Flow characteristics and heat transfer performance of a multi-layer winding hose system: theory and experimentation

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Abstract. This paper investigates the flow characteristics and heat transfer performance of a multi-layer winding hose system (MLWH) that is widely used in double-wheel trench cutters. Numerical analysis with Fluent 15.0 was performed to investigate the laminar fluid flow characteristics for the multi-layer winding hose system, especially for the study the effect of the Reynolds number and radius of curvature on the fluid flow. The radius of curvature of the multi-layer winding hydraulic hose was gradually increased in the range of 1 to 3. The Reynolds number varied between 167 and 1510. According to numerical analysis, the curvature-induced centrifugal force is found to have a significant influence on pressure drop and heat transfer. An experimental platform was presented to simulate the working conditions for the multi-layer winding hose system and collect experimental data for comparison with numerical data. The results show that the flow characteristics and heat transfer performance of the multi-layer winding hose system is strongly influenced by the Reynolds number and radius of curvature.

1. Introduction

A curved piping structure, with a compact structure and better heat transfer performance, is widely used in industrial engineering systems such as refrigerating systems[1], solar energy systems[2], processing-industry systems[3-4], and engineering machinery systems[5]. In engineering machinery systems, high requirements exist for the length and curvature of the piping system; hoses which are commonly utilized a curved piping structure by winding the hoses onto a reel owing to their flexibility. Compared with straight piping structures, secondary flow will occur in curved structures and a curvature induced centrifugal will complex the kinetic energy, heat transfer and mass transfer problems of the working fluid in the curved structures.

In this paper, the hydraulic system of a double-wheel trench cutter is taken as an example. To accomplish the formed operations, multi-layer winding hoses are presented in practice. The MLWH is a kind of common curved pipe widely used in various industrial and engineering applications. As we all know, in the stream-line motion of a fluid in a curved pipe, the primary motion along the line of the pipe is accompanied by a secondary motion in the plane of the cross-section[6]. One of the special features of multi-layer winding flow can be recognized as secondary flow, which is formed with centrifugal force due to the curvature effect[7].
Ciofalo et al. [8] numerically investigated the gravitational and centrifugal buoyancy in helical coils. Akbaridoust et al. [9] studied the laminar, steady state flow in helical coils at constant wall temperature. Sheeba et al. [10] analyzed the heat transfer and flow characteristics in a helical coil and presented a correlation to predict the Nusselt number. Saleh et al. [11] analyzed the geometrical properties (different coil pitches and coil diameters) of helical wire turbulators and carried out a related experiment for Dean numbers more than 100. Dastmalchi et al. [12] numerically investigated the geometrical parameters and compared the predicted values to the experimental results. Wen et al. [13] studied the heat transfer performance of aviation kerosene in a vertical helical tube experimentally at supercritical pressure. The centrifugal secondary flow was proved to be the key factor for heat transfer enhancement. Kurnia et al. [14] evaluated heat transfer performances of helical coiled tube with different cross section (square, ellipse and circular). Naghibzadeh et al. [15] quantitatively studied the heat transfer performance and pressure drop problems for a helical pipe with a flattened cross section in several cases (with varying cross section geometry and Reynolds numbers. Omidi et al. [16] investigated the effects of a helical coil with a lobe cross section, by analysing the physical and geometrical parameters in a helical coil heat exchanger.

However, with the development of engineering machinery, the demands for an inconstant radius of curvature have increased.

Yoo et al. [6] performed a numerical analysis for a spiral coiled tube heat exchanger. The curvature effects on the pressure drop and heat transfer were found and the relationship among the friction factor, Nusselt number and Dean number were also discussed. Patil et al. [17] introduced a new dimensionless number R to describe the heat transfer phenomenon in helical pipes. Correlations were developed for thermal systems with spiral coils. Kurnia et al. [18] performed a numerical investigation of the heat transfer performance of a laminar non-Newtonian fluid with different configurations of square cross section. In addition, more attention was given to in-plane spiral type and conical spiral type structures. Khoshvaght et al. [19] investigated the flow characteristics and thermal performance of spirally-coiled twisted tube, which also proved that the twist-pitch and coil-pitch can influence the thermo-fluidic transport characteristics of the research objects. Sreedhara et al. [20] investigated the heat transfer performance of corrugated plate heat exchangers. At the same time, experiments were presented as well.

Although previous literatures for the spiral-coiled type of structure exist, more detailed investigation is required for a multi-layer winding hydraulic hose. Reference [5, 21-22] has already analyzed the heat transfer and flow characteristic of MLWH systems under turbulent flows. However, further research is needed. In this paper, simulations on the flow characteristics of the MLWH system in laminar flow are presented. An experimental platform is presented. Experimental data were obtained to compare the simulation data. The Reynolds numbers and curvatures are proved to effect the flow characteristics and the heat transfer performance.

The rest of this paper is organized as follows. In section 2, the numerical analysis of the MLWH is established. Section 3 designs an experimental analysis of the MLWH system. Simulation results are provided in Section 4. Finally, the conclusions and future works are shown in Section 5.

2. Numerical analysis

2.1. Modelling of a multi-layer winding hydraulic hose

As shown in Fig. 1, a single layer hydraulic hose (marked 1) is winded onto a reel (marked 2) with an Archimedean spiral. The hydraulic hose is controlled by rolling the reel clockwise and anticlockwise. If the reel is rolled clockwise, the free end of the hydraulic hose will be longer as marked by the red arrows in Fig. 1. Otherwise, the free end of the hydraulic hose will be shorter (marked by the green arrows in Fig. 1), if the reel is rolled anticlockwise.
According to the mathematical definition of Archimedean spirals, the mathematical model of the MLWH is established under polar coordinates in Equ.1. As shown in Fig. 1, the main parameters in Equ.1 are listed.

\[ \rho = a + R \theta \] (1)

where, \( \theta \) denotes the rotation angle of the reel, \( d \) represents the outer diameter of the hose, \( a = d_0 / 2 \pi \). \( R \) denotes the minimum radius of the reel, where \( \theta = 0 \).

The radius of curvature is defined as follows:

\[ R_k = \frac{1}{k} = \frac{\left( a^2 \theta^2 + 600a \theta + 90000 + a^2 \right)^{3/2}}{a^2 \theta^2 + 600a \theta + 2a^2 + 90000} \] (2)

where \( k \) denotes the curvature and \( k = \frac{(\rho^2 + 2\rho' \rho - \rho')}{(\rho^2 + \rho \rho')}. \)

2.2. Governing equations

Owing to the geometric effect of the MLWH systems, the flow characteristics in the MLWH vary considerably with different configurations. The Reynolds numbers are considered as the critical parameters and are set to 1600–2000 in this paper which is determined by the material of the hose. The chosen Reynolds numbers were substituted into Eq. (3) which was presented by Dravid et al. [22] and the curvature effects were taken into consideration in the calculation of the critical Reynolds numbers.

\[ Re = 1300 \left[ 1 + 8.6 \left( \frac{d}{2R} \right)^{0.45} \right] \] (3)

The critical Reynolds numbers were set within the field of \([2950, 3260]\). Correspondingly, the Reynolds number in the MLWH were set within \([167, 1510] \). Hence, the control equations in laminar flow are listed as follows:

Continuity equation:

\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0 \] (4)
where $u$, $v$, and $w$ represent the flow velocities in the axial, radius, and azimuthal directions respectively.

Assuming steady flow for the working fluid in the MLWH and $\frac{\partial \rho}{\partial t} = 0$, the continuity equation can be rewritten in the vector form and listed as follows:

$$\text{div}(\rho \mathbf{v}) = 0 \tag{5}$$

where $\mathbf{v}$ denotes the flow velocity. The matrix $\mathbf{v}$ can be rewritten as $\mathbf{v} = (u \ v \ w)$.

Momentum equation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{v} \tag{6}$$

where $\nu = \frac{\mu}{\rho}$, $\mu$ denotes the viscosity of the working fluid. $\rho$ represents the density of the working fluid.

2.3. Data reductions

Eq. (7) is presented to describe the relationship between the inlet velocity and the Reynolds numbers.

$$\text{Re} = \frac{\rho u_{in} d_h}{\mu} \tag{7}$$

where $\rho$ represents the density; $u_{in}$ denotes the oil inlet velocity; $\mu$ represents the dynamic viscosity; $d_h$ is the hydraulic diameter which is defined as below:

$$d_h = \frac{4A_t}{A_f} \tag{8}$$

where $A_t$ and $A_f$ denote the frontal surface area and the total surface area of the MLWH, respectively; $l$ denotes the length of the MLWH.

The Nusselt number is defined as below:

$$Nu = \frac{h d_h}{\kappa} \tag{9}$$

where $\kappa$ is the thermal conductivity; $h$ is the heat transfer coefficient.

$$h = \frac{Q}{A(T_{in} - T_{out})} \tag{10}$$

where $Q$ and $(T_{in} - T_{out})$ represent the heat transfer rate and the logarithmic mean temperature difference, respectively, which are written as below:

$$Q = mC_p(T_{out} - T_{in}) \tag{11}$$

where $T_{out}$ represents fluid temperature at outlet; $T_{in}$ represents fluid temperature at inlet

$$\left( T_{in} - T_{out} \right)_{log} = \frac{\Delta T_{in}}{\log \left( \frac{\Delta T_{in}}{\Delta T_{out}} \right)} \quad \left( T_{in} - T_{out} \right)^c = \frac{\Delta T_{in}}{\Delta T_{out}} \tag{12}$$
In the equations above, \( m \) is the mass flow rate; \( C_p \) denotes the specific heat capacity; \( T_w \) represents the average wall temperature for the MLWH; \( T_{inw} \) represents the inlet wall temperature for the MLWH; \( T_{outw} \) represents the outlet wall temperature for the MLWH.

The friction factor is obtained as below:

\[
f = \frac{2\Delta p}{\rho u^2}
\]

(13)

where \( \Delta p \) denotes the pressure drop between the inlet and outlet parts of the MLWH system and is listed as follows:

\[
\Delta p = p_{in} - p_{out}
\]

(14)

2.4. Numerical simulation

The configurations for the MLWH are presented which the numbers of layers wound onto the reel are 1 and 3. The inlet velocities for the MLWH wound onto the reel considered in the current work were set as 0.63 m/s, 1.88 m/s, 3.14 m/s, 4.36 m/s, and 5.65 m/s. The Reynolds numbers for these inlet velocities were 167, 503, 838, 1170, and 1510, correspondingly. To investigate the flow characteristic and thermal performance for the considered cases, numerical simulations were performed. The boundary conditions were composed of the constant mass flow rate at the inlet, no-slip boundary wall conditions and a constant wall heat flux. A second-order upwind scheme was employed to discretize the governing equations. The momentum and continuity equations were connected by the SIMPLE algorithm. The discretized equations were solved by Fluent 15.0 software. Oil was used as the working fluid inside the MLWH.

![Simulation of the velocity and temperature contours for MLWHs with different configurations and Reynolds numbers](image)

**Figure 2.** Simulation of the velocity and temperature contours for MLWHs with different configurations and Reynolds numbers

Fig. 2 shows the simulation results for the velocity and temperature contours for MLWHs with different configurations and Reynolds numbers.

Fig. 2(a)-(b) shows the velocity and temperature contours for the MLWH in the cross section with different configurations. It is common that the highest velocity and centrifugal force for the working
fluid occurs in the center part of the MLWH at the entrance. However, one can observe from the velocity contour that at a certain distance away from the entrance, the working fluid is pushed away from the center of the MLWH by the centrifugal force which results in a shift of the maximum velocity from the center to the outer area of the hose wall. This is of great importance for enhancement of heat transfer and the shift in temperature towards the outer curvatures.

The velocity contours show that with the maximum velocity shifting to the inner bend of the MLWH, the centrifugal force also points to the inner bend under a constant Reynolds number. When the constant Reynolds numbers are 167, 503 and 838, the directions of the centrifugal force and maximum velocity are pointed towards the inner bend of the MLWH in Case 1-2. However, for constant Reynolds numbers of 1170 and 1510, the flow state in the most of the cases becomes turbulent, which makes the flow characteristics much more complex; these are not studied further in this paper.

As shown in the temperature contours for each case, the temperature of the working fluid in the MLWH varies little in Case 1. In Case 2, the temperature of the working fluid varies in different layers of the MLWH. At the innermost part of the MLWH for each case, the temperature of the working fluid varies lightly, while temperature at the outermost part varies widely. When the Reynolds number increases, the temperature increases correspondingly, especially at the outermost part.

3. Experimental analysis

3.1. Experimental principles

A multi-layer winding hose testing system is proposed according to a double-wheel trench cutter by the similarity theory. The scheme for the experiment is shown in Fig. 3.

![Figure 3. Scheme of the experiment: (1) Pump station proportional relief valve; (2) Pump station electromagnetic directional valve; (3) Outlet pressure sensor; (4) Flow sensor; (5) Output temperature sensor; (6) Output proportional relief valve; (7) Multi-layer winding hoses; (8) Output swivel joint; (9) Oil tank; (10) Main pump; (11) Main motor; (12) Input temperature sensor; (13) Input pressure sensor; (14) Input swivel joint; (15) Reducer; (16) Pump station hydraulic motor; (17) Pump; (18) Pump station motor.](image-url)

The MLWH testing system is composed of a sensor group, MLWH testing section and data collection system.

The working fluid (oil) is stored in a tank. The main motor drives the main pump which pumps the working fluid to the whole MLWH testing system. The working fluid first flows through the input sensor group at the exit of the main pump, which is used to measure the pressure and temperature of the inlet working fluid. Then, the working fluid flows through the MLWH testing section, which is
composed of a hydraulic hose with an inner diameter of 13mm and is mainly divided into a reel system and pump station system. In the reel system, the MLWH testing section is set vertically on the reel. In the pump station system, the pump station is used to drive the reel to the desired layers. An output sensor group is set at the end of the MLWH testing section to measure the output pressure, temperature and flow rate of the working fluid. After the output sensor group, a proportional relief valve is set to prevent damage to the whole system due to high pressure. Finally, the working fluid flows into a symmetric MLWH before returning to the tank.

3.2. Experimental apparatus

The experimental apparatus is presented according to the experimental principles. The output sensor group is composed of a temperature sensor, flow rate sensor and pressure sensor. The proportional relief valve is utilized to ensure the safety of the whole hydraulic system. The input sensor group is composed of a pressure sensor and a temperature sensor. The reel onto which the multi-layer winding hoses is wound. The data collecting system is composed of a TTControl screen, an IFM controller and a personal computer.

4. Results and discussion

To investigate the thermal characteristic of the MLWH with different configurations, the average heat transfer coefficient values are evaluated against the Graetz number in Fig. 4. The outcomes demonstrate that with an increasing number of layers for the MLWH, the heat transfer coefficient becomes higher. In Fig. 4, the obtained simulation and experimental data are compared. It is clear that the experimentally obtained data are much higher compared to the data obtained by simulation. This is mainly because of the complexity of the experimental conditions, while the data obtained by simulation were calculated for ideal conditions. Actually, the thermal improvement in the MLWH is attributed to the geometries (i.e. curvature).

![Figure 4. Heat transfer coefficient-Graetz number](image)

Fig. 5 shows a comparison between the data predicted by Eq.(9) and the simulation data obtained by Fluent simulations. It is clear that the data predicted by the equation agree with the simulation data while the deviation is greater than that expected through the whole range of the Graetz numbers($\frac{G_r}{\frac{D_H R_p}{L}}$). Hence, further research should present correction equations that can be used to improve the accuracy of the predicted data.
The frictional factor measures the pressure drop effect in the MLWH system. The relationship between the frictional factor and Graetz number is shown in Fig. 6. The data are obtained from the experiment. As depicted in Fig. 6, as the Graetz number increases, the frictional numbers decrease.

An analysis of the pressure drop for all the cases is demonstrated in Fig. 7. According to Fig. 7 (a)-(b), it is obvious that with increasing Graetz numbers, the pressure drop in the system increases at first before decreasing. For increasing number of winding layers for the MLWH, the pressure drop becomes lower. The reason for this is related to the curvature of the MLWH and the flow state of the working fluid. It is clear that the experimental data are much higher than those obtained from simulation. The situations considered in simulation are simpler than the experimental situations due to simplification of the complex flow state and external disturbances.

5. Conclusions
In this paper, the thermal performances and the flow characteristics of a MLWH system was studied theoretically and experimentally. Different curvatures and Reynolds numbers for the MLWH system were studied by utilizing oil as the working fluid. The conclusions are summarized as follows:

1. The simulations and experiments all involved laminar flow. The experimental data were compared to simulations. There were many uncertainties and disturbances (not concerned) in the experiment, which led to a great deviation in the data obtained compared to simulation. More attention will be paid to future researches on this topic, with more factors taken into consideration.

2. The simulation results showed that both the curvature and Reynolds numbers can influence the flow state of the MLWH system. The working fluid was pushed to the inner bend of the MLWH by interaction between gravity and the centrifugal force. The effect of curvature was proved to be stronger than that of the Reynolds number.

3. The experimental results for the MLWH system showed that the curvature induced centrifugal force can influence on the heat transfer performances and pressure drop for the MLWH system.

4. The Nusselt number utilized in this paper should be improved and future research works will focus on correction of the Nusselt number.

Our future research activities will focus on the structure-fluid interaction of the MLWH and the time delay problems in the MLWH systems.

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