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Research paper

Experimental investigation on pressure drop and friction factor of slush nitrogen turbulent flow in helically corrugated pipes

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ABSTRACT

Experiments were performed to investigate the pressure drop and friction factor for turbulent slush nitrogen in helically corrugated pipes. Comparison of pressure drops of slush nitrogen and subcooled liquid nitrogen shows no significant difference between the solid-liquid fluids and single phase turbulent flows in the corrugated pipes and the influence of particle concentration on pressure loss of slush nitrogen pipe flow is negligible. An improved experimental empirical correlation for the friction factor of slush nitrogen in corrugated pipes with the slush Reynolds number in the range of $2 \times 10^4 \leqslant Re_{sl} \leqslant 1.7 \times 10^5$ has been obtained, which takes the structural parameters (i.e., inner diameter and pitch) of the corrugated pipes as well as the fluid flow conditions into consideration. With the increasing slush Reynolds numbers, the friction factor of slush nitrogen in corrugated pipes increases, while the trend for the smooth pipe shows a contrary dependence. Moreover, the friction factor increases very slightly with the solid fraction. It can be concluded that the slush nitrogen with a solid fraction up to 20% still has comparable fluidity performance with the subcooled liquid nitrogen in the helically corrugated pipes.

1. Introduction

Cryogenic slurry fluids such as slush hydrogen and slush nitrogen have drawn much attention due to the higher density, lower temperature and higher heat capacity than those of the normal boiling point liquid fluids, which can contribute to alternatives for applications such as fuels of spacecrafts and coolants of high temperature superconducting (HTS) cables. Taking slush nitrogen as an example, superior to the normal boiling temperature of liquid nitrogen which is generally used to cool the high temperature superconductive materials, it can help to reduce the quenching risk and to decrease the size of cooling system and the coolant cost of transport and storage [1–3]. The coolant transfer tubes are very complex components of the HTS cables as they must meet severe thermal, structural, and containment integrity requirements for a cryogenic system [4–6]. Fig. 1 shows the typical structure of a HTS cable. The main body for the coolants transfer lines are usually stainless steel corrugated pipes, which can help to improve the overall thermal-hydraulic performance and flexibility of the cooling system of HTS cables [7–10].

Different methods for predicting the flow performance in corrugated pipes have been proposed. Hawthorne and Von Helms [11] derived a semi-empirical correlation for calculating the friction factor of corrugated pipes based on the structural parameters as follows

$$f = \frac{d}{s}\left[1-\left(\frac{d}{d+\gamma s}\right)^2\right]^2 \tag{1}$$

where f is the friction factor. d is the inner diameter of corrugated pipe, and s is the pitch of the corrugated wall. γ is the experimental empirical coefficient, depending on the working conditions of the corrugated wall and is taken as 0.438 for water and air at the ambient temperature. It is worth noting that the friction factor in this correlation is determined only by the structural parameters of corrugated pipes, while not affected by the flow velocity and the physical features of fluid.

Kauder [12] developed an experimental empirical correlation for corrugated pipes, as given

$$\ln F = 6.75 + 4.13\ln\left(\frac{t}{d}\right) + \left[230\left(\frac{t}{d}\right)^{2.1} - 0.7\right]\ln\left(\frac{t}{s}\right) + 0.193\exp\left[-3300\left(\frac{t}{d}\right)^{2.6}\left(\frac{t}{s}\right)\right]\ln Re \tag{2}$$

where F is the Fanning friction factor, Re is the Reynolds number and t is the height of the corrugations. However, the Kauder correlation is based on the limited parameter ranges $0.0455 \leqslant t/d \leqslant 0.0635$ and $0.2 \leqslant t/s \leqslant 0.6$, while the corrugated pipes with $t/s \leqslant 0.2$ were regarded as smooth pipes with the diameter of d.

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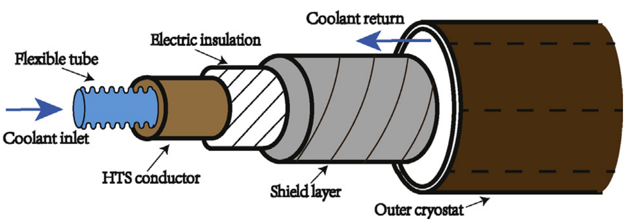

Fig. 1. Schematic of typical HTS cables.

Daniels and Cleveland [13] suggested a graphical method for predicting the friction factor based on the corrugation height, the inner diameter and the Reynolds number. It was claimed that the friction factor could be regarded constant for $Re \leqslant 5 \times 10^4$ and increased slightly with the Reynolds number when $5 \times 10^4 < Re \leqslant 1.5 \times 10^6$, and then became constant for $Re > 1.5 \times 10^6$. O'Brien and Sparrow [14] concluded that the friction factor was barely dependent on the Reynolds number (when $1.5 \times 10^3 < Re \leqslant 2.5 \times 10^4$), indicating that the pressure drop was solely caused by inertial losses. Weisend II and Van Sciver [15] conducted experiments on some cryogenic fluids (i.e., nitrogen gas, liquid nitrogen and He II) flowing through the corrugated bellows for the Reynolds number of 4×10^6, and they claimed that there was no essential difference between the behaviours of classical fluids and super fluid (He II) in the corrugated pipes and the friction factors appeared to increase slightly with increasing Reynolds number, which is consistent with the conclusions of Daniels and Cleveland [13].

To design and optimize the cooling system for HTS cables, the friction characteristics of the coolants pipe flow are some of the key performance indicators. Li et al. [5] compared the flow pressure drop of liquid nitrogen at 65 K in corrugated pipe with that in smooth pipe for HTS cables. According to the experimental and simulation results, the flow resistance of liquid nitrogen gradually increases as the pitch of the corrugated pipes decreases and the wave depth increases. The flow resistance coefficient in corrugated pipes was claimed to be at least three times as large as that in smooth pipes.

So far, the experimental researches on slush nitrogen and slush hydrogen flows have mainly been focused on the cases for the horizontal pipes. Takakoshi et al. [16] investigated the particle velocity distribution profiles of slush nitrogen in a horizontal pipe to observe the flow pattern evolution of slush nitrogen by PIV method. Jiang et al. [17] and Jin et al. [18] conducted experiments on slush nitrogen flow in a horizontal circular pipe, trying to improve the experimental empirical correlations for the friction factor of slush nitrogen. However, very few studies have been done on the cryogenic slurry flows in corrugated pipes. Ohira et al. [1,19,20] studied the pressure drop of slush nitrogen flow in the horizontal circular, corrugated and converging-diverging pipes, and found that the pressure drop reduction phenomenon (i.e., the pressure drop for slurry flow can be lower than that of the subcooled liquid) could occur for slush nitrogen under some certain operating conditions. When the solid weight fractions of slush nitrogen flow were the same, the pipe friction factor for corrugated pipe was found to be nearly constant regardless of different Reynolds numbers [19]. Sindt [21] studied the flow characteristics of slush hydrogen flow in ball valves, orifice plates and Venturi tubes, and found that the influence of particle fraction on flow resistance loss could be negligible. No further literatures have been found for the experimental investigations on the flow characteristics of cryogenic slurry fluids in a corrugated pipe.

The previous correlations for friction factor are mainly based on ambient single-phase fluids, such as water and air. The flow performance of slush nitrogen in corrugated pipes needs further investigation and a correlation applicable for cryogenic slurry flows in corrugated pipes is still absent. Moreover, the corrugated pipes used for experimental tests are mainly annular. Thus, the applicability of the existing correlations needs to be verified for different fluids and corrugations. In the present study, an experimental apparatus for the flow test of slush nitrogen in horizontal helically corrugated pipes has been built up. The pressure drops are measured for subcooled liquid nitrogen and slush nitrogen flows with the slush Reynolds number up to 1.7×10^5 and the solid volume fraction up to 20%. Comparing with the existing empirical correlations for corrugated pipes, the experimental results for the pressure drop and friction factor are discussed. An experimental empirical correlation for friction factor of slush nitrogen flow in corrugated pipes will be obtained.

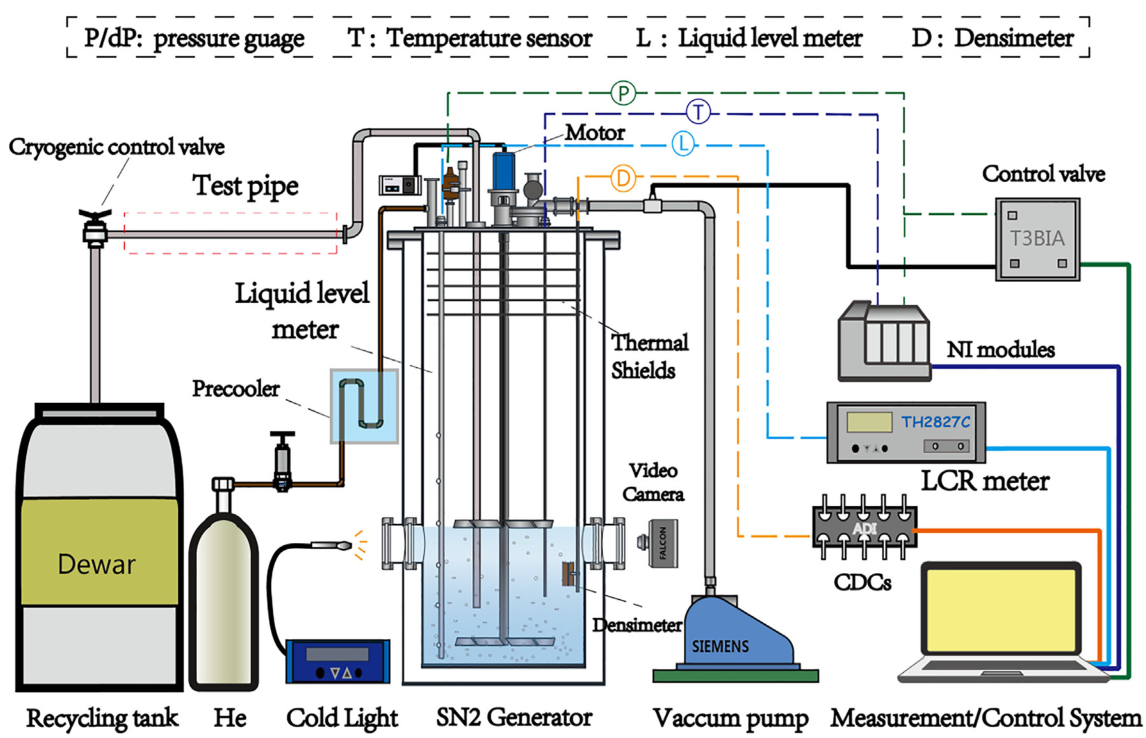

Fig. 2. Experimental apparatus for the flow test of slush nitrogen.