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The measuring and control system for improved model based diastat filling quality

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ABSTRACT

The article describes the development and testing of a measurement and control system in industrial environment. This system enables fast and accurate membrane expansion measurements. The membrane is part of the sensor system called diastat, which is filled with a special oil. The diastat is part of mechanical capillary thermostat. To demonstrate the right selection of the measurement equipment and data processing methods, several tests and analysis were performed: the dynamic response of the diastat membrane during filling, measuring accuracy, nonlinearity and temperature stability of the measurement system with integrated distance sensor and the most important verification measurements with reference control procedures in manufacturing process. It was demonstrated that a number of novel approaches need to be introduced enabling installation of the measurement and control system in the production of the thermostat diastats.

1. Introduction

The article describes the design, development, tests and evaluation results of the measurement and control system needed for control of filling procedure of a product called the diastat. The funder (project partner) for this development project was ETA Cerkno company from Slovenia. The diastat is a part of the mechanical capillary thermostat (Fig. 1) filled with a special oils. The implementation of the presented system was necessary to overcome problems with proper diastat filling and resulting quality of their products.

The main reason is to improve the quality of the manufactured products, to meet the requirements of international standards, such as the ISO standard, and to decrease the quantity of false products. These are present due to inadequate input materials or deficient manufacturing (Vacharanukul & Mekid, 2005). The following categories are often incorporated in the manufacturing production processes: computer aided manufacturing (Golnabi, 2003), various measuring systems (Rejc, Činkelj, & Munih, 2009) and automated visual inspection (AVI) systems (Chin & Harlow, 1982; Rejc et al., 2011). When these systems are introduced into the production, they need to work flawlessly in a longer time period (Nurminen, Karonen, & Hätönen, 2003).

The approach presented in our system belong to the first and second category. Several measurements are influencing the control system. The entire system consists of oil temperature control, oil pressure regulation and very accurate membrane expansion measurements.

In the field of industrial measurements, several parameters are often observed, such as pressure, temperature, distance, viscosity, mass or velocity. The most frequent in industry is distance measurement. The literature (Thiel, Pfeifer, & Hartmann, 1995) states that the most frequent distance measurement range is from 0.1 m to 40 m where contact micrometers (Zeitouny et al., 2011), calipers and incremental probes are mostly in use. In the class of contactless sensors, ultrasound, inductive (Sydenham, Taing, Mounsey, & Wen-Xin, 1995) and capacitive sensors (Zhu, Spronck, & Heerens, 1991) are dominant. Very accurate (Xing et al., 1987) distance sensors based on laser light are also being installed. The working principle can be triangulation (Ji & Leu, 1989), conoscopic holography (Spagnolo, 2006) or interferometry (Bapna, Verma, & Joshi, 1992).

Beside the distance measurement also temperature and pressure measurements are of upmost importance in industrial environments. Temperature can be measured through direct contact with the measured object or with observation of heated or cooled material (Childs, 2003). We can find several temperature measurement methods that differ in their speed and accuracy. In industry most frequently used temperature sensors are thermocouples, resistance temperature detectors and integrated temperature sensors (Campbell, 1970; Liu, Ma, & Yang, 2011). In the field of pressure measurements the capacitive pressure sensors (Kumar, Kumar, Jain, & Kashyap, 1999) are most frequently used, but also other measurement principles can be found (Harada, Ikeda, Kuwayama, & Murayama, 1999), for instance the piezoresistive measurement approach.

The most important part of our investigation was to enable very accurate distance measurements. Therefore, the developed mea-

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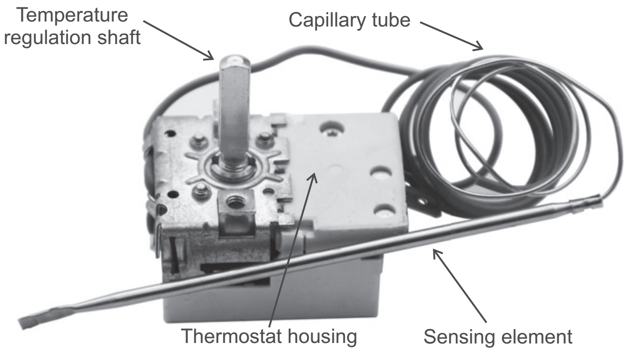

Fig. 1. Capillary thermostat.

suring system with the integrated distance sensor was verified in detail. Comparative measurements were performed by using a certified contact micrometer and real objects. The entire measurement and control system performance was verified with reference control procedures in manufacturing process. The measurement approaches and test results are presented and discussed.

2. Diastat

The diastat is one of the components in the capillary thermostat, used in everyday life for temperature regulation in household appliances (European standard, 2003; Peffer, Pritoni, Meier, Aragon, & Perry, 2011). Capillary thermostats differ in dimensions and performances. The project partner produces 6 different types of capillary thermostats, covering the temperature ranges from −5 °C to +550 °C.

The diastat consists of a membrane, capillary tube and a sensing element (Fig. 2), filled with a special oil as a heat-mechanical transducer. The oil expands with the temperature rise. Larger oil volume results in the membrane expansion that is pushing the capillary thermostat switch. Switching occurs when the membrane expansion is sufficiently large. The user predetermines the desired switching temperature with the capillary thermostat regulation shaft. This switching temperature can be also fixed in advanced by the manufacturer. The filling oils differ in viscosity and chemical properties. The details regarding the oil characteristics will not be part of this article.

The quantity of thermostat types that project partner manufactures is top grade in comparison to the number of diastat families. There are several thousands different diastat types and millions are manufactured every year. The types of diastat differ in all three component parts. The connection between the membrane and the sensing element is provided by the capillary tube. It is very thin with the outer diameter of 1 mm and inner diameter of 0.5 mm. The length varies from 470 mm to 1550 mm. Apart from the capillary tube, also the sensing element is not built into the thermostat housing. The outer diameters of the sensing element differ from 3 mm to 6 mm and the lengths between 73 mm and 201 mm.

The membrane is the most important part of the diastat. Its design enables the conversion of changes in oil temperature into linear membrane expansion. The membranes differ in radius, from 20 to 26 mm, and also in a membrane part that asserts force on the thermostat switch. This part can be made of ceramic as a ceramic button or from metal as a metallic button (Fig. 3). These differences do not influence on the thermostat performance.

3. The diastat filling procedure

Each diastat is filled with oil. The filling procedure of approximately 90% of manufactured diastats is performed on rotary filling machines (Fig. 4). The quantity of ceramic button membranes diastats that are filled on rotary machines is three times larger than those with the metallic button. In production hall six rotary machines are situated, each with 48 filling heads. The filling procedure is as follows. The workers manually position the sensor element of the diastat into the filling head, while the capillary tube and membrane hang freely in the air. The rotary machines rotates with a cycle time of cca. 2.5 s. With each cycle the diastat moves from one procedure phase to another, where the duration of the phases can be several cycles. In the first two phases several diastats are in vacuuming process, sucking out all the air and checking if the diastat does not leak. Follows the longest phase where the diastats are filled with oil. The machine is under pressure pushing the oil into the diastats and expanding the membranes. In the final phase each diastat sensor element is taken out from the filling head. This procedure can be skipped for those diastats that are filled with low viscosity oils. Finally, the tip of the sensor element is mechanically pressed and electrically welded to close the diastat.

The other cca. 10% of the diastats are meant for special purposes, where regulation tolerances are very narrow. As it is difficult to assure these tolerances with the use of rotary machines, these diastats are filled manually. This procedure lasts about 2 days. Due to long manual filling procedure the partner aimed to transfer some of these special diastat types for filling on the rotary machines after our project with the measurement and control system is implemented.

4. Influence of diastat filling on quality of the thermostat temperature control

Industrial environment requires very accurate distance measurements. The expansion of the membrane during filling can range from 0.07 mm to 0.5 mm, depending on the diastat type. The expansion of a kitchen oven thermostat diastat membrane for 0.01 mm represents a difference in temperature of 3 °C. These two facts require the measuring accuracy of the implemented measuring system within the range of 5 μm, corresponding to ±1–2 °C error for calibrated thermostat.

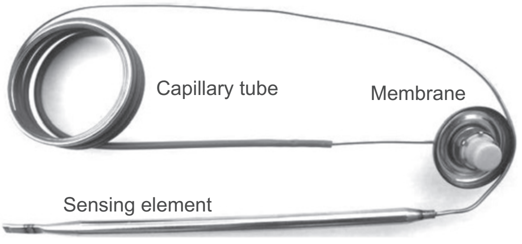

Fig. 2. Diastat.

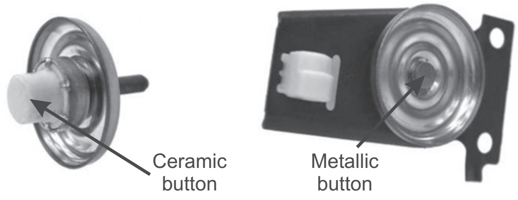

Fig. 3. Two different types of membranes.

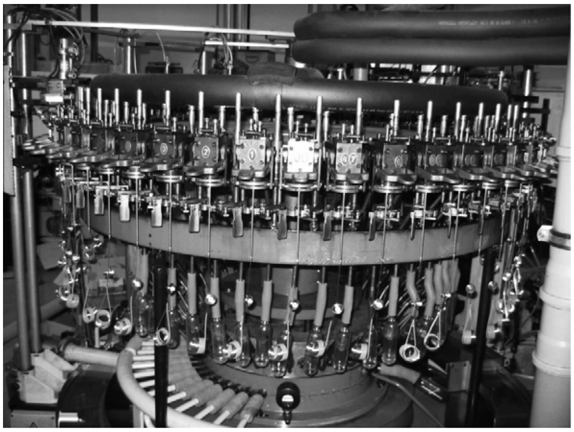

Fig. 4. Rotary machine.

The European standard EN 14597 (European standard, 2006) in the field of temperature control devices and temperature limiters for heat generating systems states that the maximum deviation from the set temperature can be ±5%. At the temperature of 200 °C this equals to ±10 °C. The partner has narrowed the internal tolerance ranges to ±8 °C. The quality of the manufacturing process of all thermostat parts directly influences the tolerance range of regulated temperature of the mechanical capillary thermostat, however the quality of the diastat filling procedure is the most influential.

Fig. 5 shows the characteristics of the membrane during expansion or contraction vs. the oil temperature. On the horizontal axis the temperature scale is displayed, on the vertical axis is given the membrane expansion in millimeters. The geometry of the membrane results in very linear transformation between temperature and expansion. The most important parameter of the diastat is the so called closing temperature, marked with T_C. In the Fig. 5 the diastat has $T_C = 25$ °C. The diastat manufacturer has set the internal tolerances for membrane contraction from the T_C downward. This range is set from 0.02 mm to 0.08 mm. In this range the membrane contraction should stop. This contraction, when the temperature is below T_C, is called membrane back movement and the expansion above T_C is labeled as membrane forward movement.

The displayed characteristics (Fig. 5) shows an incorrectly filled diastat. The back movement of the membrane is 0.17 mm until the membrane is completely contracted. This occurs at −25 °C. The safe control temperature range for this diastat type is from 25 °C to −10 °C. The back movement is too large and for this reason also the T_C is not 25 °C anymore, but is much lower. If this kind of diastat is built into the thermostat, the quality and safety point of view are critical and such thermostat must be rejected.

Suitable back and forward movement of the diastat membrane, providing adequate quality of the product, is not only desirable by the manufacturer but required also by the buyers. In the field of household appliances the international standards needs to be observed. The European standard EN 60335-1 (European standard, 2001a) states that all household appliances are constructed not to cause danger for the user in normal conditions, even when used inappropriately. This recommendation does not apply only to the apparatus as a whole, but also to its components (European standard, 2001b), and thus to the mechanical thermostats and consequently to the diastat.

To explain why the filling quality of the diastat is the most important parameter, we must go back to the kitchen oven example. When the thermostat of the kitchen oven is set to off it must not happen under any circumstances that the heater would be turned on. This is directly related to the proper amount of oil in the thermostat diastat. If too much oil is pushed into the diastat and the room temperature falls under the defined temperature (23 °C), for example to 15 °C, the thermostat would turn the heater on. Such behavior is inadmissible for safety and economical reasons.

5. Diastat filling quality control

The initial oil filling pressure on all filling machines is calculated by legacy mathematical equations. In the past, this calculation was used to fill a few hundreds of diastats and a dozen of them was taken for the quality control, where back and forward displacement of the diastat membrane is checked. The filling pressure was adjusted in accordance with the information and the same procedure was repeated. The drawback of this procedure is the delay of 15 to 30 min and many inadequately filled diastats could be produced during that time. Several parameters can influence the quality of

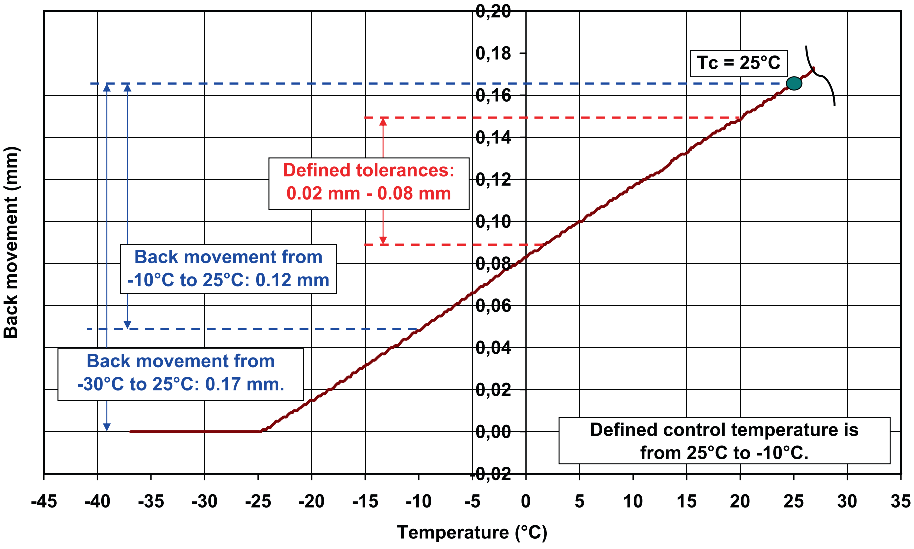

Fig. 5. False characteristics of the diastat.

filling, such as filling pressure, temperature of the oil and the membrane volume.

The procedure influenced by numerous parameters can't be controlled properly. This can be confirmed with the diastat filling quality control data. The procedure of the quality control is as follows. The membranes of several diastats are fixed into special housings and contact micrometers are positioned on the membranes' button. Then the sensor elements are put into liquid filled tubs with different temperatures. When the displacement of the membranes is stabilized for each tub, the measured expansion or contraction is assessed. In Fig. 6 the data measured for back membrane movement for diastat type A for the year 2006 is displayed. 7067 samples were included in the test. The vertical dotted lines present the limits of the theoretical back membrane displacement that ranges from 0.02 mm to 0.08 mm. It can be recognized that the majority of the tested diastats is filled with too much oil and their back movement is mostly 0.10 mm. It is also necessary to mention that the diastats on the left side are completely empty. If these diastats are integrated into the thermostat, the thermostat does not control the temperature properly or does not work at all. If too many empty or almost empty diastats of one type is discovered by the quality control, then 100% of production of this diastat type is tested. This means additional costs that our partner wants to eliminate. In the past, the solution to this problem was through raising the filling pressure. It is namely still possible to adjust the closing temperature (T_C) of the thermostats equipped with over filled diastats by adjusting a dedicated setting screw. However, the method has limited success.

In 2007 the partner introduced an additional operation, after the membranes being manufactured, to improve the filling quality. From each manufactured series some membranes are selected and their expansion is tested at 3.5 bar. The membrane is filled with air and the expansion is measured with a contact micrometer. Related to the measured expansions the manufactured series of membranes are divided into groups. This demonstrates slight differences between different production series due to the membrane input materials. This membrane classification is taken into account as a variable parameter when the initial filling pressure is calculated. The results of the quality control from the year 2007 for the diastat type A can be seen in Fig. 14.

The membrane classification parameter moved the back membrane displacement result chart slightly to the left. In Fig. 14, the majority of the tested diastats has the back movement close to the theoretical range, but the characteristics is too wide. Narrowing and increasing the number of membrane groups did not show any improvement. All these efforts have shown that the presented procedure can not improve the quality of diastat filling on the rotary filling machines and the only option was to upgrade these machines with a membrane measurement and pressure control system. This system construction and operation is described in this article.

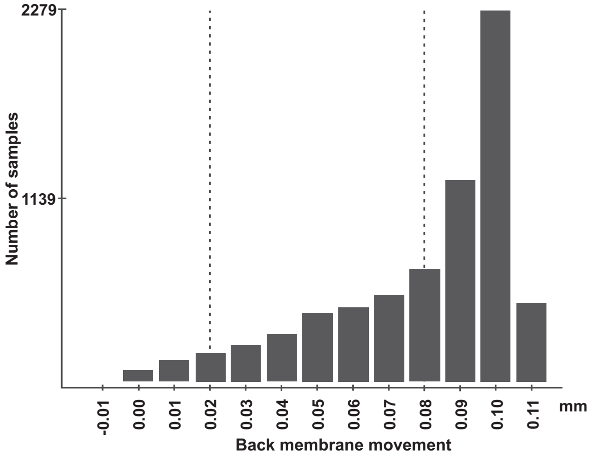

Fig. 6. Back movement of diastat type A in year 2006.

6. Equipment of measuring and control system

First task of the team working on the project was to develop the approach for controlling the filling procedure on existing filling rotary machines. The working principle is shown in Fig. 7.

The presented system must be supplied with the following momentarily data to control properly the filling pressure: oil temperature, filling pressure and membrane expansion. These data and the company's mathematical model of membrane expansion are used to calculate and adjust the new filling pressure.

6.1. Compact controller JUMO as communication interface

Between the sensors on the rotary filling machine and the central computer a compact controller JUMO dTron 304 was installed. It was used to transfer all sensor data to the central computer using the serial RS-485 interface. First, the compact controller was intended to perform pressure control, however initial tests showed that the accuracy of the pressure control was poor. For this reason a special pressure controller was used. The appropriate pressure is adjusted by sending the data from the central computer to the compact controller. Each rotary filling machine has its own compact controller.

6.2. The filling pressure measurement and control

In order to maintain the appropriate pressure level in the filling system, a nitrogen filled pressure cylinder was used to prevent reaction with the filling oil. We installed a Festo pressure controller on the intake pipe of the cylinder (type MPPE-3-1/4-10-010-B with the regulation area between 0.1 and 10 bar). The pressure is set by analog input voltage from 0 V to 10 V and adjusted by the compact controller JUMO.

The momentary filling pressure can be read from the pressure controller. To get more accurate readings an additional pressure sensor was mounted on the inlet oil pipe of the rotary machine. It is a piezoresistive pressure sensor Festo, type SDET-22T-D10-G14-U-M12 with measuring range from 0 bar to 10 bar and with analogue voltage output from 0 V to 10 V. The manufacturer specifies the accuracy of ±1% over the entire measuring range. This sen-

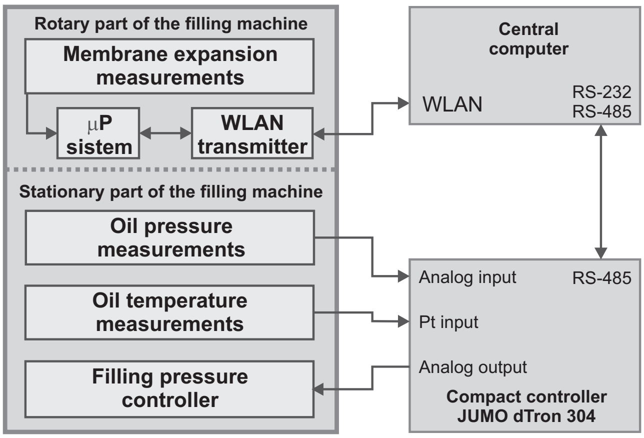

Fig. 7. Working principle of the developed system.

sor is connected to the analog input of the compact controller JUMO enabling readings of the momentary pressure from the central computer. Both the regulator and the pressure sensor are stationed at the rotary filling machine.

6.3. Oil temperature measurements

The oil temperature reading on each rotary filling machine is performed at the oil inlet entry of the filling device. The measuring sensor is a Pt-100 JUMO VIBROtemp 902004/10-390-1003-1-7,5-29-121–21. The measuring range of the sensor is from −50 °C to +300 °C, with transfer accuracy $\leqslant \pm 0.1\%$. The sensor does not need a special power supply and is connected to the Pt input of the compact controller JUMO.

6.4. The membrane expansion measurements

When choosing the appropriate measurement equipment, not only the measuring accuracy and cut-off frequency were considered, but also the fact that this measurement equipment will be installed on the existing rotary machines. The space around these machines is limited and the environment is dirty due to possible oil leakage. It was also necessary to ensure that the installed measurement equipment will not slow down the work process and jeopardize the workers' health. Also, the solution for measured data transfer from the rotary machine to the central computer had to be considered. In the initial phase, the company demanded that, because of the large number of manufactured diastats with a ceramic button, selecting and testing of the measuring equipment should be subjected to these types of membranes.

To enable very accurate distance measurements, the most suitable solution would be the use the contact sensor, where the tip of the sensor would be in contact with the membrane button. This solution would require one working phase more and would slow down the working process. Besides, also the space on the rotary machine prevents the installation of a contact sensor.

After initial tests (Rejc & Munih, 2007) a very compact optical distance triangulation sensor head, the Keyence PT-165 with controller PT-A160 was selected. Its dimensions were satisfactory and also the laser safety issue (European standard, 2007) was solved as it has an ordinary red LED light source. This sensor together with a dedicated microprocessor system and MOXA WLAN transmitter represents the entire measuring system for each of six rotary filling machines.

7. The measuring system for membrane expansion measurement

7.1. The Keyence PT-165 distance measuring sensor

The distance triangulation distance sensor head Keyence PT-165 with controller PT-A160 was tested in out study. The receiver of the LED light is a PSD (Position Sensitive Device) sensor. The measuring range of this sensor is 4 mm or ±2 mm at 22 mm distance from the head. The repeatability is specified as 3 μm on a white sheet of paper. The beam diameter is approximately 1.5 mm. The specified temperature working range for the head and the controller is between 0 °C and 50 °C. This information is very important because the temperature in the production hall can reach over 40 °C in summer. The measurement head dimensions are 36 × 39 mm.

In the specifications the manufacturer also specifies the analog voltage output temperature drift. For the measurement head it is 0.1%/° (4 μm) F.S. (Full Scale) and 0.05%/° (2 μm) F.S. for the controller. Unfortunately the manufacturer did not specify the information about measurement linearity and the environmental protection (IP – Ingress Protection) of the PT sensor.

The controller is equipped with two micro potentiometers allowing zero value and gain setting of the output analog voltage. The output voltage range is ±2 V – the same as the measuring range of the sensor in mm. A micro-switch is also available for adjustment of the frequency response of the sensor. The value of 1 ms sets the cut-off frequency (−3 dB) at 400 Hz and the value of 10 ms at 40 Hz.

The membrane expansion dynamics analysis (Fig. 8) shows that the filling characteristics of the diastat membrane filled with a low viscosity oil at 7.0 bar pressure and the oil temperature of 27.1 °C can be approximated with a 2nd degree transfer function (Eq. (1)) with the cut-off frequency of 5 Hz. This analysis showed that the selected distance sensor cut-off frequency is much higher.

$$G(s) = \frac{0.06043}{0.03928s^2 + 0.3964s + 1} \tag{1}$$

7.2. The microprocessor system for measured data sampling, analysis and transmission

The analog voltage measured needs to be converted into digital representation. For this reason a dedicated microprocessor system was developed for each of the six rotary machines. This system samples measured data, performs mean value calculation of the sampled data and transmits the data from each rotary machine to the central computer. The microprocessor system was treated also as a part of the distance measurement system.

The heart of the microprocessor system is the Mega8 processor from Atmel with dedicated written software running. The digitalization of analog voltage is performed by the 12-bit AD converter MAX128 from Maxim with I^2C bus to the microprocessor. To prevent loading effects a voltage follower with OPA27GP operational amplifier was inserted between the sensor head output and the AD converter.

The system samples the sensor output voltage with the frequency of 1 kHz, performs averaging and transmits the data to the central computer with 20 Hz. The data is sent over the RS232 communication protocol to the MOXA NPort W2150 WLAN transmitter that is connected to the access point of the central computer, where transmitted data are read over virtual serial port.

On the rotary machines the expansions of the membranes can reach 0.5 mm. This information allowed us to use only a half of the entire measuring range of the PT sensor, from 0 V to 2 V. The AD converter internal reference voltage is 4.096 V. It can be split in half to use only 2.048 V, enabling to reach resolution of 0.5 μm per bit.

This system also samples the binary data from the magnetic switches that are placed around the rotary machines. These sensors give the information of a current position of the filling head

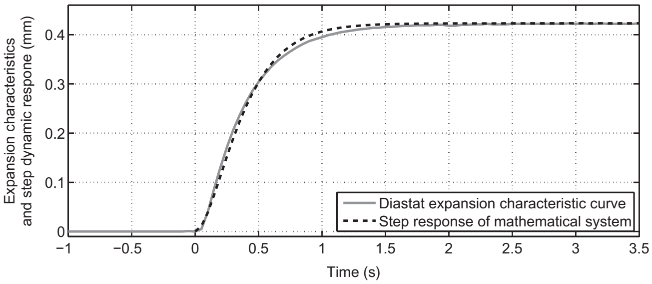

Fig. 8. Expansion characteristics and 2nd order function response.

equipped with measuring system in the filling procedure of the measured diastat.

8. Software

8.1. Microprocessor system

The Atmel microprocessor runs the dedicated software, which represents a bridge between the diastat expansion measurements and the transmission of measured data to the central computer.

For the operation of the entire system to run smoothly, the program in the microprocessor requires roughly three parts, which are displayed in Fig. 9. These parts are:

1. sampling and mean value calculation of diastat expansion,
2. nonlinearity compensation,
3. user interface.

The first part of the program contains sampling and expansion measurement mean calculation where both 8-bit and 16-bit Timer/Counters are used to set interrupts at specified counter values.

In the second part of the program not only the mean value calculation but also the assessment nonlinearity compensation is performed. This is necessary to improve the measurement characteristics. The detailed analysis of the nonlinearity compensation is described in the methodology and in the results section of this article.

The third part of the program enables the user to set the program parameters and performs the data transmission over wireless serial communication. The data sent consists of: the rotary filling machine number, serial number of the measurement, the position of the distance sensor in the filling rotary cycle and current diastat expansion measurement in micrometers.

8.2. Control program on the central computer

Adequate operation of the control program on the central computer is directly related to the functioning of the entire manufacturing process.

In the program the user determines only the type and group of the diastat to be filled on a particular filling machine and starts the control algorithm. In Fig. 10, the diastat filling characteristics is displayed in the zoomed window. The measured data are drawn in real time separately for all six filling machines. The program parameter determines the number of measured cycles after which the filling pressure is fixed.

In the Fig. 10 three measured filling characteristics are drawn. All three characteristics have the end expansion value inside the tolerance area of ±0.05 mm. For this reason no pressure change will be performed after preset number of measured diastats. The entire filling procedure lasts cca. 90 to 120 s, depending on the speed setting for each of the rotary machines. The filling procedure phases are labeled as follows:

1. Vacuuming phase. The air is sucked out of the diastat while membrane walls come in contact. This is the initial stage for the membrane expansion measurement. The stage last about 20 s.
2. Filling stage. The preset oil pressure fills the diastat with oil and the membrane expands. After the expansion is stabilized, the diastat sensor element is taken out of the filling head and the oil is pushed out of the diastat. When less viscous oil is used, the sensing element is not taken out of the head. The filling phase lasts about 50 s.
3. The sensing element is mechanically squeezed.
4. The squeezed part of the sensing element is welded to completely close the diastat system.

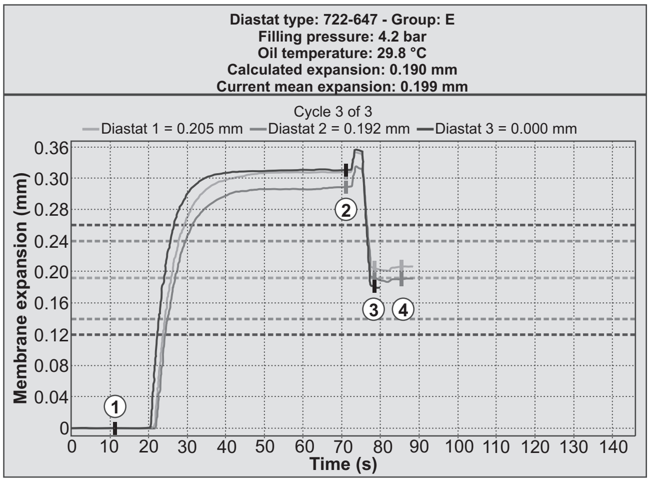
Diastat type: 722-647 - Group: E
Filling pressure: 4.2 bar
Oil temperature: 29.8 °C
Calculated expansion: 0.190 mm
Current mean expansion: 0.199 mm

Fig. 10. One of the six main program windows visualizing the measured results.

9. Methodology

9.1. The testing system with reference distance contact sensor

For the initial tests of the distance measurement equipment a special mechanical system was designed (Fig. 11). It consists of the Keyence PT contactless measuring system and a certified contact micrometer Mitutoyo MHD-164-161 with a measurement uncertainty of ±2 μm and resolution 1 μm. Between the two measurement systems a special mechanical system can be seen. This system allows the translation of a mechanical slider between both measurement systems. This mechanical system is intentionally very precisely manufactured without guidance and lubrication. At the edge of the slider the end of the micrometer is placed, which

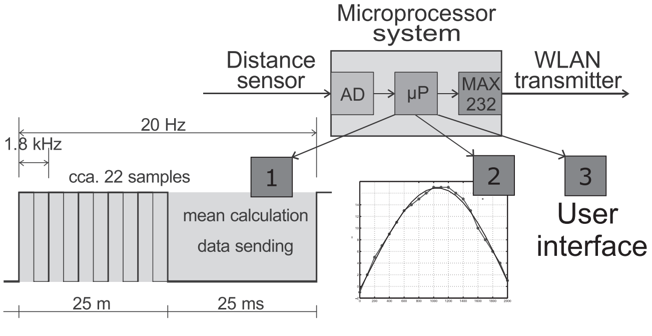

Fig. 9. The microprocessor program functions.

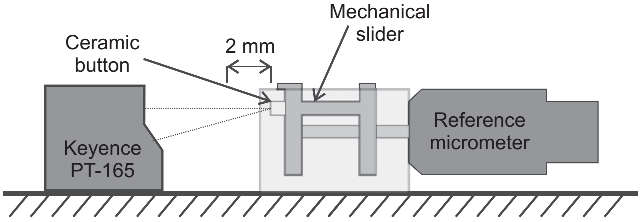

Fig. 11. Test system for nonlinearity acquisition.

allows pushing of the slider towards the Keyence measurement head.

9.2. Nonlinearity acquisition of the entire measurement system

The Keyence manufacturer gives considerable measurement information about the PT sensor, but the most important information about measurement linearity is absent. This information is a standard parameter of many distance sensors. Also by contacting the manufacturer we were not able to obtain the parameter value.

As the international standards and also the project partner set a very narrow permissible measuring error, the information on the sensor nonlinearity was required. The sensor head with its controller and microprocessor system constitute the entire measuring system. Therefore the nonlinearity was measured for the entire system in the range from 0 mm to 2 mm. The testing system can be seen in Fig. 11.

The test process was started by displacing the mechanical slider equipped with a ceramic button until the tested measurement system showed 0.000 mm. With the slider in this position, the reference contact sensor was reset to zero value. Then the reference sensor knob was rotated pushing the mechanical slider towards the sensor head until the reference value was 2.000 mm. The output of the tested system was initially different from 2.000 value. The proper value was set by rotating the gain potentiometer on the PT controller. This procedure adjusted the measurement characteristics between 0.000 mm and 2.000 mm.

To obtain the linearity information between these two points, the measurements, like those previously described, were repeated by displacing the reference distance sensor in steps of 0.1 mm. At each step, the tested system output was saved. The entire procedure was repeated several times as well as over longer time interval.

9.3. Indirect test of membrane expansion by the quality control procedure

As mentioned earlier the filling quality of the diastats is checked by the quality control where back and forward membrane movement is tested. Even when the measurement and control systems were implemented, this quality control remains to be the real reference control system during the production process. The quality control setup is computer driven and all data is saved in the database. This allows to access the test results from the previous years. Here, this feature is used to compare the filling results before and after the measurement and control system was implemented.

As an example are presented results for two of the most typical diastats in the production that are filled in the rotary filling machines. For this article purposes they are labeled as A and B. Presented are the results of back membrane movement after the membrane group information was taken into the initial oil pressure calculation. Before our investigation, the results of the quality control were worse. As a comparison we present also the result of a rotary machine filling of the diastat type C, also manufactured in large quantities. Before the measurement and control system was implemented, this diastat type was filled manually, as it is very temperature sensitive.

10. Results

10.1. Nonlinearity determination of the measurement system

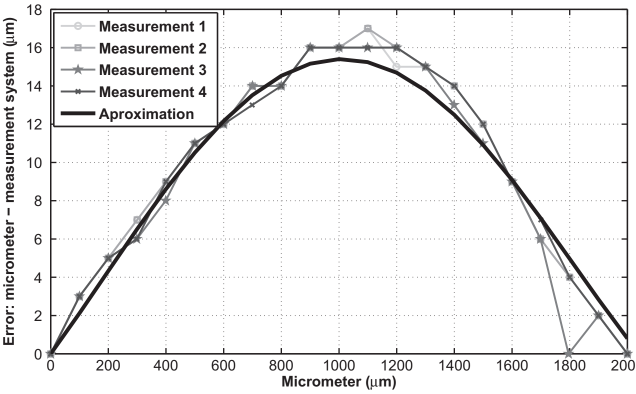

Fig. 12. The measurement system error before the use of nonlinearity compensation.

Fig. 12 shows the measurement characteristics of the entire measurement system taken from the reference micrometer values. The horizontal axis represents the reference Mitutoyo sensor values in µm and the vertical axis shows the error of the measurement system related to the reference values. In four displayed measurements can be noticed very high repeatability with maximum error 17 µm. In addition to the four characteristics, also a thicker black line is drawn, representing polynomial approximation of all four measured characteristics. The 4th order polynomial was used, described with the equation:

$$f(x) = 5 \cdot 10^{-12} \cdot x^4 - 2 \cdot 10^{-8} \cdot x^3 + 1 \cdot 10^{-5} \cdot x^2 + 0.0204 \cdot x \qquad (2)$$

It is important to notice that the displayed characteristics belongs to the measurement system of one rotary machine differing from other kits. However, all measurement systems can be linearized by the 4th degree order polynomial.

It is previously mentioned above that the maximal membrane expansion is 0.5 mm. For this reason should be the measurement error observed in a window of 0.5 mm. Considering the Fig. 12 is very important where this measurement window appears. If this window is observed from 0.0 mm to 0.5 mm, then the error is 11 µm, but if the window is observed from 0.8 mm to 1.3 mm, the error is only 3 µm.

The error can be even higher than that specified by the project partner. As the characteristics are highly repeatable, the nonlinearity compensation by using polynomials was included in the microprocessor system. In favor of the nonlinearity compensation speaks also difficulty in perfect reproducibility of the diastat membrane fixation.

For the use of polynomial (2) the results are displayed in Fig. 13. The horizontal axis represents the reference Mitutoyo sensor values in µm, the vertical axis shows the error of measurement system related to the reference values. The results of the

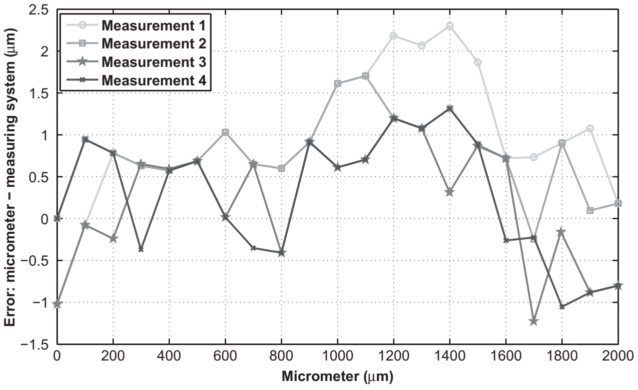

Fig. 13. The measurement system error after the use of nonlinearity compensation.

compensation are very good, with the maximum error of 4 μm over the entire 2 mm measuring range.

10.2. Indirect test of membrane expansion by the quality control procedure

First, the quality control results for back membrane displacement are presented for type A diastat. In the filling phase, where the diastat is closed, this diastat type is taken out of the filling head. The results presented (Fig. 14) belong to the time period from February 1st 2007 to August 31st 2007, when the membrane groups were taken into the initial filling pressure calculation. The horizontal axis represents the back movement of the membrane in millimeters and the vertical axis the number of samples. In all diagrams of this chapter the axes represent the same quantities.

A series of 5531 diastats of type A was tested with mean back movement value of 0.068 mm and standard deviation of 0.024 mm. As shown in Fig. 14 the characteristics is almost in the tolerance area, but it is too wide.

Fig. 15 shows the results of back membrane movement with the membrane group information and the measurement and control system included. The results are displayed for the time period from June 15th 2010 to December 1st 2010. A series of 7458 diastats was tested with the mean value of 0.064 mm and standard deviation of 0.020 mm. At this point it is good to be aware why some of the diastats are almost or completely empty. In some situations, when the diastat sensing element is taken out of the filling head, the filling machine stops. Because of the human error, these diastats are not removed out of the production. Another reason is false closing of the diastats. The quantity of empty diastats is low and for this reason the 100% quality control of the entire production series is not needed. The faulty thermostats with empty diastats are removed at the final adjustment of the thermostats.

Many types of diastats being manufactured with many different filling oil types used, allows us to present also the back movement results for some other diastat types. The diastat type B is also manufactured in high quantities. Because the filling oil for this diastat type has a very low viscosity, the sensing element was in the past not taken out of the filling head. This approach is better from the aspect of the filling quality. As the sensing element has to be longer, the material costs are considerably higher. After the closing, the sensing element part, which was inserted in the filling head, is cut off and put into waste.

Fig. 16 shows the results for the time period from October 1st 2007 to February 15th 2008, before the measuring and control system was integrated into the manufacturing process. A series of 8827 diastats was tested with mean back movement value of 0.082 mm and standard deviation of 0.026 mm.

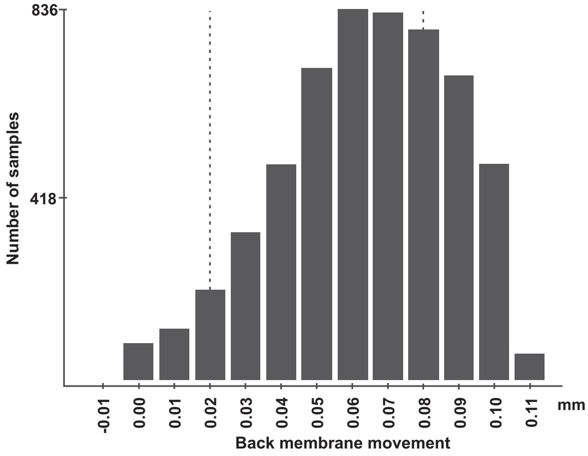

Fig. 14. Diastat A, February 1st 2007 – August 31st 2007.

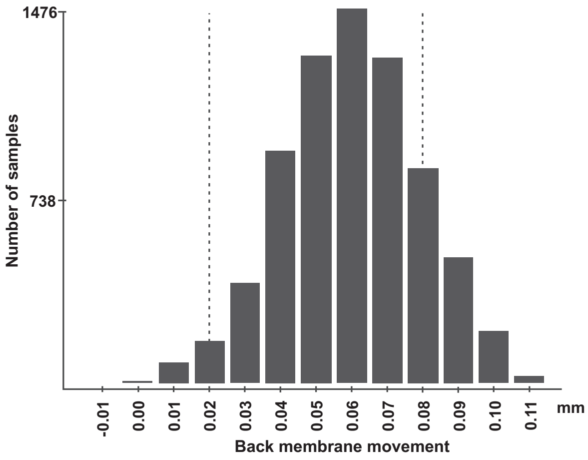

Fig. 15. Diastat A, June 15th 2010 – December 1st 2010, control system.

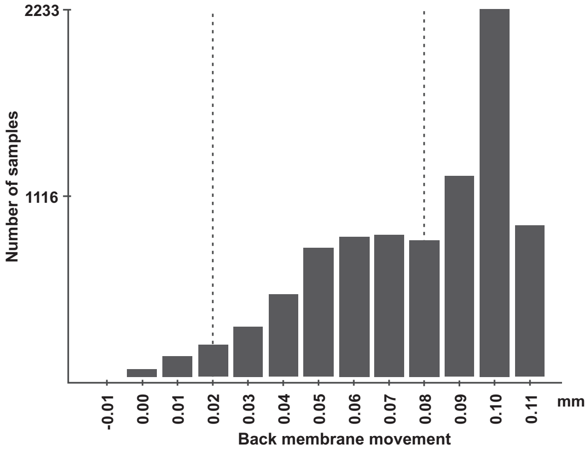

Fig. 16. Diastat B, October 1st 2007 – February 15th 2008, closing in the filling head.

In the period from September 7th 2009 to April 9th 2010, when the measuring and control system was operational, the type B was

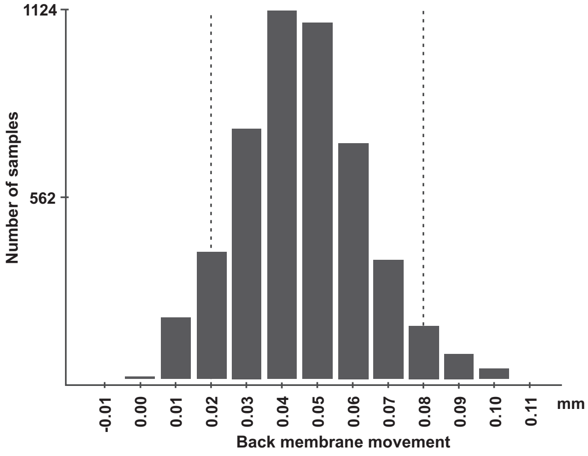

Fig. 17. Diastat B, September 7th 2009 – April 9th 2010, control system + closing in the filling head.

still closed with its sensing element not removed out of the filling head. The results for this period are shown in Fig. 17. The number of tested diastats was 4938 with mean back movement value of 0.050 mm and standard deviation of 0.018 mm. Again, it can be noticed that the implementation of the measuring and control system considerably improved the filling quality.

After some period of operation of the measuring and control system the project partner decided to close the diastat type B when the sensing element is taken out of the filling head in order to lower the production costs. The test started on September 20th 2010 with very good results. Fig. 18 is shown for the period until March th 2011. The number of diastats tested was 8553 with the mean back membrane movement of 0.053 mm and standard deviation 0.017 mm. The number of empty diastats is higher. However the costs of eliminating them is much lower than the material costs due to the requirement of a longer sensing element. These statistical data show that the filling quality is not worse in comparison with previous procedure and for this reason the type B diastat is continued to be manufactured as described.

After a longer period of using the measuring and control system the project partner producing thermostats found all the benefits that the system can provide. For this reason they tried to transfer the filling procedure of particular types of diastats from manual machine filling. As an example are shown the results of back membrane movement from quality control for diastat type C. This type is manufactured in high quantities, where the back movement of the membrane must never be higher than 0.12 mm, enabling thus very high temperature sensitivity. The defined closing temperature (T_c) is 40 °C (Fig. 5). The 40 °C information tells that the membrane movement is very small when the oil temperature is under the closing temperature (T_c). During the filling procedure the expansion of the membrane is cca. 0.05 mm at the oil temperature 27 °C. These facts prevented filling this and other similar diastat types with the filling rotary machines. The proper filling quality was in the past achieved with very slow and expensive procedure of manual filling. In Fig. 19 the results of manual filling for the entire year 2010 show that among all 12457 tested diastats none were found empty. The mean back membrane movement value is 0.040 mm (even 0.010 mm too low), the maximum measured value was 0.090 mm and the standard deviation was 0.013 mm.

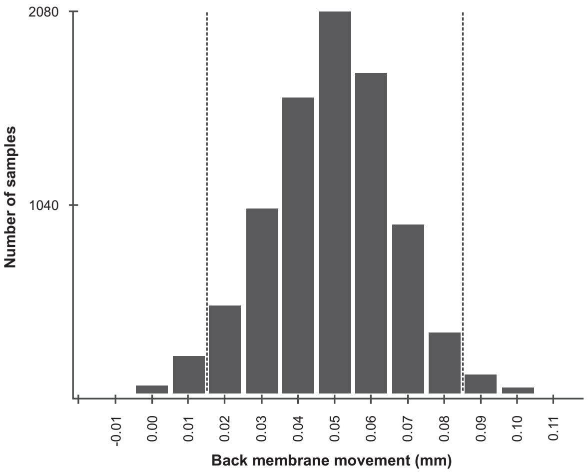

Fig. 18. Diastat B, September 20th 2010 – March 18th 2011, control system + closing out of the filling head.

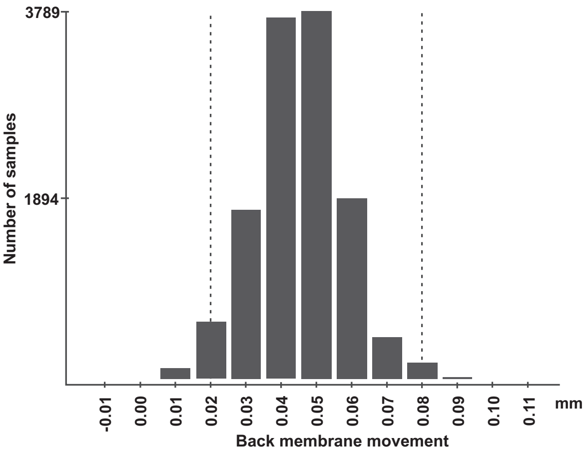

Fig. 19. Diastat C, January 4th 2010 – December 17th 2010, manual filling.

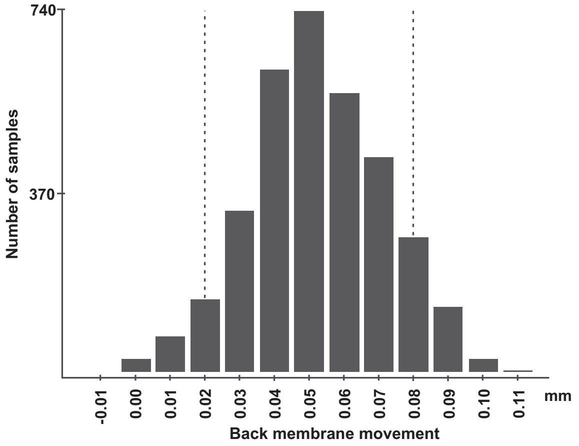

Fig. 20. Diastat C, February 1st 2011 – June 17th 2011, control system.

The diastat type C started to be filled with rotary filling machines on February 1st 2011 with very good results. Fig. 20 shows the data from the back movement quality control for the period until June 17th 2011. The number of diastats tested was 3514 with mean back membrane movement of 0.058 mm and standard deviation of 0.020 mm. The characteristics is wider than the one in Fig. 19, but the mean value is closer to the ideal value. These final results show the superiority of using the measuring and control system, namely because the last presented data belong to the closing procedure where the sensing element was removed from the filling head and the oil was leaking out for a short period of time. For this reason also empty or almost empty diastats were found. If only the presented data is taken into the account, then the manual filling is considerably more efficient than the one with the rotary filling machine. But the costs of using rotary machines is much lower due to the filling completion of one diastat in about 2 min as compared to the manual filling procedure that lasts 2 days. Until today, the diastat type C and also some other types of diastats have been successfully transferred from manual filling to the filling with rotary filling machines.

11. Discussion

Developed was a measuring and control system for a highly demanding industrial environment. It enables very accurate measurements of diastat ceramic button membrane expansion. By using the measurements the system can control the filling pressure of existing rotary filling machines. At the beginning of the project the thermostat manufacturer imposed a very narrow permissible error range for expansion measurements. This range was set to

±5 μm. The current non-contact distance sensors enable better than required. Unfortunately, they usually have much larger measuring heads than allowed by the rotary machine. We used the non-contact triangulation distance sensor with adequate dimensions and measuring characteristics. It uses ordinary LED light that is not harmful to the people working near rotary machines.

The expansion measurements need to be transferred to the central computer. For this reason a dedicated microprocessor system for measurement sampling and digitalization was developed. The digitalized data is sent to the computer wirelessly.

The development of the microprocessor board followed instructions from the literature (Lattice Semiconductor Corporation, 1999) to reduce noise. As a part of the measuring system also the software running by the microprocessor must be included. A very important part of the control loop is the software running on the central computer. In addition to the calculations and visualizations enables also periodical checking of the measuring error for each rotary filling machine. This checking is performed by using a dedicated mechanical caliber.

A series of tests showed that the measuring characteristics of the selected distance sensor together with microprocessor system is very nonlinear within the measuring range of 0.5 mm. The characteristics is linearized by using 4th degree polynomial coefficients. These coefficients are determined in advance with special mechanical micrometer system. The approach with the linearization proved to be very efficient, by enabling the maximum error of ±2 μm over the entire measuring range of 2 mm.

Because the Keyence manufacturer does not provide all necessary parameters of the sensor (PT-165) and controller (PT-A160) temperature fluctuations influencing measurement stability, it was further necessary to test the entire measuring system in production environment. The tests have shown that the measurement stability at constant distance using the entire measuring system changes with temperature in longer time period than the time necessary to fill one diastat.

After all the tests were carried out and when the entire measurement system was mounted on one filling machine, the sensor head Keyence PT-165 was quite vulnerable to external influences, especially inrush of oil. The Keyence manufacturer does not provide the security level (Ingress Protection - IP) parameter.

Since the measuring head was completely unprotected from oil, the sensor plastic optics lenses were completely destroyed. After opening the sensor head, the presence of oil in the interior was confirmed. The destruction of the lens by the oil was also confirmed by the manufacturer Keyence. Therefore, it was necessary to additionally protect the sensor head against the effects of oil (Fig. 21). This is possible only with the installation of an additional metal housing with suitable glass in the sensor optics area and rubber seals.

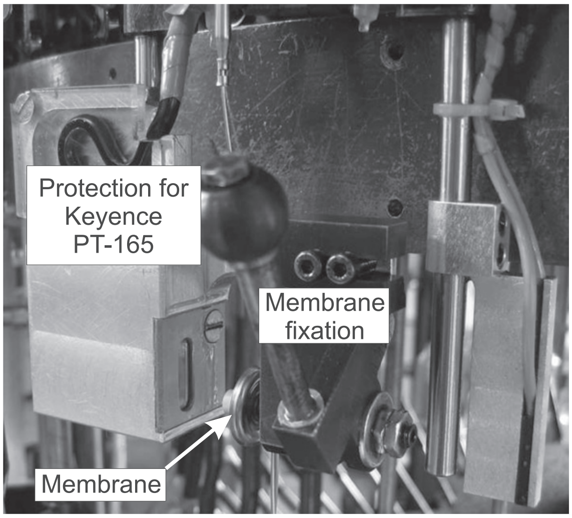

Fig. 21. Measuring head protected against the effects of oil.

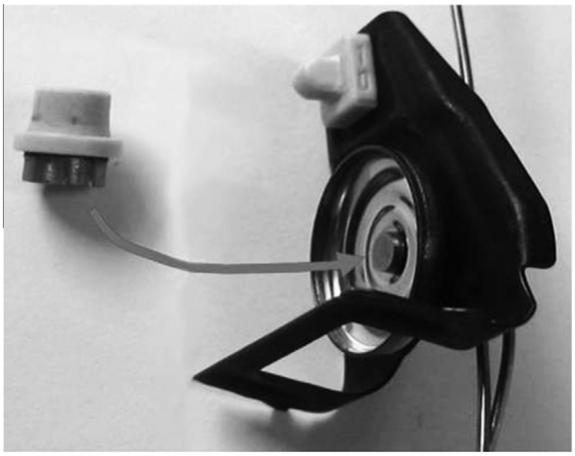

Fig. 22. Metallic button with additional ceramic button.

The thickness of the glass has a major effect on the offset, as a consequence of light traveling through the glass at an angle. By increasing the thickness of the glass the offset is larger. Our goal was to use glass as thick as possible, because often a worker with a tool or diastat can accidentally strike anywhere in the proximity of the glass. The tests revealed that the glass thickness of 1.0 mm is the best compromise.

The measuring system was originally designed for membranes with a ceramic button. Later tests showed difficulties when measuring the displacements of the membranes with a metallic button. The best solution would be to mount another measuring system that is calibrated for metallic button membrane expansion measurements. But the project partner found another solution. Each measured diastat with a metallic button is equipped with a ceramic button by the use of a magnet enabling fixation to the metal surface during the filling procedure (Fig. 22). This proved as a very elegant solution because on one filling machine among 48 filling heads only one diastat is measured at a time. During this time the co-worker can attach a ceramic button with a magnet on each measured diastat.

12. Conclusions

Developed, tested and installed was the measurement and control system for diastat membrane expansion supervision. The diastat is the most important part of the mechanical capillary thermostat.

Greatest challenge was to develop a contactless measuring system for measuring the expansion of the membranes. The main part of this system is a contactless distance measuring sensor Keyence PT-165 with an analog controller PT-A160 and microprocessor system for sampling, processing and transmission of the measured data. Also accurate pressure and temperature sensors and controllers were selected and a dedicated software was written.

The performance quality of the presented system is confirmed by the results of the diastat filling quality control used as a reference. The results showed sufficient improvement of the filling quality as compared with the results before the system was integrated into the manufacturing process. By using the measuring and control system also other manufacturing benefits were found:

- lower quantities of faulty diastats and for this reason less than 100% quality control is needed,
- possibility of automatic machine filling of some diastat types where the sensing element is taken out of the filling head before the diastat is closed, resulting in material savings,
- possibility of transition from manual filling to filling with rotary machines for some diastat types, resulting in time efficiency savings.

Acknowledgment

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