A MEMS Fluid Density Sensor Based on Silicon Rectangular Microcantilever

Libo Zhao[1], Enze Huang[1], Zhuangde Jiang[1,#], Guiming Zhang[1], Yulong Zhao[1], Xiaopo Wang[2], Bo Song[2] and Zhigang Liu[2]

1 State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an, 710049, China
2 State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, 710049, China
Corresponding Author / E-mail: zdjiang@mail.xjtu.edu.cn, TEL: +86-29-82668616, FAX: +86-29-83395139

KEYWORDS: MEMS, Density sensor, Rectangular microcantilever, Resonant frequency, Vibrating

Density is one of the important parameters of fluid. Density measurement plays an important role to assess product quality and features in petroleum industry, food production and pharmaceutical industry etc. A fluid density sensor's sensitive chip has been fabricated with silicon rectangular microcantilever by MEMS (Micro Electro Mechanical System) technology. The Ti-Pt-Au coil and four piezoresistors were manufactured on the top of the microcantilever. The optimum locations of four piezoresistors are determined by FEM (Finite Element Method) to improve the sensor's sensitivity. When the sensitive chip is placed in the uniform magnetic field and the Ti-Pt-Au coil is energized with alternating voltage peak to peak value of U_1, the silicon rectangular microcantilever can vibrate under the Ampere force. Based on the piezoresistive effect, the powered Wheatstone full bridge consisted of four piezoresistors can output different voltage signals U_2 when the sensitive chip is immersed into different fluids. The density of different fluids can be calculated by the function of U_1 and U_2. The MEMS fluid density sensor was tested in anhydrous alcohol, absolute methanol and de-ionized water respectively. The experimental results demonstrate that the sensor has good linearity, high sensitivity and its accuracy is better than ±5%.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

A, C, H = width, length and thickness of rectangular microcantilever respectively
B = total length of the sensitive chip
F_a = Ampere force
B_1 = magnetic flux density
I = alternating current
L = effective length of Ti-Pt-Au coil
U_1 = peak to peak value of the alternating voltage
U_2 = output voltage of the Wheatstone full bridge
F_r = resultant external force
F_d = fluid resistance
ρ = fluid density
a = constant
k = slope
b = intercept
T = temperature
P = atmospheric pressure

1. Introduction

In many realms of industry, it is important to measure the density of the fluid, not only because the density is one of the fundamental parameters of the fluid which directly determine the choosing of the post process equipments of whole industrial system, but also some other thermophysical parameters cannot be calculated without the value of density. Fluid density sensors are widely used in oil industry, chemical, material science etc. The ever-increasing demand for the density sensor has driven forward a great amount of applications and fundamental researches based on micro-fabrication technology, especially MEMS (Micro Electro Mechanical System) technology.[1] The MEMS density sensor with vibrating microcantilever has already been used to measure the viscosity and density of fluid,[2] chemical of environment[3] and rheology of measurements.[4] Other sensors were used to detect properties of gas and molecular in physical environment.[5-6] The sensor based on microcantilever is very sensitive to liquid properties.[7] The fluid generates additional inertia loading, which is called virtual mass on the microcantilever, to lower the resonant frequency.[8] The principle to measure fluid density is based on the fact that microcantilever has different resonant frequencies in different fluids. The resonant frequency shifts of microcantilevers in various fluids have been invested.[9] Thus, the density of fluid can be determined by the resonant frequency of the microcantilever. But it was difficult and takes a long time to find out the accurate resonant frequency of the microcantilever which was immersed into fluid because the increment between each step of frequency should be small enough in order to not ignore the resonant frequency. In this paper, it's easy to measure the fluid density by the developed sensitive chip based on the function of the peak to peak value U_1 of the alternating voltage and output voltage U_2 of the Wheatstone full bridge instead of the resonant frequency. Experimental results demonstrate that the developed MEMS density sensor has good linearity, high sensitivity and its accuracy is better than ±5%.

2. Principle of the MEMS fluid density sensor

The schematic diagram of the MEMS fluid density sensor's sensitive chip with the rectangular microcantilever is shown in Fig. 1. The microcantilever's left side is fixed, and the right side is the free end. The Ti-Pt-Au coil and four piezoresistors constituting a Wheatstone full bridge were fabricated upon the rectangular microcantilever. After the sensitive chip is placed in the uniform magnetic field and the Ti-Pt-Au coil is powered with alternating voltage, the rectangular microcantilever can vibrate by the Ampere force with the frequency of the alternating voltage. The Ampere force F_a can be calculated by the following equation:

$$F_a = B_1 IL \tag{1}$$

where, B_1 is the magnetic flux density, I is the alternating current through the Ti-Pt-Au coil and L is the effective length of the coil.

When the rectangular microcantilever is under resonance, based on the piezoresistive effect, the powered Wheatstone full bridge's output voltage reaches maximum. At the same time, the frequency of the alternating voltage is the resonant frequency of the microcantilever. The Wheatstone full bridge's output voltage was amplified by the lock-in amplifier to ensure that the output voltage was caused only by the alternating voltage.

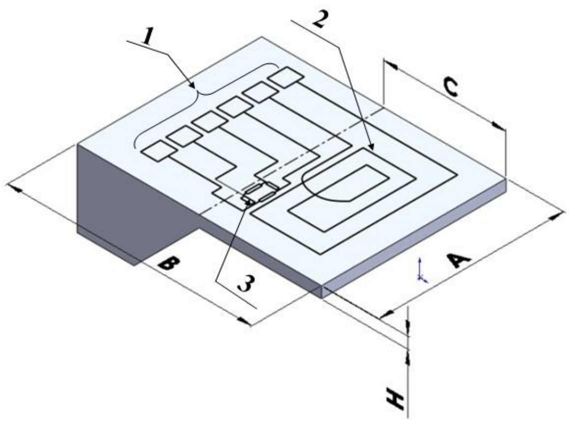

Fig. 1 Schematic diagram of the sensitive chip with rectangular microcantilever. The width A, length C and thickness H of rectangular microcantilever are 2.5 mm, 1.7 mm and 50 μm respectively. The total length B of the sensitive chip is 7 mm. 1 are bonding pads, 2 is the Ti-Pt-Au coil and 3 is the Wheatstone full bridge.

In order to gain the maximum output voltage of the Wheatstone full bridge, the resonant frequency of the microcantilever should be obtained when the sensitive chip is immersed into fluid. The normal way to find out the resonant frequency of the microcantilever was as follows. Firstly, the alternating voltage with wide range of variable frequency was acted on the Ti-Pt-Au coil. By changing the frequency of the alternating voltage with continuous small increment, when the Wheatstone full bridge's output voltage reached the maximum, the microcantilever was considered to be resonance vibration. At this time, the frequency of the alternating voltage was also considered to be the resonant frequency of the microcantilever. Then, the density of the fluid can be calculated with the resonant frequency by some empirical formula. But it's difficult to obtain the exact value of the resonant frequency.

In this paper, the fluid density was measured by the developed sensor based on the function of peak to peak value U_1 of the alternating voltage with the frequency close to the resonant frequency and output voltage U_2 of the Wheatstone full bridge instead of the resonant frequency. In order to avoid the trouble of obtaining the resonant frequency of the microcantilever, the frequency of the alternating voltage was selected by FEM (Finite Element Method) simulation. Although the U_2 was not the maximum output voltage, it can be amplified by lock-in amplifier without any interference signal.

When the sensor is immersed in liquid, the strain ε at the location of Wheatstone full bridge is proportional to the resultant external force F_r. The resultant external force F_r is the difference between Ampere force F_a as driving force and fluid resistance F_d on the surface of the microcantilever, so that

$$F_r = F_a - F_d \tag{2}$$

The Ampere force F_a is proportional to peak to peak value U_1 of the alternating voltage that is supplied to the coil of the sensitive chip. The fluid resistance F_d is proportional to fluide's density ρ, The resultant external force F_r is proportional to output voltage U_2 of the Wheatstone full bridge, so that

$$U_2 = kU_1 + b \tag{3}$$

$$b = a\rho \tag{4}$$

where, a is a constant that is only determined by the microcantilever and is nothing to do with fluid density. For the same sensor, a is the fixed constant. According to U_1 and U_2, the slope k and intercept b are calculated easily by linear fit. Thus, based on the obtained intercept b and the known density ρ of a standard fluid, the constant a can be calculated by the equation (4). When the same sensor is used to measure other fluid density, which can be easily calculated by the equation (4) with the intercept b.

3. Analysis and fabrication of the sensitive chip

The aim of harmonic analysis is to simulate the distribution of strain on the surface of the rectangular microcantilever in real circumstance. The first and second order resonant frequencies can be determined from modal analysis. In this experiment, the second order resonant frequency is used because the first mode would couple the resonant frequency to the fixed edge of the microcantilever and the second mode may reduce this potential error.[10] When the second order resonance with frequency of 48196 Hz occurred, the von Mises elastic strain on the surface of rectangular microcantilever was show in Fig. 2.

From FEM results, the Wheatstone full bridge consisted of four piezoresistors should be placed on the corner of fixed side of the rectangular microcantilever where the von Mises elastic strain can reach about 500 με when the microcantilever is resonant.

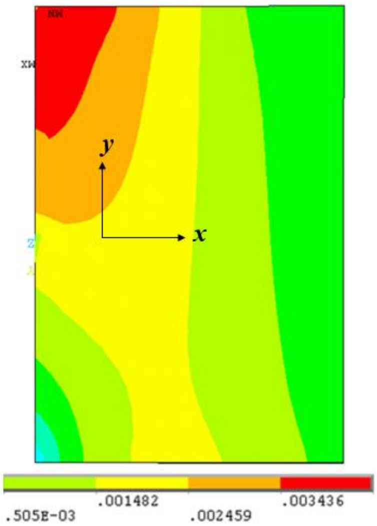

Fig. 2 Distribution of von Mises elastic strain on surface of the rectangular microcantilever when second order resonance occurs.

The sensitive chip with rectangular microcantilever was fabricated with a 3 inch (100) plane N-type silicon wafer. Four piezoresistors were made on top surface of the microcantilever. The effective length of each piezoresistor is 350 μm with sheet resistance of 100 Ω/□. The resistance of each piezoresistor is about 4 kΩ under 298 K. Four piezoresistors form a Wheatstone full bridge as shown in Fig. 3. The effective length of piezoresistors 1 and 4 are arranged in *y* direction, and the effective length of other piezoresistors 2 and 3 are arranged in *x* direction (that is [011] crystal orientation). The sensitive chip was fabricated by MEMS technology as shown in Fig. 4. The thickness of the rectangular microcantilever is around 50 μm, and there are 22 turns of Ti-Pt-Au coil with effective length of 26 mm. Thermistors are two boron-doped piezoresistors. The angle between the effective length direction of thermistors and [011] crystal orientation is 45° so that the changes in resistance of thermistors are only related to ambient temperature and are nothing to do with the stress. The effective length of each thermistor is also 350μm with sheet resistance of 100Ω/□. The resistance of each thermistor in 298K is also about 4 kΩ.

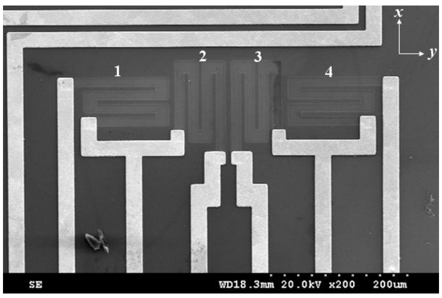

Fig. 3 SEM (Scanning Electron Microscope) picture of Wheatstone full bridge. 1, 2, 3 and 4 are piezoresistors.

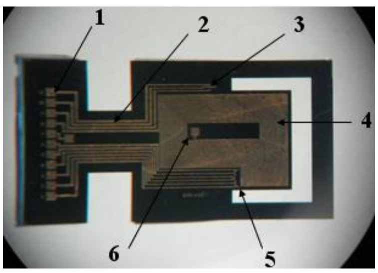

Fig. 4 Top view of the sensitive chip with rectangular microcantilever. 1 is bonding pad. 2 is inner lead. 3 is thermistor. 4 is Ti-Pt-Au coil on the rectangular microcantilever. 5 is Wheatstone full bridge. 6 is another bonding pad.

4. Experiments and results

The sensitive chip was packaged on a PCB (Printed Circuit Board) with wire bonding process. The magnetic field was generated by a solenoid which is fabricated by 1200 turns of enameled copper wire with diameter of 0.3 mm. The magnetic field in the middle of the solenoid where the rectangular microcantilever is arranged can be approximately considered as uniform magnetic field for the sensitive chip, because the vibration amplitude of the rectangular microcantilever is tiny. Fig. 5 is the complete packaged sensor.

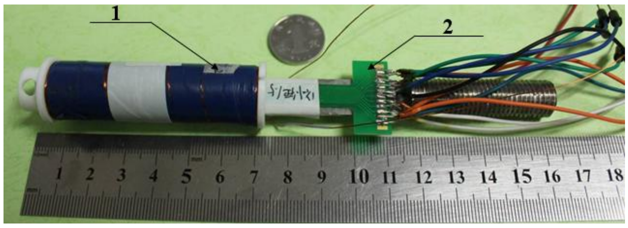

Fig. 5 Complete packaged sensor. 1 is the solenoid. 2 is the PCB.

The Wheatstone full bridge was powered with 2 mA constant current, and the solenoid was supplied with 0.5 A constant current to form an uniform magnetic field with magnetic flux density's value of about 0.1 T. After an alternating voltage which had 100 mV peak to peak value at the beginning with frequency of 48196 Hz was supplied to the Ti-Pt-Au coil, the rectangular microcantilever began vibrating under the Ampere force. Then the output signal U_2 of the Wheatstone full bridge can be detected by lock-in amplifier. The alternating voltage's peak to peak value U_1 was changed from 100 mV to 600 mV with increment of 50 mV. The experimental equipments are shown in Fig. 6.

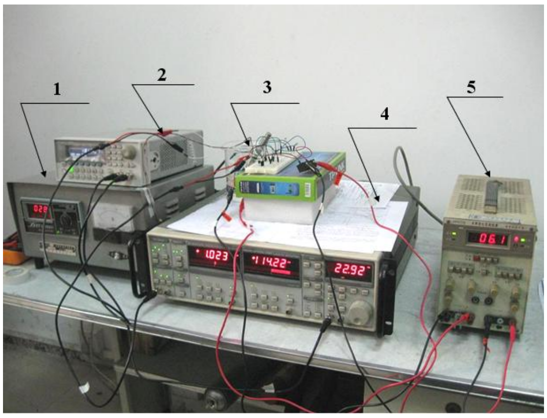

Fig. 6 Experimental equipments. 1 is thermocouple temperature sensor. 2 is signal generator. 3 is MEMS fluid density sensor. 4 is SR830 lock-in amplifier. 5 is dual DC power supply.

Data were recorded when the sensor was immersed in anhydrous alcohol, absolute methanol and de-ionized water. The parameter *b* in equation (4) can be calculated with the experimental data by linear fit. Combining with the known density of anhydrous alcohol, *a* can be calculated. The following data were obtained based on alternating voltage's frequency of 48196 Hz, the temperature of 303 K, and the atmospheric pressure of 0.09791 MPa.

When the sensitive chip was immersed into anhydrous alcohol, absolute methanol and de-ionized water respectively, the experimental data were obtained and shown in Table 1, Table 2 and Table 3, as well as the fitting curves of U_1 and U_2 were calculated and shown in Fig. 7, Fig. 8 and Fig.9 accordingly.

U_1 (mV)	100	150	200	250	300	350
U_2 (mV)	4.13	6.21	8.16	10.25	12.74	14.66
U_1(mV)	400	450	500	550	600	
U_2(mV)	16.97	18.81	20.92	23.43	25.29	

Table 1. U_1 and U_2 in anhydrous alcohol.

U_1(mV)	100	150	200	250	300	350
U_2(mV)	4.09	6.2	8.32	10.63	12.12	15.51
U_1(mV)	400	450	500	550	600	
U_2(mV)	16.27	18.84	20.55	22.97	25.89	

Table 2. U_1 and U_2 in absolute methanol.

U_1(mV)	100	150	200	250	300	350
U_2(mV)	5.59	8.47	11.15	13.76	16.94	19.22
U_1(mV)	400	450	500	550	600	
U_2(mV)	21.39	24.86	27.57	28.52	32.85	

Table 3. U_1 and U_2 in de-ionized water.

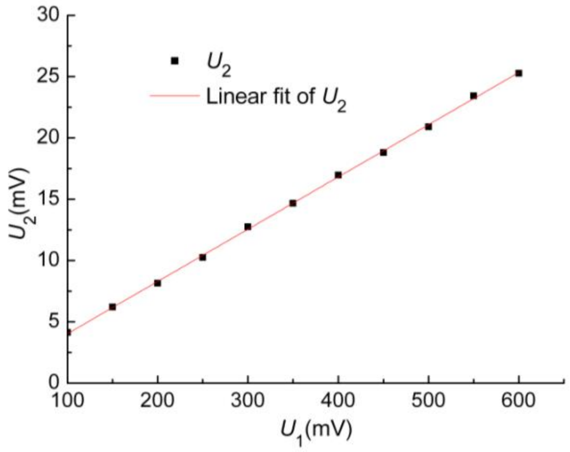

Fig. 7 Fitting curve between U_1 and U_2 in anhydrous alcohol, $y = kx+b$, $k = 0.0426$, $b = -0.22245$.

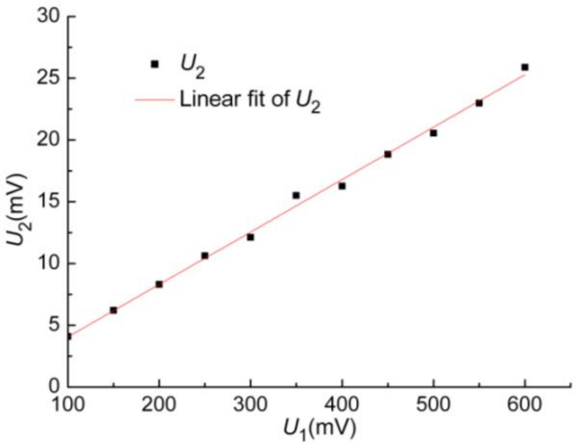

Fig. 8 Fitting curve between U_1 and U_2 in absolute methanol, $y = kx+b$, $k = 0.04243$, $b = -0.268$.

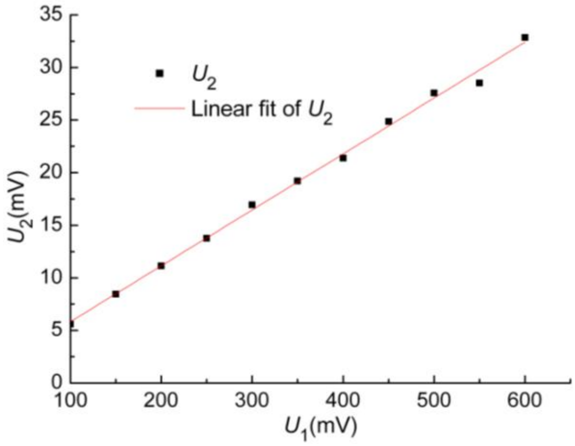

Fig. 9 Fitting curve between U_1 and U_2 in de-ionized water, $y = kx+b$, $k = 0.05317$, $b = -0.51209$.

The density of anhydrous alcohol is 781.22 kg/m^3 at temperature of 303 K and at atmospheric pressure of 0.09791 MPa. From Fig. 7, b=-0.22245, from equation (4), $a=b/\rho=2.8475\times10^{-4}$. The density of absolute methanol and de-ionized water can be calculated with the obtained a and the intercepts b in Fig. 8 and Fig. 9. The measurement results are shown in Table 4 and Table 5.

Absolute methanol		Experimental value	Literature value	Relative error
T / K	P / MPa	ρ / kg.m^{-3}	ρ / kg.m^{-3}	%
303	0.09791	941.19	781.62	20.41

Table 4. Density of absolute methanol.

De-ionized water		Experimental value	Literature value	Relative error
T / K	P / MPa	ρ / kg.m^{-3}	ρ / kg.m^{-3}	%
303	0.09791	1798.40	995.65	80.63

Table 5. Density of de-ionized water.

The calculated results had large relative error. So intercept b was not linear with fluid density ρ. The equation (4) was amended to

$$b^{0.25}=a\rho \quad (5)$$

The results calculated by amended equation (5) are shown in Table 6 and Table 7.

Absolute methanol		Experimental value	Literature value	Relative error
T / K	P / MPa	ρ / kg.m^{-3}	ρ / kg.m^{-3}	%
303	0.09791	818.46	781.62	4.71

Table 6. Density of absolute methanol after amending.

Absolute methanol		Experimental value	Literature value	Relative error
T / K	P / MPa	ρ / kg.m^{-3}	ρ / kg.m^{-3}	%
303	0.09791	962.28	995.65	-3.35

Table 7. Density of de-ionized water after amending.

From Fig. 7 to Fig. 9, it is known that the Wheatstone bridge's output voltage U_2 and the peak to peak value U_1 of the alternating voltage is linear, so the MEMS fluid density sensor based on silicon rectangular microcantilever has good linearity. With the same voltage U_1, the sensor's output voltage U_2 in anhydrous alcohol, absolute methanol and de-ionized water are obvious different, which indicates the MEMS fluid density sensor has good sensitivity. From Table 6 and Table 7, it is known that the relative errors of measured density are better than ±5%.

5. Conclusions

A MEMS fluid density sensor was developed. The sensor's sensitive chip was fabricated with a silicon rectangular microcantilever using MEMS technology. The sensitive chip consists of four piezoresistors constituting Wheatstone full bridge, thermistors, Ti-Pt-Au coil, some bonding pad and inner leads. The optimum locations of four piezoresistors are determined by FEM analysis. The fluid density is measured by the sensor based on the function of peak to peak value U_1 of the alternating voltage and output voltage U_2 of the Wheatstone full bridge instead of the resonant frequency. The sensor was tested in anhydrous alcohol, absolute methanol and de-ionized water respectively. The experimental results prove that the sensor's accuracy is better than ±5%.

ACKNOWLEDGEMENT

The authors acknowledge the fund supports of projects of National Natural Science Foundation of China (No. 50836004 and 90923001) and the Fundamental Research Funds for the Central Universities (No. xjj20100140).

REFERENCES

1. C. Harrison, E. Tavernier, O. Vancauwenberghe, E. Donzier, K. Hsud, Goodwin A. R. H., F. Marty and B. Mercier, "On the response of a resonating plate in a liquid near a solid wall," Sensors and Actuators A, Vol. 134, pp. 414-426, 2007.
2. W. Y. Shih, X. Li, H. Gu, W. H. Shih, I. A. Aksay, "Simultaneous liquid viscosity and density determination with piezoelectric unimorph cantilevers," J. Appl. Phys, Vol. 89, pp. 1497-1505, 2001.
3. N. V. Lavrik, M. J. Sepaniak, P. G. Datskos, "Cantilever transducers as a platform for chemical and biological sensors," Rev. Sci. Instrum, Vol. 75, pp. 2229−2253, 2004.
4. S. Boskovic, J.W.M. Chon, P. Mulvaney, J.E. Sader, "Rheological measurements using microcantilevers," J. Rheol, Vol. 46, pp. 891−899, 2006.
5. Goodwin A. R. H, "A MEMS Vibrating Edge Supported Plate for the Simultaneous Measurement of Density and Viscosity: Results for Argon, Nitrogen, and Methane at Temperatures from (297 to 373) K and Pressures between (1 and 62) MPa," J. Chem. Eng. Data, Vol. 54, No. 2, pp. 536-541, 2009.
6. T. Braun, V. Barwich, M.K. Ghatkesar, A.H. Bredekamp, C. Gerber, M. Hegner, H.P. Lang, "Micromechanical mass sens ors for biomolecular detection in a physical environment," P hys. Rev. E 72, No. 031907, 2005.
7. Z. G. Wu, X. H. Ma, P. N. Brett, J. W. Xu, "Vibration analysis of submerged rectangular microplates with distributed mass loading," Proc. Roy. Soc, Vol. 465, No. 2104, pp. 1323-1336, 2009.
8. M. K. Ghatkesara, E. Rakhmatullina, H. P. Lang, C. Gerber, M. Hegnera, T. Braun, "Multi-parameter microcantilever sensor for comprehensive characterization of Newtonian fluids," Sens and Actuators. B. Chem, Vol. 135, No. 1, pp. 133-138, 2008.
9. S. Weigert, M. Dreier, M. Hegner, " Frequency shifts of cantilevers vibrating in various media," Appl. Phys. Lett, Vol. 69 No. 19, pp. 2834–2836, 1996.
10. Goodwin A. R. H, Donzier E.P, Vancauwenberghe O, et al, "A Vibrating Edge Supported Plate, Fabricated by the Methods of Micro Electro Mechanical System for the Simultaneous Measurement of Density and Viscosity: Results for Methylbenzene and Octane at Temperatures between (323 and 423) K and Pressures in the range (0.1-68) MPa" J. Chem. Eng. Data, Vol. 51, pp. 190-208, 2006.