective heat loss. Reduction of convective heat losses by controlling secondary flow is an effective method for improving the cooling performance of pulse tube refrigerators.

For practical applications, pulse tube refrigerators are used not only in vertical positions but also in inclined positions. When a refrigerator is used in an inclined position, a gravity-driven secondary flow is induced, which significantly influences the cooling performance. The cooling performance changes drastically when the refrigerator is increasingly inclined from 0° to 180° from vertical [2]. Here, we defined the inclination angle θ as shown in the inset of Fig. 1. In a previous study, we found that an effective approach was to reduce the convective heat loss in inclined pulse tube refrigerators was the use of an additional DC flow generated by a second orifice valve [3].

Here, the objective was to clarify in further detail the effectiveness of using an additional DC flow to reduce convective heat losses in inclined pulse tube refrigerators. First, the oscillating flow in an orifice pulse tube refrigerator was visualized. Then, the gas temperature distribution at the hot and cold ends of the pulse tube was measured as an indicator of cooling performance.

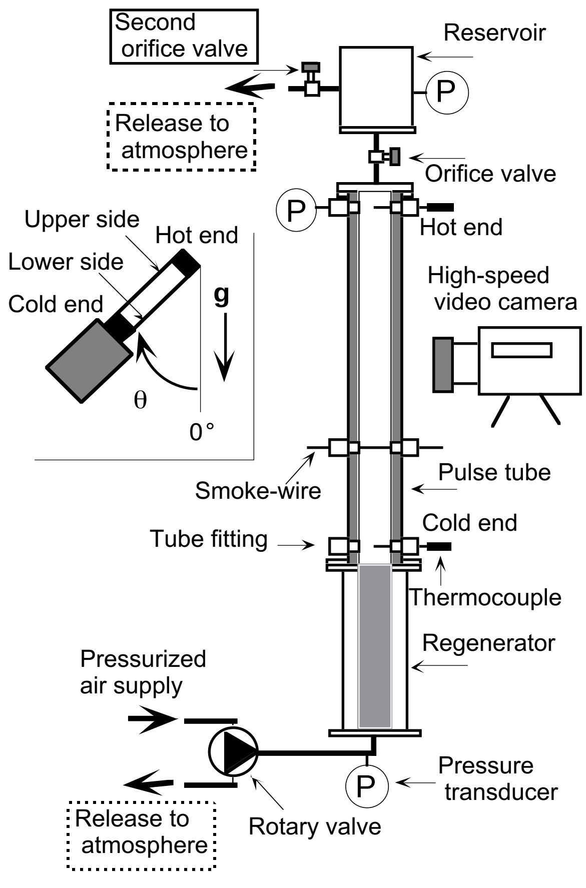

Figure 1 Schematic of the experimental apparatus used to visualize flow in an inclined orifice pulse tube refrigerator with a second orifice valve. The second orifice valve released air to the atmosphere, thus inducing additional DC flow toward the hot end through the pulse tube. Inset shows the definition of inclination angle θ.

EXPERIMENT

Figure 1 shows the experimental apparatus used to visualize oscillating flow in an orifice pulse tube refrigerator at various θ and to measure the gas temperature at the cold and hot ends. Details of the apparatus are described elsewhere [3]. In brief, the pulse tube was made of transparent plastic and was 16 mm in diameter and 320 mm long. The regenerator was made of #100 stainless-steel screen and was 18 mm in diameter and 170 mm long. The volume of reservoir was about 10 times larger than that of the pulse tube. The first orifice valve connected the hot end of the pulse tube to the reservoir, and the second orifice valve was fitted to the reservoir and had its outlet to the atmosphere. Thus, a pressure oscillation of air as the working gas was generated between the high pressure of the pressurized air of about 0.2 MPa and the low pressure of the atmosphere by introducing pressurized air into the rotary valve during the compression phase and releasing it into the atmosphere during the expansion phase. The second orifice valve released air from the reservoir into the atmosphere, generating an additional DC flow toward the hot end through the pulse tube. Each valve was fully open after 6 turns of the valve, and each turn was graduated into 25 divisions, thus totaling 150 "turn-divisions" at the fully open position. The valve opening was expressed in these divisions as arbitrary units; Vo and Vso are openings of the first and second orifice valves, respectively. Thermocouples were installed at the cold and hot ends to measure the gas temperature. Three pressure transducers were respectively installed near the warm end of the regenerator, at the hot end of the pulse tube, and in the reservoir. The smoke-wire was a 0.1-mm-diameter tungsten wire. Both ends of the wire were soldered to copper supports acting both as electrodes and as supports to keep the wire taut, and the wire was tightened by using the tube fittings located about one-third of the pulse-tube length from the cold end.

Suitable experimental conditions were determined based on the results of preliminary experiments; frequency was 6 Hz, amplitude of the pressure wave (defined as the compression ratio between the high and low pressures) was 1.2, and Vo was set at 10 turn-divisions to maximize the cooling performance at $\theta = 0°$ with a closed second orifice valve [4]. Visualization was done by increasing Vso in intervals of 10 turn-divisions up to a maximum 30 turn-divisions. Then, the visualization and the evaluation of cooling performance (i.e., gas temperature measurement) were done under these conditions at five different θ (0°, 90°, 120°, 150°, and 180°) typical for inclined pulse tube refrigerators. The movement of the smoke-line was recorded for more than five cycles by using a high-speed video camera with a frame rate of 400 frames/sec.

RESULTS AND DISCUSSION

Here, only the results for $\theta = 120°$ are presented because this angle is one of the best angles to evaluate the effectiveness of this approach in the inclination region where the effect of θ on cooling performance is strongest. Figure 2 shows typical visualization results for Vso = 0 turn-divisions (i.e., second orifice valve was closed) for the oscillation of the smoke-line during the first three cycles of oscillation as representative results. The smoke-line was emitted at the moment when the flow direction changed (due to a pressure oscillation) from expansion to compression in the cycle. Frames 1-5 show smoke-lines at three representative points in a cycle (explained in the figure caption). The smoke-line near the wall was elongated toward the hot end, while the smoke-line in the core region lagged toward the cold end. The smoke-line profiles gradually became asymmetric in which the leading edge of the smoke-line in the core region drifted toward the upper side wall of the pulse tube (left side of each frame) due to the gravity-driven secondary flow [3].

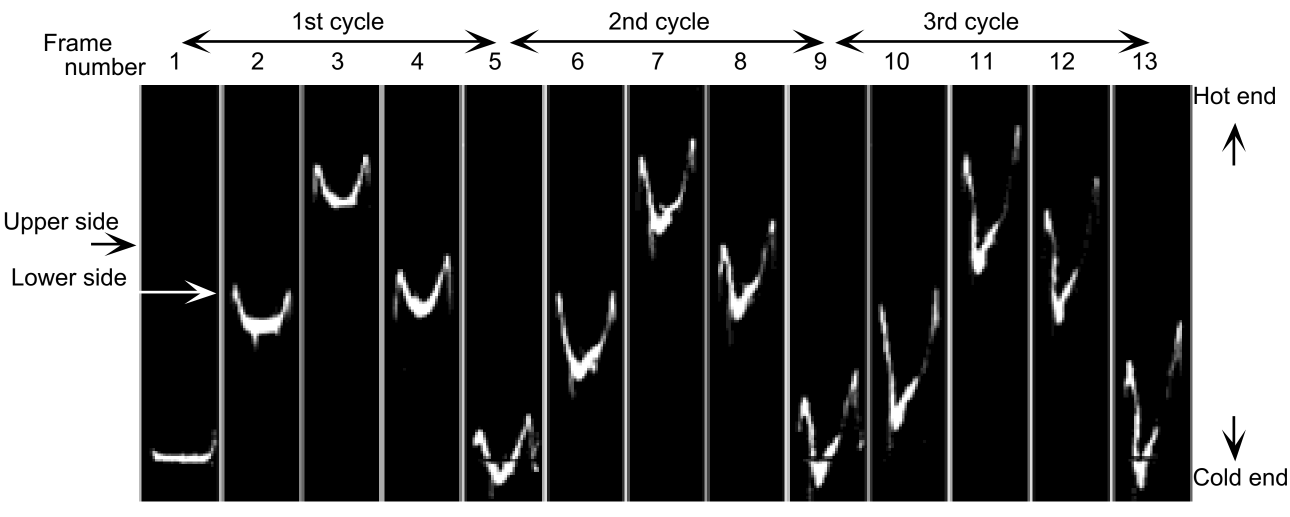

Figure 2 Typical visualization results for Vso = 0 turn-divisions (closed second orifice valve) during the first three cycles at $\theta = 120°$. Left and right sides of each frame correspond to the upper and lower side-walls of the pulse tube, respectively (see Fig. 1). The top and bottom of each frame are towards the hot and cold ends of the pulse tube, respectively. The smoke-line was emitted at the moment when the flow direction changed (by a pressure oscillation) from expansion to compression in a cycle: just after the smoke-line was emitted (Frame 1), at the turning point of the hot end where the smoke-line changed its direction of motion (Frames 3, 7, and 11), at the turning point of the cold end (Frames 5, 9, and 13), and halfway between these turning points (Frames 2, 4, 6, 8, 10, and 12).

The effect of Vso on the secondary flow was evaluated based on the smoke-line at the hot-end turning point (see caption of Fig. 2) of every cycle, assuming that the change in the smoke-line shape before and after a cycle was due only to secondary flow. Figure 3 shows the smoke-lines at the hot-end turning point for Cycles 1, 3, and 5 for Vso = 0, 20 and 30 turn-divisions. In the figure, three representative points on the smoke-line are marked A, B and C (in the frame for Vso = 0 turn-divisions and cycle 5), corresponding to the leading edges in the core region, near the upper wall, and near the lower walls, respectively. When the second orifice valve was closed (Vso = 0 turn-divisions), the smoke-line was elongated toward both sides of the cold end (downward) and hot end (upward), while its center remained at the initial position seen for Cycle 1. In contrast, when the second orifice valve was open (Vso > 0 turn-divisions), the smoke-lines for Vso = 20 and 30 turn-divisions were less elongated in the axial direction than that when the valve was closed (Vso = 0 turn-divisions), as evidenced by the distance between the leading edges of the smoke-line in the core region (A) and near the walls (B and C). This less elongation indicates that the secondary flow for Vso = 20 and 30 turn-divisions was slower than that for Vso = 0 turn-divisions. Moreover, for Vso = 20 turn-divisions, the leading edge in the core region (A) roughly remained as it was at the position of cycle 1, and for Vso = 30 turn-divisions, the leading edge in the core region (A) gradually shifted toward the hot end with time as seen from the change in the position of the leading edge.

From the smoke-lines in Fig. 3, we evaluated the velocities of the representative points A, B, and C on a smoke-line as V-core, V-upper, and V-lower, respectively. Here, negative and positive velocities in the figures correspond to flows going towards the cold end and hot end, respectively. Figure 4 shows the result. With increasing Vso, V-core monotonously changed from negative to positive velocity when Vso was between 20 and 30 turn-divisions, and therefore the absolute value of V-core was minimum when Vso was between 20 and 30 turn-divisions. In contrast, V-upper and V-lower had only positive values, indicating that the flow was only toward the hot end.

To clarify the effect of secondary flow on gas temperatures at the cold end (Tg-cold) and hot end (Tg-hot), the measured Tg-cold and Tg-hot were plotted together with V-core in Figure 5. Also plotted in the figure is the difference in these two temperatures (i.e., Tg-diff = Tg-hot - Tg-cold) by which the cooling performance was evaluated. Each temperature was normalized by the difference from its respective temperature for Vso = 0 turn-divisions. With increasing Vso up to about 10 turn-divisions, Tg-cold decreased and then increased, while Tg-hot increased slightly (compared to Tg-cold) and then decreased. Thus, Tg-diff (the cooling performance) increased with increasing Vso, peaking when Vso approached 10 turn-divisions, and then decreased, indicating that the cooling performance was improved when Vso was around 10 turn-divisions.

This result can be explained as follows. When the second orifice valve (Vso) was opened to about 10 turn-divisions, an additional DC flow appeared in the pulse tube. In the core region, this induced flow counteracted the convective secondary flow, causing a decrease in V-core, thus decreasing the flow to the cold end. Because this decrease in flow to the cold end also decreased the heat transfer, the gas temperature decreased at the cold end and increased at the hot end. Thus, the cooling performance improved, as revealed by an increase in Tg-diff. In contrast, when Vso was further increased to more than 10 turn-divisions, although the absolute value of V-core remained lower than that near Vso = 0 or 30 turn-divisions, the gas temperature increased at the cold end and decreased at the hot end. As a result of this change in gas temperatures, the cooling performance degraded, as evidenced by a decrease in Tg-diff. The additional DC flow

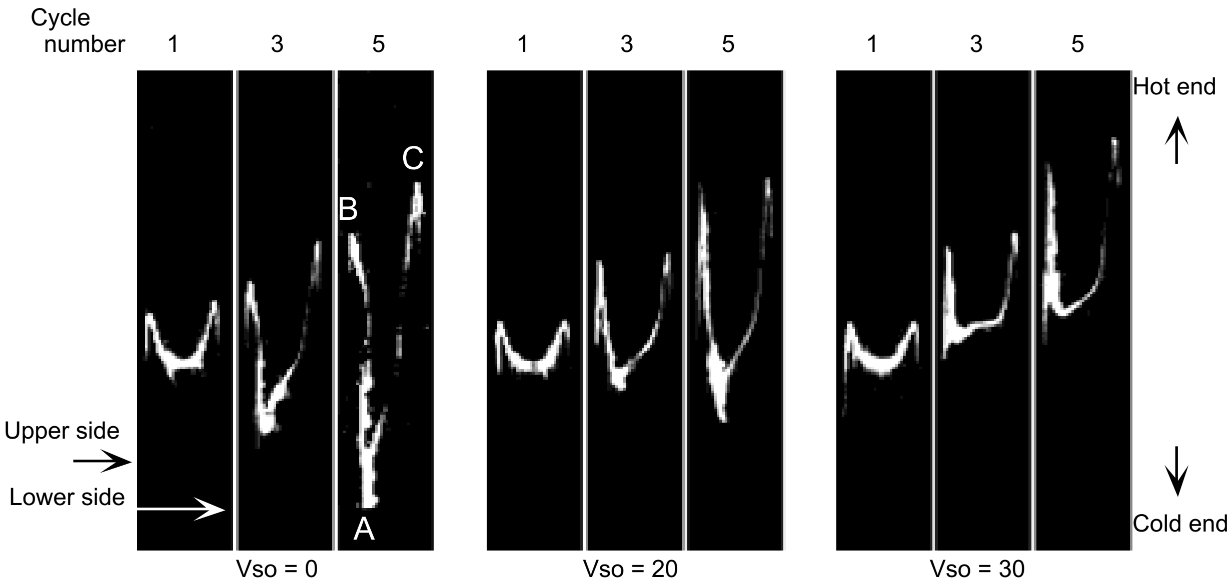

Figure 3 Smoke-lines at the turning point of the hot end for three representative cycles (Cycles 1, 3, and 5) for Vso = 0, 20, and 30 turn-divisions and θ = 120°. Marks A, B, and C in the figure indicate representative points on the smoke-line.

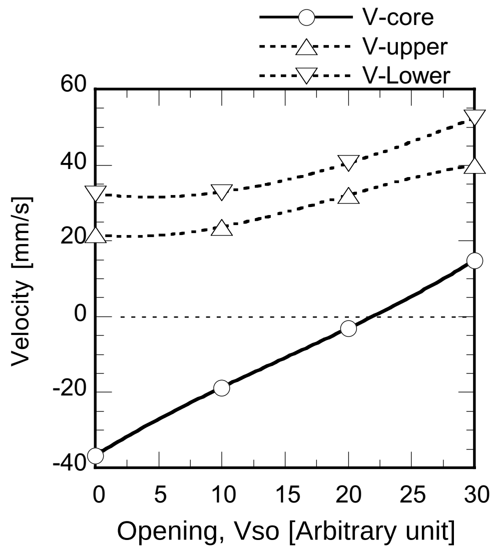

Figure 4 Effect of orifice opening (Vso) on flow velocities (V-core, V-upper, and V-lower) in a pulse tube refrigerator at θ = 120°. Velocities were obtained from the change in points A, B, and C, respectively, in Fig.3. Positive and negative values of velocity correspond to flow to the hot and cold ends, respectively.

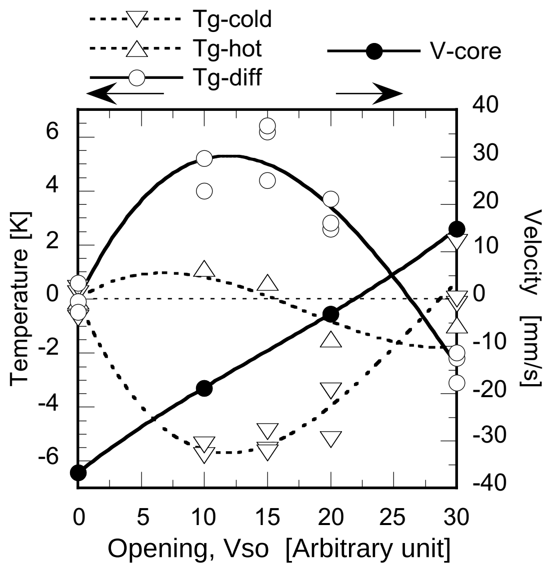

Figure 5 Gas temperatures at the cold and hot ends (Tg-cold and Tg-hot, respectively), gas temperature difference (Tg-diff) between the hot and cold ends (as an indicator of cooling performance), and V-core versus Vso at θ = 120°. Each temperature was normalized by difference from respective temperatures for Vso = 0 turn-divisions.

caused V-core to decrease, and caused the flow to the hot end to increase, as revealed by the increase in V-upper and V-lower (Fig. 4). The flow to the hot end transported fluid that had a relatively lower temperature compared to the hot-end temperature, and thus the increase in this flow caused a decrease in the hot-end temperature. Moreover, because the additional DC flow passed through the refrigerator, it introduced additional heat loss to the cold end where heat was transferred through the regenerator by the additional DC flow. Therefore, too large an increase in the DC flow, such as when Vso > 20, causes an increase in the gas temperature at the cold end and a decrease at the hot end, thus degrading the cooling performance.

Vso for maximum Tg-diff (i.e., Vso ~12 turn-divisions estimated from Fig. 5), and thus maximum cooling performance, did not coincide with that for V-core = 0 mm/s (Vso ~22 turn-divisions estimated from Fig. 5). V-core corresponds to the maximum velocity of a velocity profile of the secondary flow in the core region, whereas heat transfer from the hot end to the cold end by the flow in the core region depends on its mass flow rate. This mass flow rate roughly varies as $(\text{V-core})^3$, if the velocity profile is assumed a conical profile. Consequently, with increasing Vso, heat loss by the heat transfer abruptly decreases compared to a decrease in V-core. Therefore, the optimum second-valve opening for cooling performance, namely, an optimum Vso ~12 turn-divisions (estimated from Fig. 5) was much lower than Vso for V-core = 0 mm/s.

SUMMARY

The effectiveness of using an additional DC flow to reduce convective heat losses in inclined orifice pulse tube refrigerators was studied by clarifying how an additional DC flow affects convective heat losses. Results revealed that the gas temperature decreased at the cold end and increased at the hot end by decreasing the convective secondary flow to an optimum level in the core region generated by the additional DC flow, and that the gas temperature increased at the cold end and decreased at the hot end when the additional DC flow exceeded this level. These results confirmed that convective heat loss can be effectively reduced by using an additional DC flow, if the level of the flow is optimized, and that the cooling performance of the refrigerator can thereby be improved.

REFERENCES

1. Olson, J. R. and Swift, G. W., Acoustic streaming in pulse tube refrigerators: tapered pulse tubes, Cryogenics (1997) 37, 769-776.
2. Thummes, G., Schreiber, M., Landgraf, R.and Heiden, C., Convective heat losses in pulse tube coolers: Effect of pulse tube inclination, Cryocoolers 9, Plenum Press, New York, (1997) 393-402.
3. Shiraishi, M., Fujisawa, Y., Murakami, M. and Nakano, Reduction of the Effect of Secondary Flow in Inclined Orifice Pulse Tube Refrigerators by Additional DC Flow Generated by a Second Orifice Valve, Advances in Cryogenic Engineering 49, American Institute of physics, New York, (2004), (*to be published*).
4. Shiraishi, M., Takamatsu, K., Murakami, M. and Nakano, Visualization study of secondary flow in an inclined pulse tube refrigerator, Advances in Cryogenic Engineering 45, Kluwer Academic/Plenum Publishers, New York, (2000) 119-125.