Effect of inserted HTS power transmission cables on friction loss in corrugated pipes

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Abstract. Pressure drop behavior of cryogenic flow in corrugated pipes is one of the most important design parameters for high temperature superconducting (HTS) power transmission line systems. Most studies on pressure loss and temperature rise study the liquid nitrogen flow in annularly corrugated pipes focused on the pipe geometries. However, the positioning and configuration of the HTS cables in the corrugated shell tube are of great concern in practical application. In addition, helically corrugated pipes are more popular than annular ones for long distance deployment of HTS transmission lines. This paper focuses on the influence of inserted cable configuration in helically corrugated pipes on the surrounding subcooled liquid nitrogen flow. Triple and quadruple cables with diameters of 5 mm and 8 mm configured in different forms in a Φ40 mm helically corrugated pipe are comparatively studied with a 3D model. Results show that the Darcy friction factor is related to the pitch of the cables. The gaps and the cable size will directly influence the level of friction loss in the pipe.

1. Introduction

High temperature superconducting (HTS) power transmission lines are regarded as a promising solution to the future power grid. HTS cables only work at cryogenic temperatures and are normally immersed in cryogens. Liquid nitrogen is the most competitive fluid for HTS application\(^1\) because of its proper boiling temperature, superior economic benefits, and high safety. Vacuum jacketed corrugated pipes are widely used as the liquid nitrogen carrier for keeping the HTS cable safe against thermal intrusion, contraction stress at low temperatures, and mechanical damage by collision and bending. However, the corrugation of the shell pipe itself and the inserted cable makes the LN\(_2\) flow completely different from that in plain pipes. In addition to the flow resistance caused by the peaks and valleys on the internal surface wall, the helical structure of wire spins of the fluid and creates a longer flow path. In other words, the flow in corrugated pipes along with cable insertion is much more complicated. Meanwhile the deployment of the HTS cable should carefully consider the distance between two adjacent stations and the pressure head of the cryogenic pump, for which the pressure drop behavior in such corrugated pipes is a key design parameter.

Early studies on flow in corrugated pipe were mainly directed towards water and air, in particular focusing on the heat transfer enhancement by the corrugated structure \(^2\). With the development of HTS cable technology, liquid nitrogen flow in corrugated pipes has caused extensive concern, which is significantly different from water in boiling temperature, latent heat,
and viscosity. Table 1 gives some typical correlations in the explicit form of Darcy friction factor \( f \) for the classical Darcy’s Law applied to corrugated pipes. The symbol \( Re \) stands for Reynolds number, \( d \) is the mean diameter of the corrugated pipe, \( e \) is the distance between peak and valley, \( p \) is the pitch, \( d_h \) is the hydraulic diameter, \( \epsilon \) is the roughness of the shell, \( d_i \) is the inner diameter.

### Table 1. Typical correlations for flow in corrugated pipes.

| Author          | Year | Method | Fluid | Correlation                                                                 | Reynolds number |
|-----------------|------|--------|-------|----------------------------------------------------------------------------|-----------------|
| Kauder et al. 3 | 1974 | Exp.   | H₂O   | \( f = Re^{0.14 \pm 0.02} \)                                               | 0 ~ 1E5         |
| Weisend et al. 4| 1990 | Exp.   | He    | \( f = Re^{0.12 \pm 0.02} \)                                            | 8E4 ~ 1.5E5     |
| Fuchino et al. 5| 2001 | Exp.   | N₂    | \( f = 0.096Re^{-0.2} - 0.32 \)                                         | 5E3 ~ 2E4       |
| Lee et al. 6    | 2003 | Sim.   | N₂    | \( 1/\sqrt{f} = 2.5\ln(d/2e) - 3.75 + 0.95(p/e)^{0.53} \)          | 1E4 ~ 8E5       |
| Koh et al. 7    | 2004 | Exp.   | N₂    | \( f = 2.60(e/d)^{1.08}(p/d)^{-0.57} \)                                 | 1E4 ~ 4E4       |
| Sasaki et al. 8 | 2011 | Sim.   | N₂    | \( 1/\sqrt{f} = -\log(e/(25d_h)) + 18.7/(Re\sqrt{f}) - 2\log(5.75(1 - e/d_h)) \) | 6E3 ~ 2E4       |

2. Physical and numerical Model

Darcy’s law describes the pressure loss in a plain pipe, written as,

\[
\Delta P = f \frac{L}{d_h} \rho \frac{v^2}{2}
\]

where \( L \) is the length of the pipe, \( d_h \) is the hydraulic diameter, \( v \) is the mean velocity and \( f \) is the Darcy friction factor. Hydraulic diameter is adopted to consider the effect of the insertion of the cables. The hydraulic diameter is calculated as

\[
d_h = \frac{4 \times A}{P} = \frac{d_o^2 - Nd_c^2}{d_o + Nd_c}
\]

where \( A \) is the cross sectional area, \( P \) is the wetted perimeter of the cross section, \( N \) is the number of inserted cables, and \( d_c \) is the diameter of the cables. Darcy friction factor is related to Reynolds number. Reynolds number is the ratio of inertial forces to viscous forces. The insertion of cables reduces the flow area and adds extra no-slip wall boundary.

The pipe consists of three parts: the inlet, bellows and outlet part. The diagram of helically corrugated pipe is shown in Figure 1. Liquid nitrogen flows into the inlet with a set of velocities, and exits the pipe at the outlet with constant relative pressure of 0 Pa. The lengths of the inlet and outlet are \( S = 100 \text{mm} \), and the length of bellows part is \( L = 210 \text{mm} \). Pitch of the corrugations is \( p = 6\text{mm} \). Wave height of the corrugation is \( e = 2.5 \text{mm} \). Outer and inner diameter of the pipe are \( d_o = 40 \text{mm} \) and \( d_i = 35 \text{mm} \), respectively. Pitch of cable is labeled \( P \). Inserted cables share the same pitch and are spirally entangled. Coordinate system is shown in Fig. 1.

Fig 1 shows the cross section of the corrugated pipe, the number of inserted cables is set to 3 or 4, and the cables are evenly distributed along x axis. Little gaps exist between contiguous
Single phase simulations are done using a 3D hybrid mesh in ANSYS CFX. The temperature rise are small and the initial temperature is set to 70K, and far below saturation temperature, so evaporation is not considered. Physical properties of liquid nitrogen are obtained from NIST Refprop 9[9]. Shear Stress Transport (SST) model is used for simulating turbulence because its superiority in simulating spin flow. Uniform heat flux are applied on the cable surface and pipe wall. Convergence for convection and turbulence are set to be High Resolution with a residual target of $1 \times 10^{-4}$, which is enough for accuracy in this study.

3. Results and discussion

Examples of the pressure and velocity distribution in the pipe with three spiral cables inserted are shown in Fig. 3. Pressure decrease is a smooth process along the corrugated pipe. In fully developed region, the pressure drop in the bellows part is significantly larger than that in plain part of the inlet and outlet. The pressure profiles are similar with different cable geometries. Fully developed flow is reached in the pipe as liquid nitrogen mainly flows outside of the cable region. However, the velocity is not zero between the cables, which means, despite being weak, there is liquid nitrogen flow in the gaps between the cables.

To study the influence of changing the cables from straight to spiral inside the pipe, a comparison of pressure drop and friction factor between cases with straight cables and three...
cables with 75 mm pitch is shown in Fig. 4. The solid symbols represent pressure drop with unit of Pa/m. Hollow labels represent calculated Darcy friction factor. The trend for both pressure and friction factor in the cases are the same. Friction factor slightly increases as Reynolds number increases. Pressure drops both agree well with the 2nd order polynomial correlation. However, the friction factor with spiral cables is 15.2% higher than that with straight cables. It is also noticeable that as Reynolds number increases, friction factors with spiral cables experience a little fluctuation while that with straight cables increase smoothly.

![Figure 4](image-url)

**Figure 4.** Comparison of pressure drop and friction factor between straight cable and spiral cables with a 75 mm pitch.

Fig. 5 presents the comparison of friction factors with a change of cable geometry. In Fig. 5(a), the cable number is three and the diameter of the cables is 5mm. In contrast, in Fig. 5(b), four cables with the diameter of 8mm are inserted in the pipe. Both the cable size and the pitch of the cables have influence on the friction factor. In both cases, when the pitch of the cables decreases, the friction factor get higher. For different reasons, in three cables’ case, with the reduction in pitches, the flow resistance in the gaps get higher, and the friction factor gets higher. In four cables’ case, the inserted cables are the largest in simulated cases, and the flow in the corrugations is affected by the inserted cables. As the pitch of the cables decreases, the liquid nitrogen near the pipe wall is disturbed. Therefore, a vortex appears and the friction factor increases. Based on the results, 20% reduction in flow area will bring a 55% increase in the friction factor.

The discussion in the previous section also explains why friction factor first increases in Fig. 5(a) and decreases in Fig. 5(b). In Fig. 5(a), flow resistance in the gap and the center hole is a large part of the friction losses. When the mass flow rate increases, the gap flow encounters larger resistance. Therefore, the friction factor will increase when Reynolds number increases. In contrast, Fig. 5(b), the gap only makes up a small partition of the contact line between liquid nitrogen and the wall surfaces. And the friction loss is related to viscous sublayer both on the pipe wall and the cables surface. As Reynolds number increases, the sublayer gets thicker and the friction factor decreases. When the Reynolds number is larger than 300, the fluid is fully developed, and the friction factor remains a constant value.

4. Conclusions

In this paper, we studied the influence of inserted of cables on the pressure drop in a corrugated pipe by CFD simulations. Number, diameter and pitch of the cables are
parametrically studied with a 3D model. Based on simulation results, the following conclusions can be drawn:

(i) Pressure drop in the bellows part is significantly larger than that in the plain part.
(ii) The insertion of cables will increase the friction factor in the pipe. When the cables are spiral, the friction factor will be further increased by 15.2%.
(iii) The pitch and the size of the cables influence the friction factor. With the decrease in cable pitch, the friction increases. With the increase in cable size, the friction factor will increase. In simulated cases, a 20% increase in flow area will reduce the friction factor by 55%.

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