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Research Paper

A novel shell-tube water-cooled heat exchanger for high-capacity pulse-tube coolers

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HIGHLIGHTS

- A novel shell-tube water-cooled heat exchanger is proposed.
- The shell-tube heat exchanger achieves better heat-transfer performance.
- Temperature uniformity has significant effects on global cooling performance.

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ABSTRACT

Large-capacity pulse-tube coolers are considered promising candidates for applications in high-temperature superconductivity technology, small gas liquefiers, and cryogenic storage tanks. This paper introduces a novel shell-tube heat exchanger particularly designed for such a cooler. In one heat-transfer subunit of this configuration, several small-diameter copper tubes are welded inside a large-diameter tube. This heat exchanger is characterized by small hydraulic diameter, high porosity and uniform gas temperature distribution. To verify its performance, a numerical simulation was first carried out to compare the temperature distributions of the shell-tube and plated-fin configurations. Experiments were then conducted to investigate their cooling performance. According to the experimental results, the shell-tube heat exchanger achieved better heat-transfer performance, especially with large input power. The gas temperature at the inlet of the heat exchanger and the temperature gradient in the regenerator were significantly decreased in the novel shell-tube design, which further demonstrated its better performance.

1. Introduction

Since Gifford and Longsworth first introduced pulse-tube refrigerators in 1966 [1], Stirling-type pulse-tube coolers have attracted wide attention. Unlike conventional cryocoolers, such as Gifford-McMahon cryocoolers and Stirling coolers, pulse-tube coolers contain no moving parts at the cold head and are characterized by high reliability, high efficiency, and compact size. The Stirling-type pulse-tube cooler was initially used mainly in infrared detectors that required a cooling power of less than 10 W. Recently, with the large demand for small gas liquefiers, cryogenic storage tanks and high-temperature superconductivity (HTS) devices, such coolers with high-capacity cooling powers (100 W to 1 kW), which generally work in the temperature range of liquid nitrogen, are urgently needed. In 2003, a pulse-tube cooler capable of providing a cooling power of 200 W at 80 K was successfully developed by Zia [2]. A later version, with an improved cold head, achieved a cooling power of 300 W with an exergy efficiency of 19.2% [3]. In 2007, Praxair Inc. reported a pulse-tube cooler that produced a cooling power of 1100 W at 77 K [4]. Two sets of such coolers were installed in parallel to provide cryogenic environments for HTS cable [5]. Recently, a high-efficiency coaxial pulse-tube cooler was proposed, which offers more than 520 W cooling power at 80 K with an overall exergy efficiency of 18.2% [6].

The water-cooled heat exchanger (WCHX) is the core component in a pulse-tube cooler that is responsible for removing heat from the system. Many researches focus on heat transfer mechanism or new exchanger configuration [7–13]. Generally, plated-fin WCHXs (shown in Fig. 1(b)) are widely used in small-capacity pulse-tube coolers because of their compact size and easy processing [14]; however, with large amounts of transferred heat, it is easy to cause a large temperature difference across a long fin,

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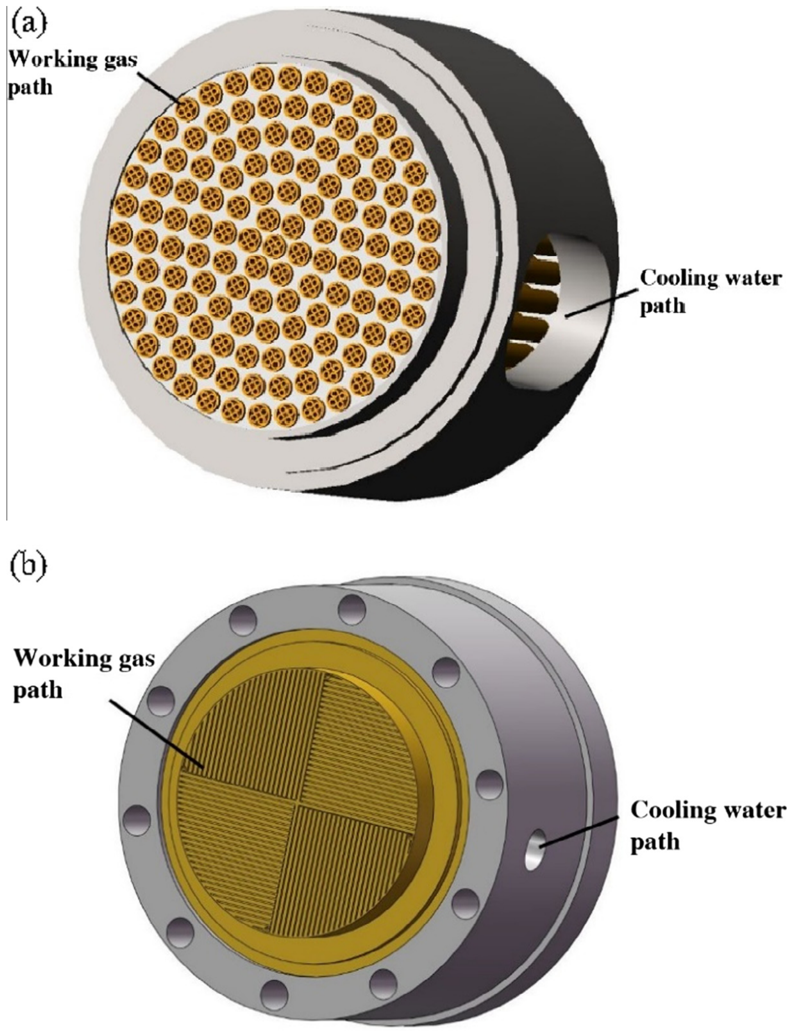

Fig. 1. Schematic diagram two types of heat exchangers: (a) shell-tube type; (b) plated-fin type.

which will lead to a large temperature difference between the gas and the cooling water. The gas-water temperature difference in the main WCHX is reported to reach as high as 50 K [6] or 57 K [15]. As a result, more effort is required for the gas to pump the heat, thereby degrading global cooling performance. To solve this problem, a shell-tube WCHX is a good choice, owing to its more uniform gas temperature distribution [16]. A conventional shell-tube configuration is generally formed by many regular tubes. Unfortunately, it is difficult to simultaneously ensure a small enough hydraulic diameter and high enough porosity. Taking a frequency of 50 Hz as an example, the helium gas thermal penetration depth (a characteristic length defined as $\sqrt{2\kappa/\omega}$, which tells how far heat can diffuse laterally during a time interval of the period of the oscillation divided by π. κ is the thermal diffusivity of the gas and ω is the angular frequency) is less than 0.5 mm, so the hydraulic diameter (four times of the ratio of flow area to wetted perimeter) of each tube should be controlled to as small as 1 mm to fully exchange heat. Unfortunately, it was found that the highest porosity attained under these conditions was often less than 12%, even if the tubes were closely arranged. This regular-tube design also has an insufficient heat-exchange area on the gas side. It is because the heat-transfer coefficient on the gas side is more than an order of magnitude lower than that on the water side, whereas the heat-transfer areas of the two sides are almost the same in this regular-tube design. Therefore, the heat-exchange area of the gas side should be increased. One feasible way is to add rectangular fins inside the tubes, but with present machining process technics, it is hard to produce such fins in a small hydraulic-diameter tube.

A novel shell-tube WCHX is therefore proposed to solve these problems in this paper. This novel configuration consists of a few hundred pipes, within each of which are several small-diameter tubes. In the following sections, this configuration is detailedly introduced, and a comparison with a typical plated-fin WCHX is made.

2. A novel shell-tube heat-exchanger

2.1. Configuration

Fig. 1(a) presents schematic diagram of the novel shell-tube WCHX. Each large-diameter copper tube contains four small-diameter copper tubes that act as heat-transfer fins. By adjusting the number and diameter of the smaller-diameter tubes, enough heat-exchange area at the gas side and a small enough hydraulic diameter can be obtained. Moreover, porosity of the heat exchanger can be changed in a wide range by adjusting the wall thickness and number of the small-diameter tubes. As a result, this novel design can simultaneously ensure a small enough hydraulic diameter and high enough porosity.