Using an optical micrometer for mechanical thermostat membrane expansion measurements

Jure REJC, Marko MUNIH

Abstract: This paper presents a series of preliminary tests for measuring expansion of the mechanical thermostat diaphragm during filling with appropriate expansion medium. Presented is a solution with a high-precision optical micrometer thrubeam laser sensor and a reference crevice, enabling compensation of undesired rotations. With this system is possible to measure expansions down to a few micrometers accurate. All measurements were compared to a mechanical, calibrated micrometer.

Keywords: mechanical thermostat, expansion medium, optical micrometer, precise measurements, mechanical micrometer,

1 Introduction

A proper regulation of temperature is in present time very important, because it can be found everywhere: at home, at work, in industry, etc. All devices that enables regulation of temperature have a name: a thermostat.

The thermostat is a device for regulation of the temperature in a system in a way that the system's temperature is maintained near a de-sired temperature (Snajder, 1982). The thermostat does this by controlling the flow of heat energy in or out of the system. That is, the thermostat switches heating or cooling devices on or off as needed to maintain the correct temperature. Thermostats can be constructed in many ways and may use a variety of principles to measure and regulate the temperature. The output of the thermostat then controls the heating or cooling gadgets. Common sensors include: bi-metal mechanical sensors, expansion medium sensor, electronic thermistors, electrical thermocouples etc. This article describes the preliminary tests for controlling of the expand medium filling in production of expansion medium sensor based ther-mostats, such can be seen in *figure 1*. The whole temperature sensor consists of probe, capillary tube, diaphragm with ceramic button and expansion medium. When the sensor is heated, the medium heats up and expands. The expansion of the medium increases the pressure in the closed-circuit system. The pressure increase is converted into a displacement in the diaphragm. This displacement, also called travel, actuates a snap-action switch which opens or closes the contacts in the electric circuit. The reference variable is set via the thermostats adjusting spindle.

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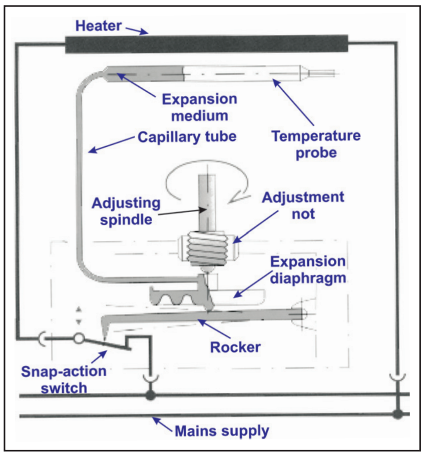

Figure 1. *Description of a mechanical thermostat*

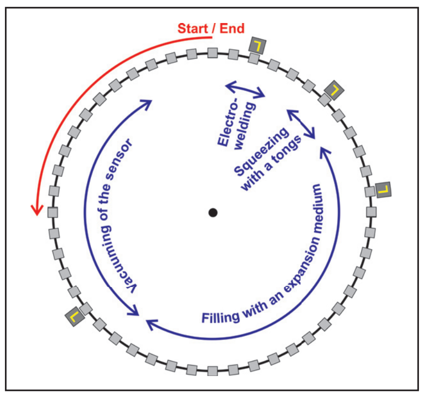

Figure 2. *Filling sequence of filling machine*

For thermostat that switches at set temperature is important that the process of expansion medium filling is controlled, so that diaphragm is properlyexpanded for desired thermostat working range.

This must be done at proper temperature and fill pressure. In the current production line, the temperature of the expansion medium can not be controlled to full-fill the predefined temperature and this temperature difference must be compensated with higher or lower filling pressures, which is set manually.

Before filling with expansion medium, the temperature sensor is opened at the probe side, enabling expansion medium to be filled. Filling procedure is done on the rotary machines, where many sensors can be filled at once. Installing of the sensors into the filling machine special heads is done manually. The four stages of filling that follow are evident in *figure 2* and in *figure 3*.

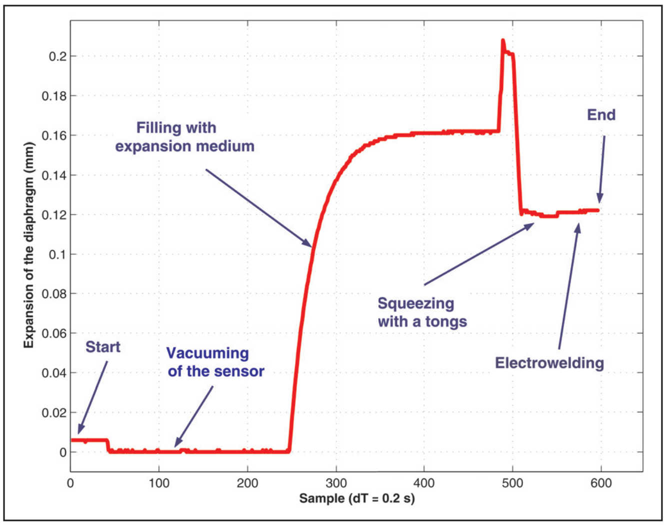

Figure 3. *Filling diagram of the thermostat sensor*

First stage is vacuuming of the sensor, where it is tested for airtightness. Follows a filling procedure with the expansion of the diaphragm dependent on the medium filling pressure. After a few cycles, expansion is stopped, some types of the sensors stay in filling heads and some are pushed out, but all are squeezed with a tongs to be closed. After this stage, electrowelding is performed to reliably close the sensor. At the end each sensor is automatically removed from the filling machine. The maximum expansion of the diaphragm during filling, for all types of thermostats, is from 0.046 mm to 0.46 mm.

Our research team worked on a task to find a proper technical solution for measuring expansion of the diaphragm in all four the most important stages of filling procedures of the thermostat sensor on the current filling machines. From upper information the measuring system must be able to measure expansion to less than 0.01 mm and without major remaking of the current filling machines.

In the work described in this article, we have made a series of comparison measurements, utilized high-accuracy sensors and some simple mathematical calculations. To check the measuring method, some mechanical micrometer comparison measurements were performed and analyzed. The final mathematical analysis is also presented at the end, but only the main idea with a basic equation.

2 Diaphragm expansion measurement approach

Due to a fact that current filling machines should not be changed or modified considerably, an approach presented in *figure 4* for performing measurements was tested. The whole measurement system consist of a fixed curtain laser micrometer, expanding diaphragm, the fixation object and the reference object. To measure expansion in four points at the machine, also four measuring systems would be needed, as can be seen on figure 2, marked with a letter L. These sensors are fixed and are not part of the rotary machine, only sensor diaphragms are rotated repeatedly into the mea-suring position. At the vacuuming phase, a hole or crevice between the diaphragm ceramic button and a reference object would be measured and set to 0.000 mm initial value. In all other positions, the same distance would be measured. Since only first and last position is needed for appropriate pressure regulation, the rest two positions are needed for additional filling information. For this kind of measurements it is important that the machine places all measured heads in the same position. This is done completely mechanically and very accurately.

3 Hardware

The following equipment was used (*Figure 5*) :

- laser optical micrometer sensor Keyence,
- reference mechanical micrometer Mitutuyo,
- Epson robot.

3.1 Laser optical micrometer sensor Keyence

For testing purpose a local representative for Keyence Corporation lent us the optical mi-crometer sensor LS-5041 with LS-5501 controller. (Keyence, 2006). Measurement system consists from two parts, transmitter and receiver, joined in a metal rod setting, both parts being mounted 160 ± 40 mm from each other. Light source is a visible red semiconductor laser with 670 nm wavelength, Class 2 by IEC specifications. Measuring range is from 0.2 mm to 40 mm, with measurement accuracy of ± 2 μm and repeatability of ± 0.3 μm.

3.2 Reference micrometer

Every measurement should be compared to a higher class calibrated measurement device. We used a mechanical micrometer manufactured by Mitutuyo Corporation (Mitutoyo, 2006). It has a mark 293-666, measuring range of 30 mm, linear scale with a resolution of 1 μm, error limit of 2 μm, flatness less than 0.3 μm and with parallelism less than 2 μm. It has a digital data output, non rotating spindle and measuring faces are made out of a carbide. To imitate real conditions a ceramic button was attached to one of the tips.

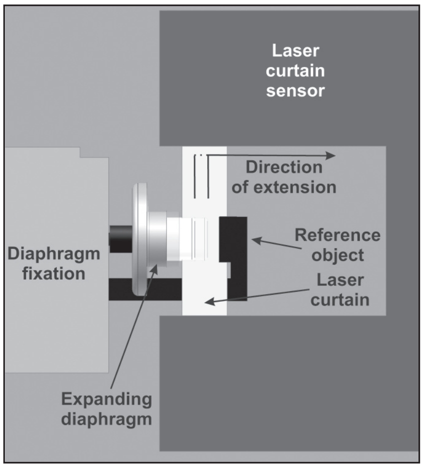

Figure 4. *Tested measuring principle*

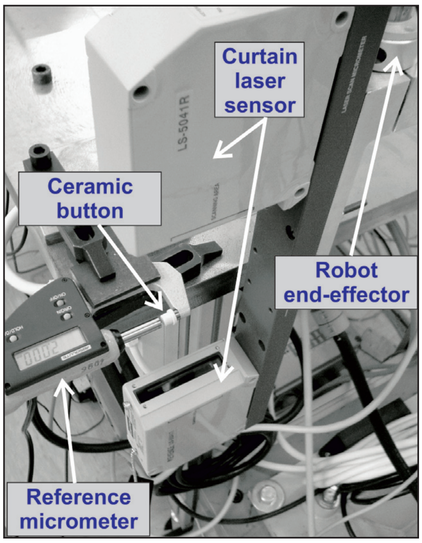

Figure 5. *Measurement equipment*

3.3 Epson robot

The SCARA Epson E2S651 robot with 4 DOF (RRTR - Rotation, Rotation, Translation, Rota-tion) is frequently used for automation of assembly in industrial processes. It has a cylindrical working range with radius 280 mm to 650 mm. The velocity can be up to 6300 mm/s for the first and second axes, 1100 mm/s for the Z-axis and 1870°/s for the rotational U-axis. The repeatability specifications are very good: 15 μm for the first and second axes, 10 μm for the Z-axis and 0.02° for the U-axis. The Epson robot was used as an carrier for the laser measurement sensor.

4 Methodology

4.1 Variable crevice width

Measurements of a variable crevice width were performed to determine if the selected laser micrometer is appropriate for desired measurements. On the end-effector of the robot a laser measuring system was attached. Robot use was necessary for positioning of the laser system and also for performing some additional tests.

In front of the robot a special table was set and with another laser system levelled to 0.1 mm. On the table a reference micrometer was attached with a few cramps and additional metallic parts. One of the micrometer measuring faces was equipped with a ceramic button to simulate real conditions of the diaphragm (Figure 5). Surrounding temperature was stable at 23 °C.

Both, micrometer and laser controller, were connected to the personal computer via serial port for data sampling with frequency of 2 Hz. The initial crevice width was set to 0.3 mm. At this width the whole system was positioned and rotated to laser sensor returning as close as 0.3 mm. This procedure involved laser system positioning and rotating as well as micrometer levelling to set micrometer faces as parallel to the laser curtain as possible. During measurements, the crevice width was manually changed by hand with a step of 0.100 mm to the final width of 2.000 mm. At every step of 0.100 mm a small pause was made to sample a few measurements. Four series of measurements were performed, two while enlarging the crevice width and two while reducing the width. This was necessary to check possible laser micrometer hysteresis existence.

4.2 Stability of fixed width of micrometer crevice

The measurement conditions and equipment in this set of tests did not differ from conditions in previous test. Measurements were performed to determine if laser measurements of fixed width of mechanical micrometer crevice is stable in longer period. Four series of measurements were performed, where the width of the micrometer crevice was 0.500 mm, 1.000 mm, 1.500 mm and 2.000 mm. The appropriate width was set and left for approximately 15 minutes with sample frequency of micrometer and curtain laser sensor set at 2 Hz.

4.3 Stability of moving laser system when width of micrometer crevice was fixed

These measurements are totaly equal to the previous, except the laser micrometer was moved by the Epson robot. These tests should verify if the laser micrometer system shows different measurement values if the mechanical micrometer crevice lying in different positions of a laser curtain. Again, four fixed width of micrometer crevice was set: 0.500 mm, 1.000 mm, 1.500 mm and 2.000 mm. The laser system curtain width was large enough to move laser system for 20 mm in 1 mm step.

5 Results

5.1 Variable crevice width

Figures 6 and *7* show measurement results for conditions when reference micrometer crevice width was changing - enlarging or reducing. Both figures show on the horizontal axis the value measured by reference micrometer and on vertical axis the difference between the micrometer value and value measured by laser curtain sensor. All measured laser values at certain reference width were averaged and for this reason also values in range of 1 μm arise. As can be seen, the diference on figure 6 is between 34 μm and 38 μm and has a positive tendency, probably originating from a temperature influence or even from the human manually rotating micrometer spindle. On figure 7 difference is between 38 μm and 40 μm.

It can be seen that the error value is quite constant in a range from 0.3 mm to 2 mm, between 36 μm and 39 μm. This is a systematic error, probably originating from parallel misalignment of the mechanical micrometer faces, influencing the laser micrometer measurements. When the relative measurement values are observed the differences are below the desired 0.01 mm, having values between 2 μm and 4 μm.

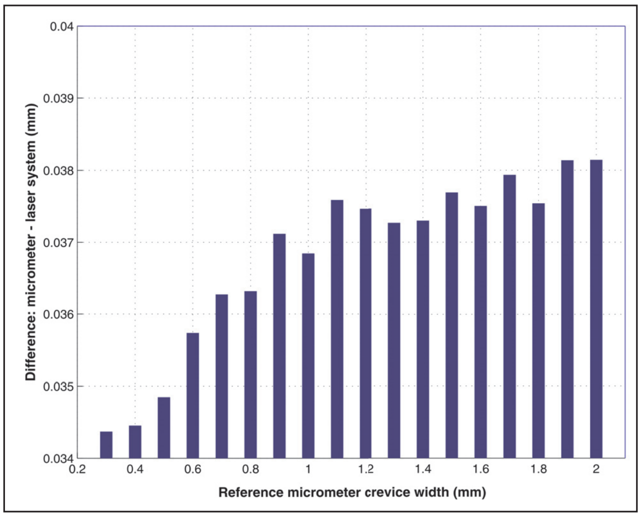

Figure 6. *Difference between mechanical and laser micrometer when crevice width was enlarged*

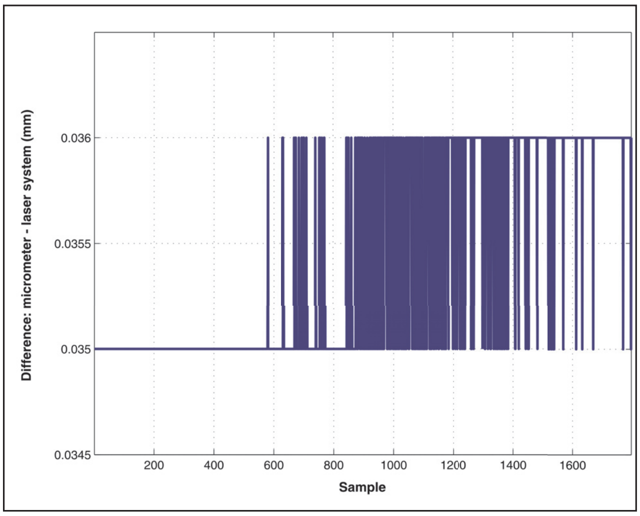

Figure 8. *Difference between mechanical and laser micrometer with crevice fixed width at 1 mm*

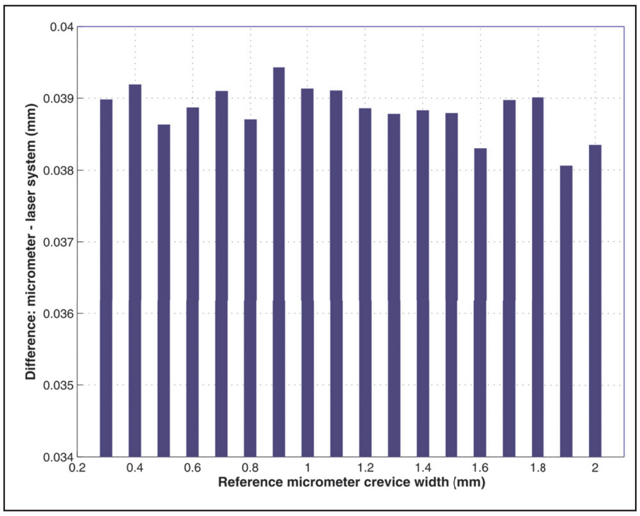

Figure 7. *Difference between mechanical and laser micrometer when crevice width was reduced*

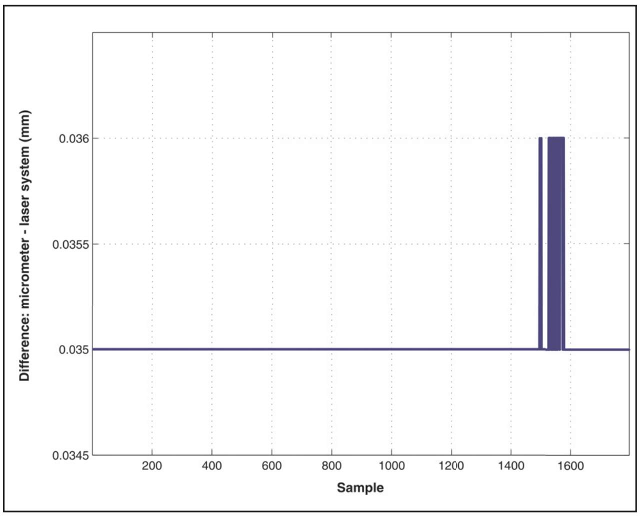

Figure 9. *Difference between mechanical and laser micrometer with crevice fixed width at 2 mm*

5.2 Stability of fixed width of micrometer crevice

Figures 8 and *9* show the stability of the fixed width of micrometer crevice over longer period of time. Horizontal axis represents samples with frequency of 2 Hz while the vertical axis shows difference between reference micrometer value and a value measured by laser system.

Figure 8 shows results for crevice width of 1 mm and figure 9 for width of 2 mm. Again systematic error of cca. 35 μm is present. Observing the value over the whole time period, very stable measurement value can be observed not changing more than 1 μm.

5.3 Stability of moving laser system when width of micrometer crevice was fixed

Figure 10 shows results of measurements where laser system was moved by the robot at some fixed width of micrometer crevice. Horizontal axis represents the position of the laser system relative to the start position, while the vertical axis shows difference between reference micrometer value and a value measured by laser system.

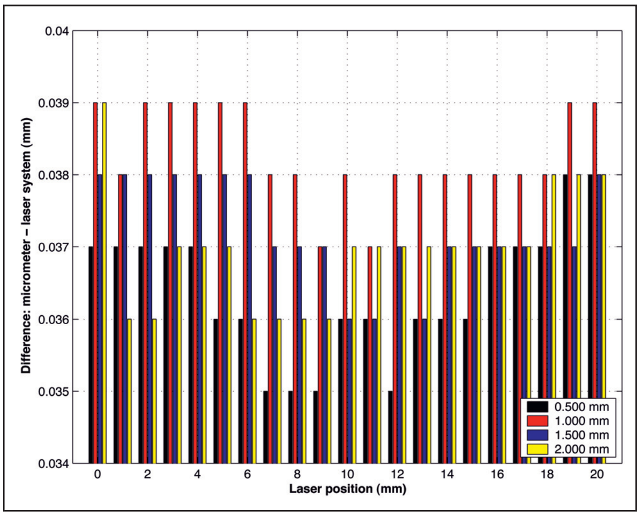

Figure 10. *Difference between mechanical and laser micrometer with crevice fixed width and laser system being moved*

Legend shows which bar column belongs to a certain crevice width.

Again systematic error exists having value from 35 μm to 39 μm. From the measured data can be concluded that moving the laser do not influence measurement values compared to the case when it was fixed.

6 Compensation of parallel misalignment between laser micrometer curtain and measuring object

6.1 Theory

Tests and results above demonstrated that is possible, by using tested laser micrometer curtain sensor, to measure the expansion of the diaphragm in the process of thermostat sensor filling. These results also showed that perfect parallelism between ceramic button attached on the diaphragm and the reference object can ba a problem if various sensors are used. This problem does not fade away if some reference crevice is used for calibration and then all four sensors are levelled in a way that the error, due parallel misalignment, is on all stages the same. It might happen that all diaphragms are not completely the same in dimension, the fixation rod is not bend by the same angle, etc. For this reason it is necessary to be able to measure or calculate and compensate the diferences in rotation that can occur during manufacturing.

6.2 Possible solution

In the figure 4 one reference object can be seen. In order to compensate for diaphragm errors then only one reference object is not enough, an additional reference crevice must be used.

A situation is sketched in *figure 11*, where diaphragm fixation object, middle cube and right reference ceramic are fixed together.

In the upper right-hand part of the figure is a ceramic button, part of the expanding diaphragm. The radius of

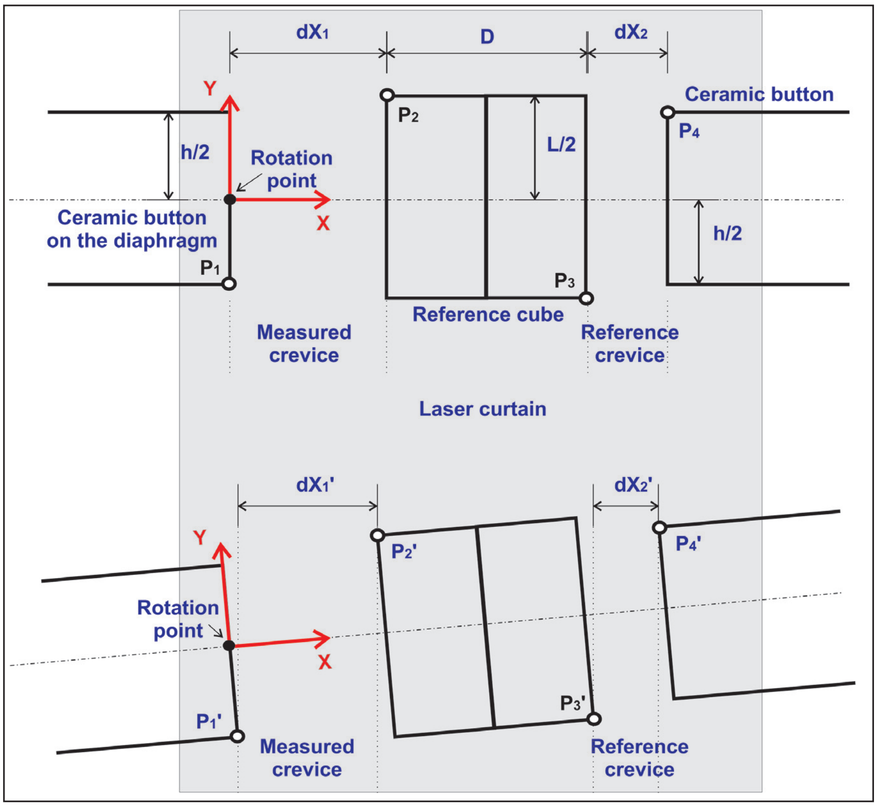

Figure 11. *Difference between micrometer and laser system when crevice width was reduced*

this round button is marked with h/2. In the upper middle part is a reference cube with a half of dimension of L/2 and D. The dimension dX_1 is a measured crevice dimension, when no rotation error is present. In the upper righthand part of the figure is another ceramic rounded button, but this one is fixed. Dimension dX_2 is fixed and well known or premeasured with some high accurate device.

At the bottom of the figure is depicted a situation, where the whole system is rotated over the rotation point. In the real situation both, diaphragm and laser system, can be rotated, but here only the diaphragm system with appropriate mechanical parts are virtually rotated. If some rotation is applied then dimension dX_1 is changed, to the dX'_1. Also the measured dimension dX_2 changes to dX'_2.

6.3 Mathematical analysis

In figure 11 we can see that four edges of present objects are marked with a dot or a point. These points have a coordinates dependant to the rota-tional point coordinate system:

$P1=(0, -h/2)$
$P2=(dX_1, L/2)$
$P3=(dX_1 + D, -L/2)$
$P4=(dX_1 + D + dX_2, h/2)$

When the dimension of the second or reference crevice is premeasured and then the same crevice is measured at some rotation, then is possible to calculate the rotational angle of the whole system for one dimension. After some simple mathematical calculations, mainly by using homogeneous transformation matrices (Lenarcic and Bajd, 2003), the rotational angle can be calculated, by getting two solutions, only the smaller angle is the right one. When this angle is calculated it is possible to calculate the crevice width dX_1 (Equation 1), even if width dX'_1 was measured by curtain laser system.

$$dX_1 = \frac{dX'_1 + y_2 \sin\varphi - y_1 \sin\varphi}{\cos\varphi} \quad (1)$$

7 Conclusion

The manufacturing of expanding medium sensor thermostats is a very difficult process. As pre- sented here, the process of filling of the sensor system has to be accurate to a few hundreds of a millimeter. That is why is most necessary to equip current filling machines with appropriate high-tech and precise measurement systems in order to monitor the production quality and be able to respond and control the necessary process parameters.

The presented idea was fully tested in the laboratory. The results show that Keyence laser cur- tain micrometer system enables measurement of desired parameters with an accuracy of a few micrometers. This system is also very stable over longer period of time. The system is also inde-pendent to position of the crevice inside the laser curtain.

In the tests also demonstrated that the reference system should be parallel to the diaphragm ce- ramic button for accurate measurements. This is impossible in production line and for this reason a solution with one variable and one reference, dimensionally known crevice is also presented, where simple mathematical analysis is needed.

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Uporaba optičnega mikrometra za merjenje raztezka membrane mehanskega termostata

Razširjeni povzetek

Članek opisuje testiranje idejne zasnove sistema za nadzor oziroma merjenje raztezanja membrane mehanskega termostata v procesu polnjenja sistema diastata z ustreznim oljem. Sistem diastata je sestavljen iz membrane in temperaturnega čutila, ki ju povezuje tanka kovinska cevka, imenovana kapilara. Diastat se v neki proizvodni fazi napolni s posebnim oljem, ki služi kot razteznostni medij. Za pravilno delovanje oziroma preklapljanje stikala mehanskega termostata pri nastavljeni temperaturi je najbolj pomembno, da je proces polnjenja diastata s posebnim oljem nadzorovan in se membrana v tem postopku raztegne za določeno razdaljo. To razdaljo je potrebno doseči na nekaj stotink milimetra natančno.

V članku predstavljamo rešitev, za katero smo kot merilnik raztezka membrane uporabili zelo natančen laserski zavesni mikrometer podjetja Keyence LS-5041 s krmilnikom LS-5501, raztezek membrane pa smo simulirali z referenčnim kljunastim mikrometrom Mitutoyo 293-666. Zavesni merilnik Keyence ima definirano natančnost ±2 μm in ponovljivost ±0,3 μm. Referenčni merilnik Mitutoyo ima merilno napako 2 μm, podatek o ponovljivosti pa ni bil podan. Opisani merilni sistem bi namestili poleg obstoječe rotirajoče polnilne naprave, saj zaradi vrtenja in izredno malo prostora namestitev merilnikov na samo napravo ni mogoča. Testiranja so pokazala, da uporabljeni merilnik Keyence ni samo natančen, ampak so meritve tudi zelo stabilne v daljšem časovnem obdobju, položaj merjene špranje v merilnem območju laserja pa tudi ne vpliva na natančnost meritev, saj se vse merjene vrednosti nahajajo znotraj podanega območja ±2 μm.

Žal pa so poskusi pokazali, da merjenje širine ene špranje ni dovolj, da bi lahko kompenzirali nepravokotnost laserske zavese merilnika Keyence in špranje, ki smo jo ustvarili z referenčnim kljunastim mikrometrom Mitutoyo. Zato je za kompenzacijo potrebno uporabiti še dodatno špranjo. Njena velikost pa mora biti znana vnaprej. Z meritvijo te špranje in primerjavo z njeno dejansko širino pa lahko izračunamo naklon oziroma nepravokotnost v vseh potrebnih oseh. V članku podajamo tudi grafično ponazoritev in osnove matematične analize za kompenzacijo nepravokotnosti med lasersko zaveso in špranjo.

Izvleček: V članku predstavljamo nekaj začetnih meritev raztezanja membrane mehanskega termostata v procesu polnjenja s posebnim oljem. Prikazujemo rešitev z zelo natančnim laserskim zavesnim mikrometrom in referenčnim mehanskim kljunastim mikrometrom. S tem sistemom je mogoče meriti raztezke membrane na nekaj mikrometrov natančno. Vse meritve smo primerjali z referenčnim mehanskim mikrometrom.

Ključne besede: mehanski termostat, polnilno olje, laserski mikrometer, natančne meritve, mehanski mikrometer,