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Design and Optimization of Graphene Membrane Differential Pressure Microflowmeter Based on CFD

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Abstract

In view of the design requirements of the measurement pipeline of the differential pressure micro-flow meter based on graphene membrane, the relationship between the pressure difference and the flow velocity between different pressure points in the micro-pipe was deeply studied, and the relationship between the flow rate and the pressure difference in the pipeline was established. The relational model is verified by CFD simulation calculation . The influence of parameters such as the diameter of the pipe , the length of the pressure pipe and the inlet flow rate on the measurement results were studied respectively , which provided a reference for the optimal design of the sensitive structure of the differential pressure micro flowmeter based on the graphene membrane .

1.Introduction

Sensors can be seen everywhere in daily life, industrial production, medical biology, military and national defense, and are closely related to social development. It is worth noting that when using sensors to collect information data, it is extremely important to ensure that the measurement results are accurate, safe and reliable. In industrial production control, pressure is one of the most important process control parameters, and flow is the most difficult parameter to measure. Micro flow is an unconventional small flow that requires higher measurement accuracy, and its measurement is more difficult. In the past ten years, with the continuous development of flow measurement -related technologies, manufacturers have developed flowmeters of different types, structures and working principles. These meters are developed according to the requirements of different occasions. With the discovery of new materials and the development of microfabrication technology , MEMS technology has been applied to many disciplines, and the flow control part involved [1] has a very high demand for the design and market application of new micro flow sensors .

Facing the needs of micro flow measurement in the market, this paper studies the optimization of the design structure of a differential pressure micro flowmeter based on graphene membrane. The ANSYS method is used to conduct simulation experiments to study the influence of parameters such as pipe diameter, pressure pipe length and inlet flow velocity on the measurement results, and then improve the design structure of the micro flowmeter.

1.1. Graphene overview

In 2004, physicists Andre Geim and Konstantin Novoselov of the University of Manchester in the United Kingdom successfully separated graphene from graphite for the first time by micromechanical exfoliation, for which they also won the Nobel Prize in Physics. Nominations for academic awards. Since its discovery, graphene has become a research hotspot in the field of materials due to its unique mechanical and electrical properties.

Graphene has excellent mechanical properties and is one of the strongest materials known to date. It also has good toughness and can be bent . Graphene has a theoretical Young's modulus of 1.0 TPa and an inherent tensile strength of 130 GPa [2]. Single-layer graphene is only about 0.335 nm single-atom thickness and can withstand a maximum strain of about 25% [3].

Graphene has excellent electrical properties, and the carrier mobility at room temperature is about 15000 cm 2 /(V·s), which is more than 10 times that of silicon material . In addition, the half-integer quantum Hall effect of electron carriers and hole carriers in graphene can be observed by changing the chemical potential through the action of an electric field, and scientists have observed this quantum Hall effect in graphene at room temperature [4].

Graphene has excellent optical properties, with an absorptivity of about 2.3% over a wide wavelength range, making it appear almost transparent. When the graphene thickness is within a few layers , the absorption rate increases by 2.3% for each additional layer of graphene thickness [5] .

Have shown that graphene has strong adsorption to SiO_2 substrates [6], and gas molecules (including helium atoms) cannot penetrate [7]. In addition, graphene also has a good piezoresistive effect [8]. These properties make graphene a promising new sensitive material with broad application prospects in the field of high-performance pressure sensors .

With the development of society, the application of graphene to the sensor field will become an inevitable trend. Because the thickness of the single-layer graphene film is too thin, about 0.335 nm , its deflection deformation is much larger than the film thickness under the action of uniform pressure [9], so it is suitable for measuring pressure and designing pressure sensors. Combined with the optical properties of graphene and the fiber Fa-Per cavity, a differential pressure micro flowmeter based on graphene membrane can be designed, which is the design idea of this paper.

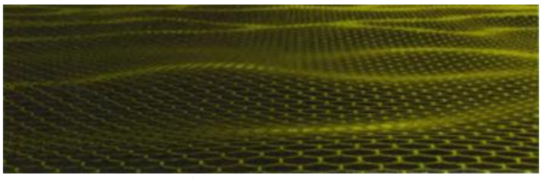

Figure 1: Structure of graphene.

1.2. Differential pressure flowmeter

Differential pressure flow sensor used for small flow measurement has also developed relatively mature. In the past few decades, due to its simple structure and easy implementation, a variety of small flow sensors based on the principle of differential pressure have appeared structure [10] .

In 1995, Boillat et al. studied the principle and method of micro-silicon pressure sensor and designed a differential pressure flow sensor for measuring micro-pump. In 1996, Lofdahl et al. designed a differential pressure flow sensor for turbulent boundary layer experiments . The principle is the piezoresistive effect of polysilicon film. In 1998, Berberig et al. researched and designed a sensor to measure the flow of MEMS by using a miniature pitot tube . Oosterbroek et al. used silicon and glass as substrate materials in 1999, and designed a miniature differential pressure flow sensor. The size of the sensor is very small , 10mm × 5mm × 0.9mm. The principle of resistance is used to measure the pressure and then calculate the flow [10] .

Literature [11] utilizes the stable seepage performance of stainless steel capillary, and measures the liquid flow by measuring the pressure difference at both ends of the capillary. The research of Harbin Institute of Technology [12] is based on a silicon differential pressure flow sensor . The main structure includes two silicon cup structures and a groove connecting the two silicon cup pressure chambers. The pressure of the pressure chamber is measured by the silicon piezoresistive effect, and then the flow rate is calculated. .

1.3. Differential pressure flowmeter based on graphene membrane

Differential Pressure Flowmeter (DPF) is an instrument that detects the flow by detecting the pressure difference between the upstream and downstream ends of the throttling device in the pipeline. The sensitive structure of the differential pressure microflowmeter based on graphene membrane is composed of the graphene membrane pressure sensitive structure and the microfluidic tube. The composition of the graphene film pressure-sensitive structure is to fix the graphene film on the end face of the optical fiber ferrule, insert the optical fiber at the other end, and make the end face of the optical fiber and the graphene film form a Faber cavity. The graphene film is deformed due to the pressure change, which leads to the change of the cavity length of the Fa-Per cavity, and the Fa-Per cavity converts the cavity length change into the reflected light intensity change. Microfluidic pipes are designed microfluidic chips that can install graphene membrane pressure-sensitive structures and connect water sources and other devices, which need to be simplified in CFD

The manufacturing process of the graphene film pressure-sensitive structure is to first perform cleanliness and flatness treatment on the end faces of the optical fiber and the optical fiber ferrule; then, the graphene film is cut into a circle of suitable size, and the PMMA coating is removed by acetone solution. The optical fiber ferrule is immersed under the suspended graphene film, and after film extraction and wet transfer are performed, the fiber ferrule with adsorbed graphene film is placed in a drying box, heated to 40 ° C, and kept for 1 hour, then the dried graphite The graphene film is adsorbed on one end of the optical fiber ferrule; after the graphene film is fixed on one end of the optical fiber ferrule, the optical fiber is connected and fixed with the other end of the optical fiber ferrule, so that the end face of the optical fiber and the graphene film form a Fa-Per cavity .

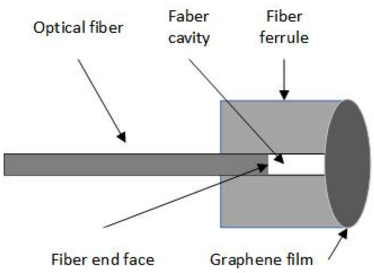

Figure 2: Graphene membrane pressure-sensitive structure.

The microfluidic pipeline is the research focus of this paper. It is a channel for water flow. One end is connected to the syringe pump through a hose, and the other end is directly connected to the atmosphere. The water flow with different flow rates can be set by the syringe pump. There are small holes in the microfluidic channel, and a graphene membrane pressure-sensitive structure is installed in the hole to measure the pressure at both ends of the pipeline , and the differential pressure is obtained by subtracting the previous pressure.

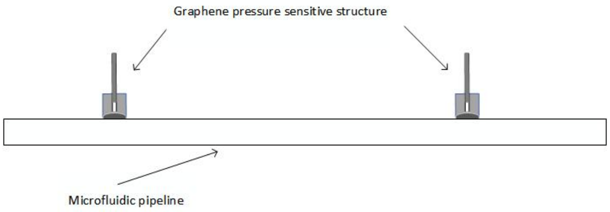

Figure 3: Differential pressure microflow meter based on graphene membrane.

Under the influence of the pressure change caused by the fluid in the microfluidic pipe, the graphene film is deformed, which makes the cavity length of the Fa-Pert cavity change, which in turn leads to the change of the reflection interference spectral line in the fiber, and the length is obtained by demodulating the spectrum. The relationship between the change and the spectrum, and then the mathematical model of differential pressure and cavity length, pressure and flow rate, can measure tiny flow.

2. Mathematical model of differential pressure and flow

2.1. Derivation of mathematical model

Differential pressure flowmeter is relatively simple. As long as the pressure difference between the upstream and downstream fluids of the pipeline is measured, the flow information can be obtained by calculation , so it has become one of the most used flow measuring instruments in industrial fields . In March 2003, the International Organization for Standardization (ISO) officially announced the latest international standards ISO5167-1, ISO5167-2, ISO5167-3 and ISO5167-4 to implement standardized differential pressure flowmeters, allowing differential pressure flow The relationship between differential pressure and flow is directly determined by the pressure difference and the size of the test piece without the need for calibration experiments. This is the only "standardized" flow measuring instrument at present [13, 14] . The publication of these standards also contributed to the popularity of differential pressure flow meters. The measurement principle of the differential pressure flowmeter in this paper has been described, and the derivation process of its mathematical model is described below.

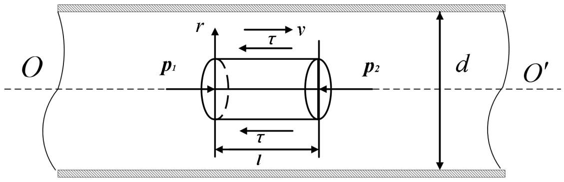

Figure 4: Force analysis of fluid in a circular tube.

As shown in Figure 4 , the fluid flows at a flow velocity v in a pipe with a diameter d , OO' is the central axis of the pipe, and a fluid micro-cylinder with a length of l is taken in the fluid with OO' as the axis, and the radius of the bottom surface of the micro-cylinder is is r . Analyzing its force in the pipeline, the micro-cylinder is subjected to the upstream and downstream pressures, respectively denoted as p_1 and p_2 , and $p_1 > p_2$, the fluid can flow in the pipeline, the pressure on the surface of the cylinder cancels each other, and at the same time There is a shear stress τ acting in the opposite direction to the flow direction. The force balance of the micro-cylinder in the direction of the central axis is expressed as:

$$(p_1 - p_2)\ \pi r^2 - 2\pi r l \tau = 0 \qquad (1)$$

By Newton's law of internal friction:

$$\tau = -\mu \frac{\mathrm{dv}}{dr} \qquad (2)$$

Where μ is the dynamic viscosity of the fluid (Pa s), and the Formula (2) is substituted into the Formula (1) and integrated to obtain:

$$v = -\frac{\Delta p}{4\mu l} r^2 + C \qquad (3)$$

From the boundary conditions: when r = d / 2, v = 0, the integral constant C can be obtained , namely:

$$C = \frac{\Delta p}{16\mu l} d^2 \qquad (4)$$

Substitute into the above formula to get:

$$v = \frac{\Delta p}{4\mu l}\left(\frac{d^2}{4} - r^2\right) \qquad (5)$$

From Formula (5) that when the fluid flows in the pipeline, the velocity of its flow section is distributed in a parabolic shape, and on the axis of the pipeline (ie r=0), the maximum flow velocity is:

$$v_{\max} = \frac{\Delta p}{16\mu l} d^2 \qquad (6)$$

The flow through the entire flow section can be obtained by integrating the velocity expression, namely

$$q = \int_0^{\frac{d}{2}} u \mathrm{d}A = \int_0^{\frac{d}{2}} \frac{\Delta p}{4\mu l}\left(\frac{d^2}{4} - r^2\right) 2\pi r \mathrm{d}r = \frac{\pi d^4}{128\mu l}\Delta p \qquad (7)$$

After finishing:

$$\Delta p = \frac{64}{\mathrm{Re}}\frac{l}{d}\rho\frac{v^2}{2} = \lambda\frac{l}{d}\rho\frac{v^2}{2} \qquad (8)$$

In the formula, Re is the Reynolds number of the fluid, λ is called the resistance number along the path, and the theoretical value of λ is $\frac{64}{\mathrm{Re}}$. The actual resistance coefficient of water in the laminar flow state is very close to the theoretical value.

2.2. Derivation of other channels

If it is a square channel, the derivation process is similar to 2.1.

The speed *v* is as follows:

$$v = \frac{\Delta p}{32\mu l}(d^2 - a^2) \qquad (9)$$

The flow *q* is as follows:

$$q = \frac{d^4}{32\mu l}\Delta p \qquad (10)$$

Where d is the side length of the square tube, and a is the side length of the fluid micro-square column.

3. Simulation models and calculations

3.1. Simulation model

In order to further discuss the design parameters of the graphene differential pressure micro flowmeter to optimize this, a simulation model of the pressure difference of the micro flow channel is constructed, and the method of ANSYS-CFD simulation analysis is applied.

(1) . Geometry: The Fluid Flow module is used for fluid simulation analysis. Based on the principle of model simplification, the graphene differential pressure micro-flowmeter is simplified into a round and straight pipe model, and the pressure is extracted at different sections of the original pipe model.

(2) . Mesh: Take the designed circular and straight pipe model as a fluid domain, select the tetrahedral mesh division method, select On: Proximity and Curvature for the mesh size, add an expansion layer to refine the pipe wall, and select a smaller size parameter , so that the number of meshes is sufficient and the mesh quality parameters meet the standard.

(3) . Solution: Use the laminar flow formula. The fluid medium is water-liquid, the standard water in the material library, with a density of 998.2kg/m 3 , the inlet boundary is the velocity inlet, and the outlet boundary is the natural outflow. The calculation method remains the default, and the calculation is performed.

(4) . Post-processing: use the formula to calculate the pressure at each section of the pipeline and draw the pressure cloud diagram of the interface in the pipeline.
The sensitive structure and CFD simulation model of the differential pressure microflowmeter based on the graphene membrane are shown in Figure 5 .

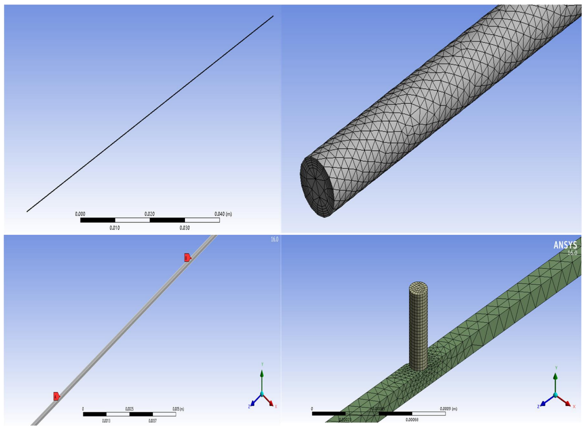

Figure 5: CFD model and mesh diagram.

3.2. Analysis of CFD simulation results under different conditions

For comparison, the control variable method was used, and CFD simulation was used to study the influence of the inlet velocity of the pipeline, the diameter of the pipeline, and the length of the pipeline to take pressure on the simulation results. The influence of the measurement results of the differential pressure micro flow meter provides an important reference for the structural design and optimization of the graphene membrane differential pressure micro pressure flow meter.

For a circular channel with a pipe diameter of 1cm and a pipe pressure length of 10cm, only the inlet velocity of the pipe is changed, and set to 10mL/min, 1mL/min, 0.1mL/min, 0.01mL/min, 0.001mL/min, 0.0001mL/min for simulation. The obtained simulation results for different pipe inlet velocities are shown below.

Table 1 : Simulation of Pipeline Inlet Velocity.

Ingress traffic mL/min	Differential Pressure Pa	Calculate traffic mL/min
10	5758.05	10.8805
1	538.4	1.0174
0.1	52.57	0.0993
0.01	5.259	0.0099
0.001	0.5258	0.0010
0.0001	0.05262	0.0001

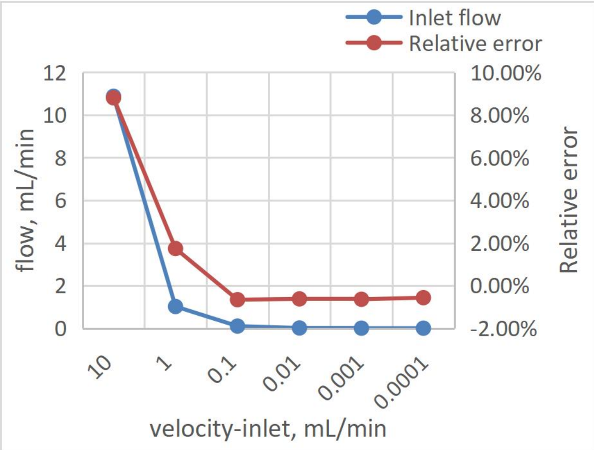

Figure 6: Effect of Pipe Inlet Velocity on Simulation.

From the figure, it can be seen that as the flow rate decreases, the relative error between the flow rate calculated according to the formula and the inlet flow rate becomes smaller and smaller.

For a circular channel with a pipeline pressure length of 10cm and a pipeline inlet velocity of 1mL/min that remains unchanged, only the diameter of the pipeline is changed and set to 0.1mm, 0.3mm, 0.5mm, 0.6mm, 0.7mm, 0.8mm, 0.9mm, 1mm, 1.5mm, 2mm, 2.5mm, 3mm, 5mm for simulation. The obtained simulation results for different pipe diameters are shown below.

Table 2 : Simulation results for different pipe diameters.

Pipe diameter mm	Differential Pressure Pa	Calculate traffic mL/min
0.1	818748	1.1938
0.3	8635	1.0198
0.5	1104	1.0060
0.6	530.129	1.0017
0.7	286.909	1.0044
0.8	168.5	1.0063
0.9	104.875	1.0033
1	68.7	1.0017
1.5	13.98	1.0319
2	4.413	1.0295
2.5	1.824	1.0389
4	0.276146	1.0307

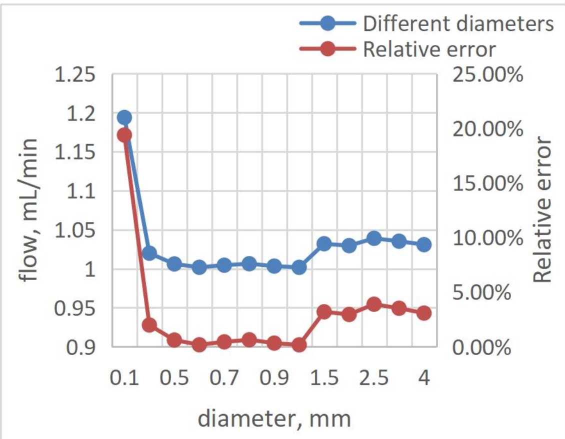

Figure 7: Effect of Pipe Diameter on Simulation.

It can be seen from the figure that when the pipe diameter is in the range of 0.5mm to 1mm, the relative error between the flow rate calculated according to the formula and the inlet flow rate is less than 1%, and when the pipe diameter is 1mm, the relative error is the smallest, reaching 0.2%. Therefore, the diameter of the pipe is selected as 1mm.

For a circular channel with a pipe diameter of 1cm and a pipe inlet velocity of 1mL/min remaining unchanged, only the pipe pressure taking length was changed, and set to 5cm, 6cm, 7cm, 8cm, 9cm, 10cm, 11cm, 12cm, 13cm, 14cm, 15cm in turn. , 16cm, 17cm, 18cm, 19cm, 20cm for simulation. The obtained simulation results for different pipe pressure tap lengths are shown below.

Table 3 : Simulation results of different pipeline pressure taking lengths

Taking pressure length cm	Differential Pressure Pa	Calculate traffic mL/min
5	268.2	1.0136
6	321.7	1.0132
7	375.8	1.0145
8	428.6	1.0124
9	482	1.0120
10	535.6	1.0121
11	588.9	1.0116
12	642	1.0109
13	695.1	1.0104
14	748.1	1.0097
15	803.6	1.0123
16	853.6	1.0081
14	906.5	1.0076
18	959.4	1.0072
19	1012.23	1.0067
20	1065	1.0062

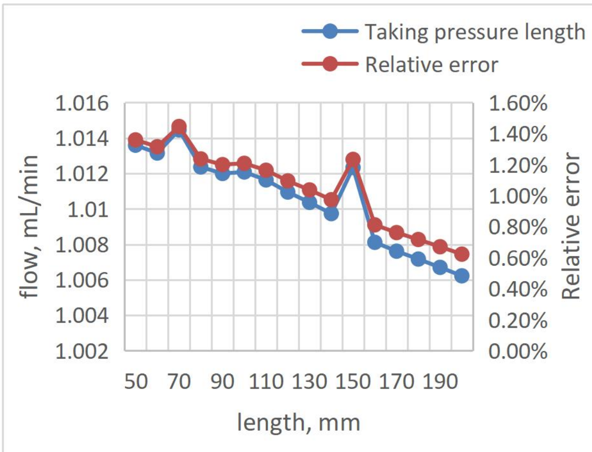

Figure 8: Influence of Pipe Pressure Tap Length on Simulation.

It can be seen from the figure that with the increase of the length of the pipeline, the relative error between the flow rate calculated according to the formula and the inlet flow rate generally shows a decreasing trend, and some points fluctuate slightly . Among them, when the pipe length is greater than 15mm, the relative error is less than 1%. Taking the pipeline pressure taking length greater than 15mm as a reference, the appropriate pipeline pressure taking length can be selected according to the actual design requirements and constraints.

In this part of the simulation experiment, I studied the influence of the three parameters of inlet flow rate, pipe diameter and pipe pressure length on the actual structural design. The inlet flow rate should be set to less than 1mL/min, but it is too small to be detected. At the same time, the inlet velocity is reduced, but the relative error is not greatly reduced; when the diameter of the pipeline is within 0.5mm to 1mm, the relative error is less than 1%; when the pipeline length is greater than 15mm, the relative error is less than 1%. According to these simulation results, combined with the constraints of the actual design, the diameter of the pipeline is 1mm, the length of the pipeline is 16mm, and the corresponding flow source is selected according to the flow rate.

4. Results and discussion

In this paper, the influence of parameters such as pipe diameter, pressure pipe length and inlet flow rate on the measurement performance of the graphene-based differential pressure micro-flowmeter is modeled and analyzed. The simulation results show that the inlet velocity of the pipeline has little effect on the formula, but the relative error decreases as the velocity decreases, but the smaller the velocity, the more difficult it is to measure; when the diameter of the pipeline gradually decreases, the relative error decreases gradually. When the diameter of the pipeline is in the range of 1mm-0.5mm, the relative error is small. When the diameter of the pipeline is less than 0.5mm, the relative error will increase; the relative error of the pipeline pressure taking length also decreases with the increase of the pipeline pressure taking length. For further conclusions to follow, better planned simulations are needed.

Acknowledgement

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