

THE METHOD OF MEASUREMENT OF THERMAL DEFORMATION PISTON ANALYSIS OF MEASUREMENT ERROR

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Summary

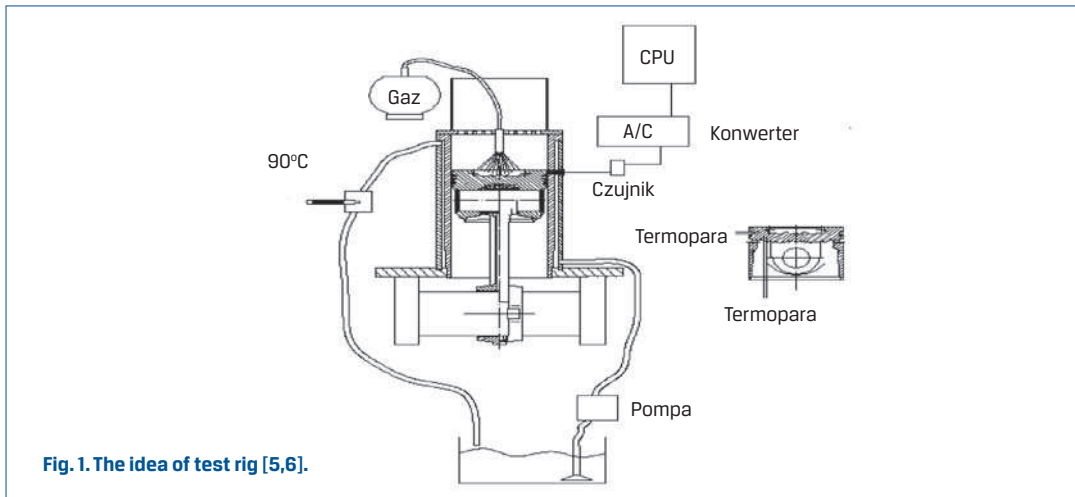
At the Department of Vehicle and Fundamentals of Mechanical Engineering of Technical University of Lodz the test rig was built to measure the thermal deformation of the piston. The article shows how to measure thermal deformations of the piston on this rig. For the measurement were used laser sensors for distance measurement, which measure the distance from the object to the sensor with a resolution of $4\mu\text{m}$. The piston expands during heating and it resulting as a reduction in the distance between the sensor and the piston. The changes of geometric dimensions of the piston was determined using the geometrical dependence. The temperature of the piston was measured with 4 thermocouples placed near the piston crown. Distance measurements were measured simultaneously on two axes: the axis perpendicular to the axis of piston pin and the piston pin axis. A research position with the burner used to heat the piston and the temperature stabilization system were described. Specially designed burner was powered by propane gas. To ensure proper conditions for combustion of gas in addition to the mixer is fed compressed air. By adjusting the expense of gas and air could affect on the flame temperature. Temperature stabilization system allowed to maintain a constant coolant temperature of $60\text{ }^{\circ}\text{C}$. In the second part of the article presents the analysis undertaken, the systematic error of measurement and statistical processing of the preliminary results of measurements on this test rig.

Keywords: internal combustion engines, pistons, thermal loading

1. Introduction

The evaluation of thermal deformation of the piston taken repeatedly, as evidenced by the attached literature [1,2,3,4,5]. Taking into account the restrictions contained in the literature, in the Department of Vehicle and Mechanical Engineering Fundamentals it was built the test rig to measure thermal deformation of the piston. Its schematic diagram is shown in figure 1.

Studies here rely on direct measurement of the piston deformations with the laser sensors, reflectance, and value measured directly is the distance beetwen the piston and the sensor. The piston expands during heating and as result we get the reduction in the distance between



the sensor and the piston. The temperature of the piston is measured by thermocouples [7,8], located near the piston crown as shown in Figure 1.

The test rig provides for the measurement of SW680 engine piston, whose nominal diameter is about 127 mm. After the initial simulation calculations, it turned out that changing the dimensions of the piston diameter may be about 700 microns, and maximum differences using different combustion chambers can reach 40 microns. It was decided therefore to apply a laser sensor with a resolution of 4 microns to provide adequate accuracy.

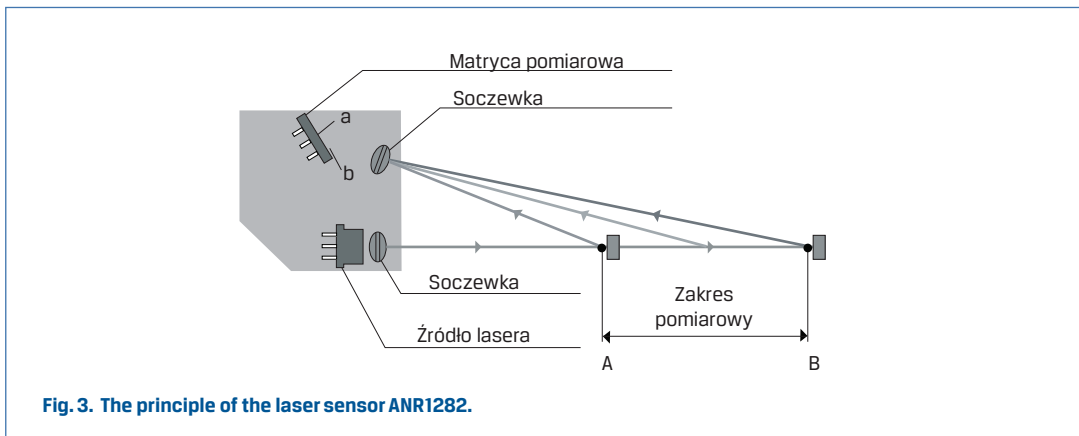
On the test rig (fig. 2) were measured the thermal deformation of pistons:

- with the same volume of the combustion chamber located in the axis of the piston differing only in the shape of the combustion chamber [6]
- with the same combustion chamber positioned differently in relation to the axis of the piston [9].

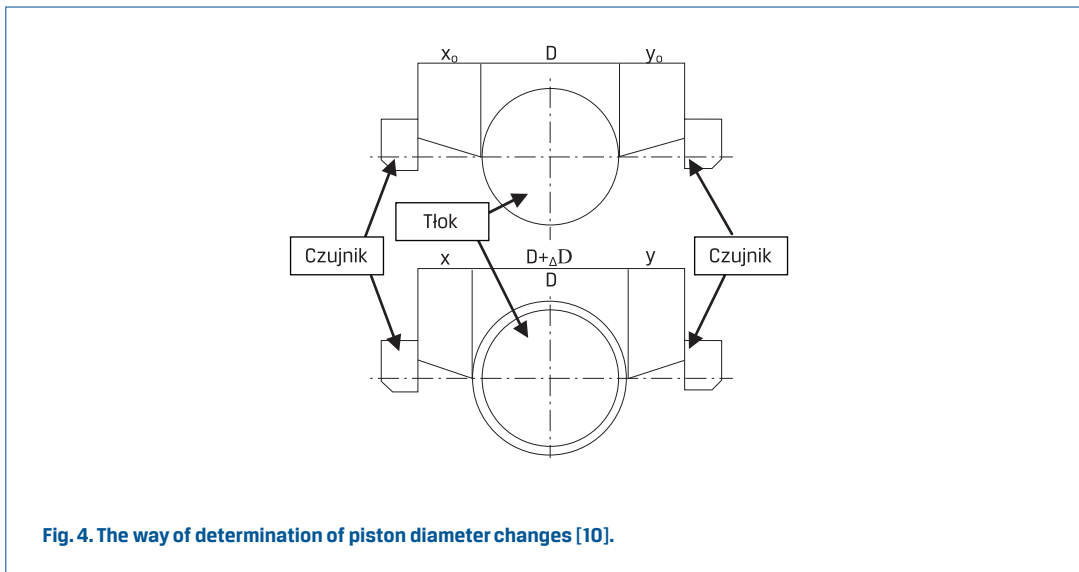


2. The concept of measuring changes in diameter of the piston

Figure 3 shows a laser sensor, which was used to measure changes in geometrical dimensions of the piston. The measurement principle is as follows. If the item is at the point "A", the laser beam reflected from it falls to position sensing device (PSD) in "a" and as a result we obtain a voltage value. If the object is at the point "B", the laser beam reflected from it falls to PSD at the point "b", and as a result we get a higher voltage.



In the test rig were mounted four such laser sensors in two sets, so that they having done measurements in the pin axis and perpendicular to the axis of the pin. Based on these data, you can specify a change in geometric dimensions of the piston measured in the plane (fig. 4).



When the distance between the sensors is an "L" can be written:

$$L = X_0 + D + Y_0 . \quad (1)$$

After heating, the distance L can be represented as:

$$L = X + D + \Delta D + Y . \quad (2)$$

Assuming that the distance between the sensor does not change during the measurement are:

$$X_0 + D + Y_0 = X + D + \Delta D + Y ,$$

hence the change in diameter of the piston:

$$\Delta D = (X_0 + Y_0) - (X + Y) . \quad (3)$$

Note that to determine changes in diameter of the piston is not necessary to know its diameter. This way the initial error of measuring the diameter of the piston is avoided.

3. Analysis of measurement error

The systematic error of the measurements presented above consists of two sources of error:

1. errors resulting from incorrect determination of the values of physical quantities included in the phenomenon of thermal expansion (δ_1)
2. errors due to geometric inaccuracies
 - a. improper setting of the sensor relative to the piston
 - eccentricity e (δ_2),
 - angular deviation α (δ_3),
 - angular deviation β (δ_4),
 - b. improper location of the object of research
 - inclination of the piston axis to the cylinder axis by an angle ψ (δ_5),
 - piston displacement (δ_6).

1. errors resulting from incorrect determination of the values of physical quantities included in the phenomenon of thermal expansion,

To those largest were included: thermal expansion coefficient of piston material (α), the radius of the piston at the reference temperature (r) and temperature rise (ΔT).

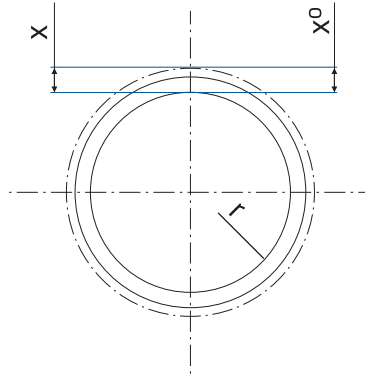


Fig. 5. Differences in deformation due to wrong determining of thermal expansion and temperature factors.

According to the definition we can write that measurement error is the difference between the measured value X^o , and an unknown amount of the actual X , hence:

$$\delta_1 = X^o - X = \text{alfa}^o \cdot 2 \cdot r^o \cdot \Delta T^o - \text{alfa} \cdot 2 \cdot r \cdot \Delta T. \quad (4)$$

Values without the index "o" refer to the actual values.

Table 1 shows the measured values of searched physical quantities.

Table 1. Physical largeness influenced on deviation δ_1 .

Physical Quantity	Symbol	Value	Uncertainty
thermal expansion coefficient	alfa^o	$2,32 \cdot 10^{-5} \text{ m/K}$	$\pm 1 \cdot 10^{-7} \text{ m/K}$
piston radius	r^o	0,0635 m	$\pm 0,0001 \text{ m}$
temperature change	ΔT^o	450 K	$\pm 5 \text{ K}$

2. errors due to geometric inaccuracies

This kind of error consists of the geometric relationship between the location of the sensor and the piston. As a standard solution assumed the situation in which the laser sensor is positioned so that the laser light falls radial on the side surface of the piston and the piston is located exactly in the axis of the cylinder liner (not moved or tilted). It was assumed cylindrical shape of the side surface of the piston.

The possible cases deviating from the adopted system are describes as follow:

a. improper setting of the sensor relative to the piston,

- eccentricity e,

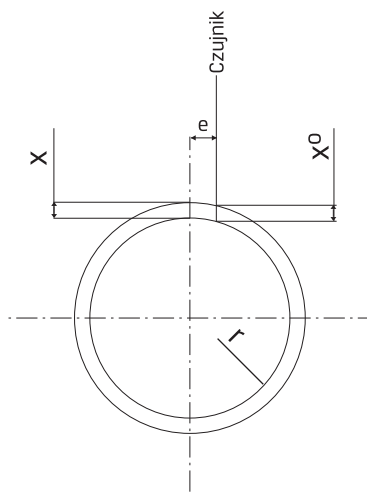


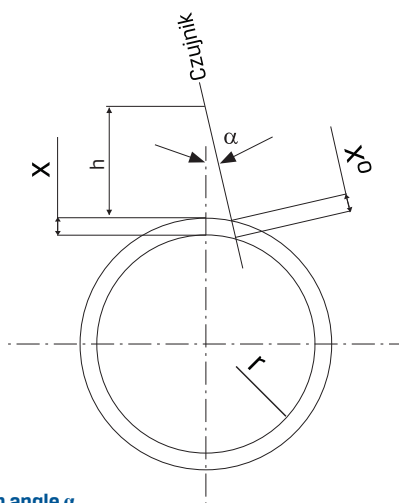
Fig. 6. Missaxis sensor setting.

$$\delta_2 = X^0 - X = \text{alfa} \cdot 2 \cdot r \cdot \Delta T \cdot \frac{1}{\sqrt{1 - \frac{e^2}{r^2}}} - \text{alfa} \cdot 2 \cdot r \cdot \Delta T \quad (5)$$

Table 2. Physical largeness influenced on deviation δ_2 .

Physical Quantity	Symbol	Value	Uncertainty
eccentricity	e	0 m	$\pm 0,003$ m

- angular deviation of the sensor at an angle α with respect to the axis of the pin,

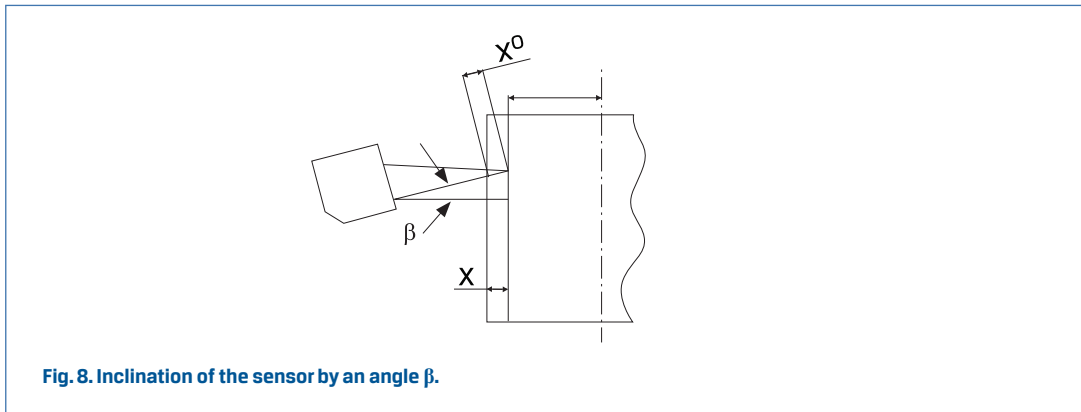
Fig. 7. Inclination of the sensor by an angle α .

$$\delta_3 = X^\circ - X = \text{alfa} \cdot 2 \cdot r \cdot \Delta T \cdot \frac{1}{\sqrt{1 - \frac{(h+r)^2}{r^2} \cdot \sin^2 \alpha}} - \text{alfa} \cdot 2 \cdot r \cdot \Delta T \quad (6)$$

Table 3. Physical largeness influenced on deviation δ_3 .

Physical Quantity	Symbol	Value	Uncertainty
The distance from the piston to the sensor	h	0,08 m	$\pm 0,004$ m
Angle	α	0°	$\pm 1^\circ$

- angular deviation of the sensor at an angle β with respect to the axis of the pin,

**Fig. 8. Inclination of the sensor by an angle β .**

$$\delta_4 = X^\circ - X = \text{alfa} \cdot 2 \cdot r \cdot \Delta T \cdot \frac{1}{\cos \beta} - \text{alfa} \cdot 2 \cdot r \cdot \Delta T \quad (7)$$

Table 4. Physical largeness influenced on deviation δ_4 .

Physical Quantity	Symbol	Value	Uncertainty
Angle	β	0°	$\pm 3^\circ$

In order to reduce (eliminate) the error components arising because of improper settings of the sensor to the piston the way of measurement was changed through the introduction of special rods.

Figure 9 shows the way to measure the distance between the sensor and the piston by using measuring rods, which task is not only to protect the measuring signal from the effects of external factors (fire – infrared radiation, water vapor), but also give the assurance that regardless of the position of the piston measured distance is performed to piston diameter.

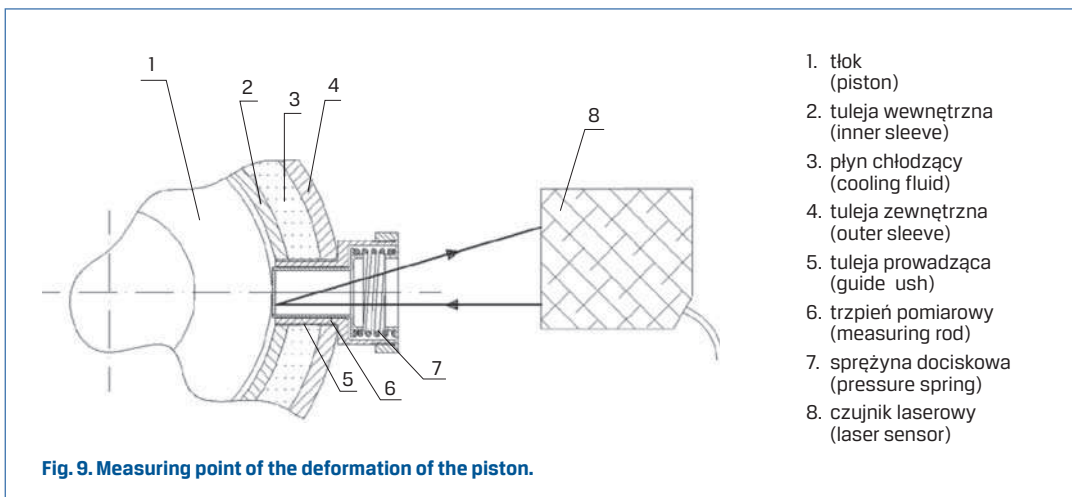


Fig. 9. Measuring point of the deformation of the piston.

The error caused by setting the sensor eccentricity disappear ($\delta_2 = 0$). In addition, significantly reduces the error caused by deviation angle α , since it no longer consists of determining the error of the distance between sensor and the piston (Fig.10).

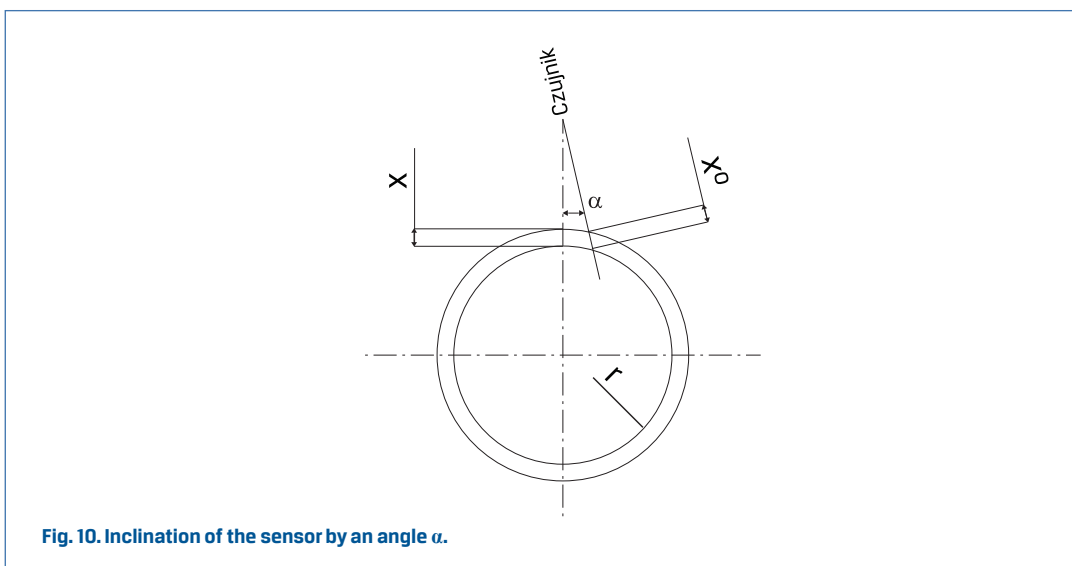


Fig. 10. Inclination of the sensor by an angle α .

$$\delta_3 = X^0 - X = \alpha \cdot 2 \cdot r \cdot \Delta T \cdot \frac{1}{\cos \alpha} - \alpha \cdot 2 \cdot r \cdot \Delta T \quad (8)$$

Table 5. Physical largeness influenced on deviation δ_3 .

Physical Quantity	Symbol	Value	Uncertainty
Angle	α	0°	$\pm 1^\circ$

The way to identify the error due to δ_4 caused by deviation of angle β does not change.

Before proceeded to determine the measurement error resulting from incorrect positioning of the piston, maximum displacement of the piston as well as the maximum possible angle between the axis of the piston and cylinder axis was calculated.

Clearance between the piston and the cylinder can be determined on the basis of figure 11.

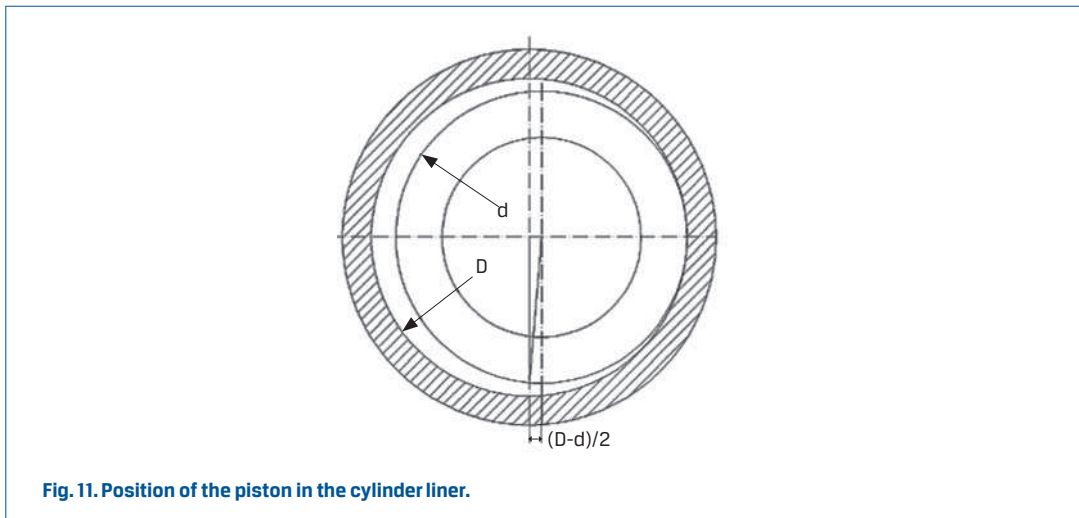


Fig. 11. Position of the piston in the cylinder liner.

Assuming as known: the piston diameter $D = 127\text{mm}$, and diameter of the sleeve $D_c = 128\text{mm}$, the maximum displacement piston in the sleeve can be determined from the relation:

$$w = \frac{D_c - D}{2} = \frac{128 - 127}{2} = 0,5\text{mm}$$

Then set the maximum tilt of the piston axis relative to the axis of the cylinder (Fig.12).

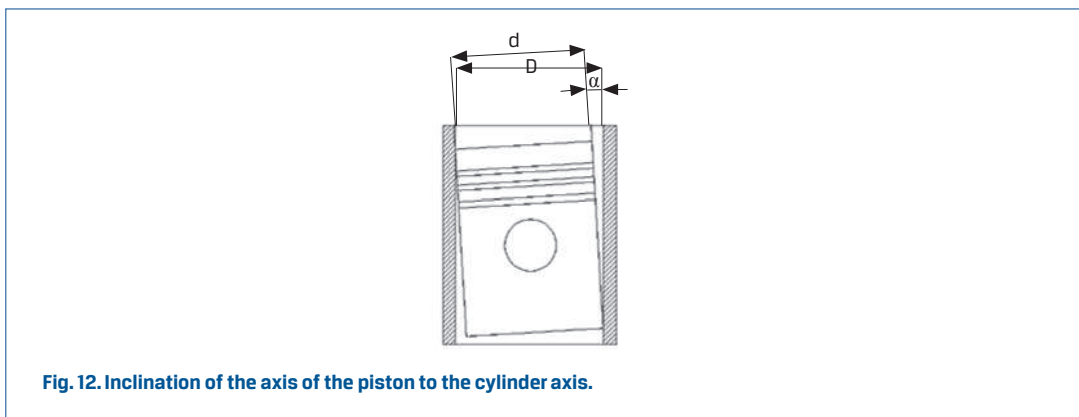


Fig. 12. Inclination of the axis of the piston to the cylinder axis.

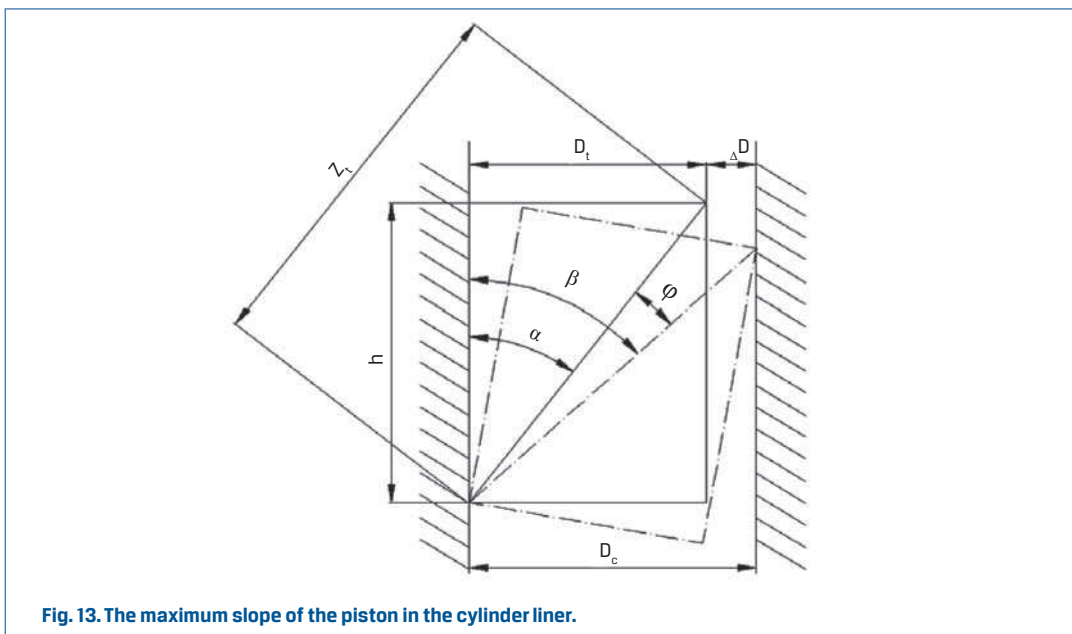


Fig. 13. The maximum slope of the piston in the cylinder liner.

Using trigonometric dependence in Figure 13:

$$Z_t = \sqrt{h^2 + D_t^2} = \sqrt{173^2 + 127^2} = 214,61 \text{ mm}$$

$$\sin \alpha = \frac{D_t}{Z_t} = 0,5918 \quad \alpha = 36,2848^\circ$$

$$\sin \beta = \frac{D_c}{Z_t} = 0,5964 \quad \beta = 36,6125^\circ$$

hence,

$$\psi = \beta - \alpha = 0,3277^\circ$$

Knowing that the maximum linear displacement of the piston in the cylinder liner is 0.5 mm, and the largest possible tilt of the piston axis to the cylinder axis is 0.33° proceeded to analyze the impact of those values to the result.

b. error resulting from improper position of the research object (piston).

- inclination of the piston axis relative the cylinder axis by an angle ϕ

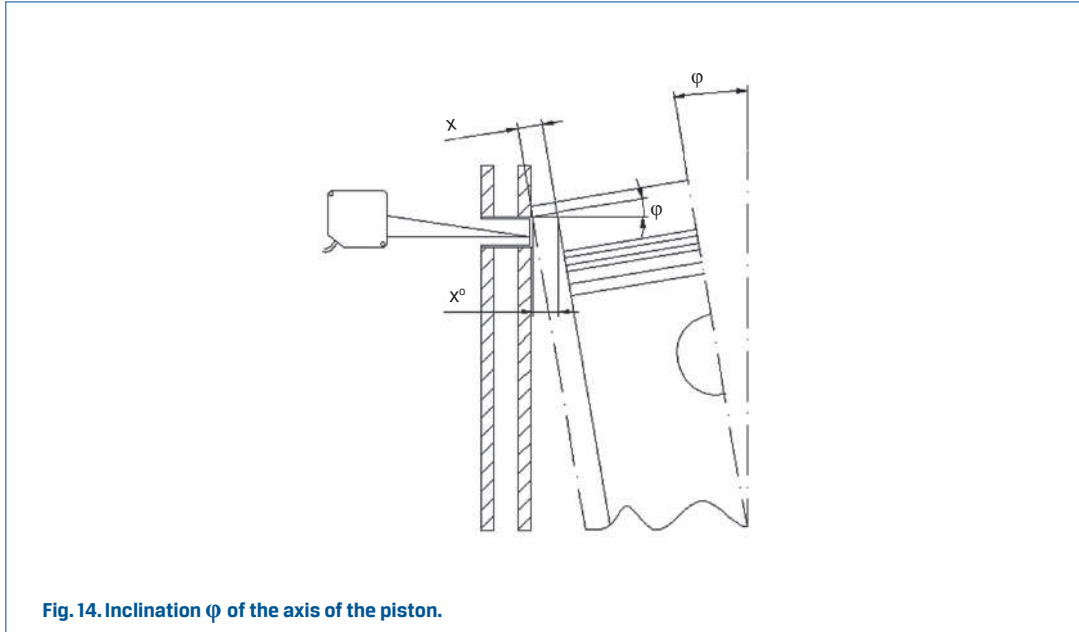


Fig. 14. Inclination φ of the axis of the piston.

$$\delta_5 = X^o - X = \alpha \cdot 2 \cdot r \cdot \Delta T \cdot \frac{1}{\cos \varphi} - \alpha \cdot 2 \cdot r \cdot \Delta T . \quad (9)$$

Table 6. Physical largeness influenced on deviation δ_5 .

Physical Quantity	Symbol	Value	Uncertainty
Angle	φ	0°	$\pm 0,33^\circ$

- piston displacement w ,

When the axis of the measuring rods are perpendicular to the direction of the piston displacement error resulting from this shift is 0. The problem appears only in the case of inaccurate performance holes leading the measuring rods (Fig. 15). Assuming that the position of the piston during the measurement does not change, it turns out that even the wrong location of the measuring rods does not affect to the result.

$$\delta_6 = X^o - X = 0 \quad (10)$$

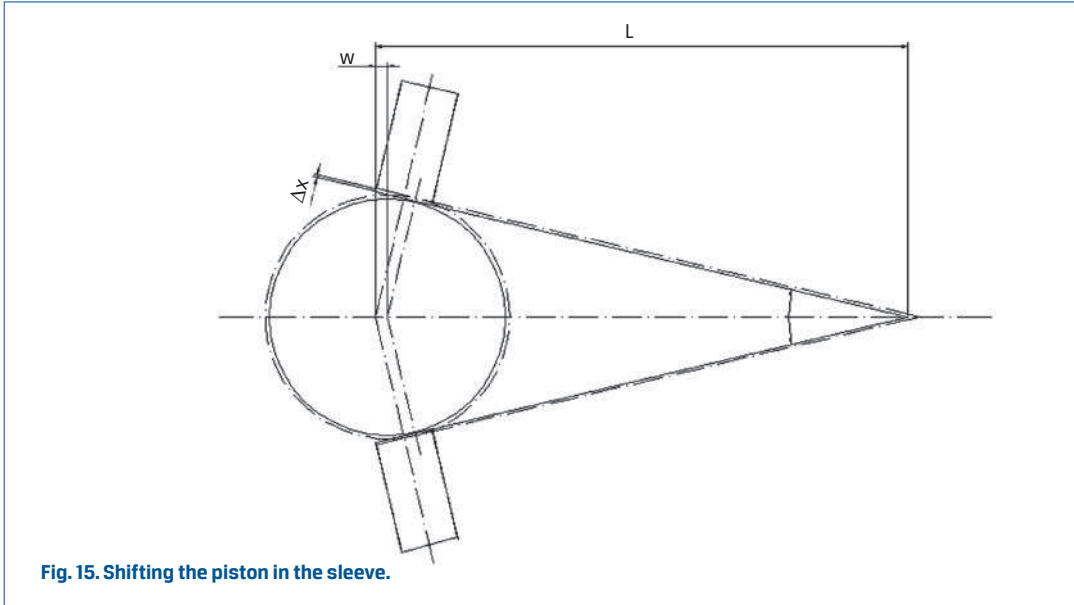


Fig. 15. Shifting the piston in the sleeve.

Summarise the various components of a systematic error of measurement are:

- error resulting from incorrect determination of physical quantities included in the phenomenon of thermal expansion

$$\delta_1 = X^\circ - X = \text{alfa}^\circ \cdot 2 \cdot r^\circ \cdot \Delta T^\circ - \text{alfa} \cdot 2 \cdot r \cdot \Delta T$$

- errors resulting from geometric inaccuracies:

$$\delta_2 = X^\circ - X = 0$$

$$\delta_3 = X^\circ - X = \text{alfa} \cdot 2 \cdot r \cdot \Delta T \cdot \left(\frac{1}{\cos \alpha} - 1 \right)$$

$$\delta_4 = X^\circ - X = \text{alfa} \cdot 2 \cdot r \cdot \Delta T \cdot \left(\frac{1}{\cos \beta} - 1 \right)$$

$$\delta_5 = X^\circ - X = \text{alfa} \cdot 2 \cdot r \cdot \Delta T \cdot \left(\frac{1}{\cos \varphi} - 1 \right)$$

$$\delta_6 = X^\circ - X = 0.$$

The systematic error can be determined from the relation:

$$\Delta = \sqrt{\left(\frac{\partial \Delta \delta_1}{\partial \text{alfa}} \cdot \Delta \text{alfa} \right)^2 + \left(\frac{\partial \Delta \delta_1}{\partial r} \cdot \Delta r \right)^2 + \left(\frac{\partial \Delta \delta_1}{\partial \Delta T} \cdot \Delta \Delta T \right)^2 + \left(\frac{\partial \Delta \delta_3}{\partial \alpha} \cdot \Delta \alpha \right)^2 + \left(\frac{\partial \Delta \delta_4}{\partial \beta} \cdot \Delta \beta \right)^2 + \left(\frac{\partial \Delta \delta_5}{\partial \varphi} \cdot \Delta \varphi \right)^2}$$

(11)

Partial derivatives are as follows:

- derivative relative to the thermal expansion coefficient α :

$$\frac{\partial \Delta \delta_1}{\partial \alpha} = 2 \cdot r \cdot \Delta T$$

- derivative relative to the piston radius r :

$$\frac{\partial \Delta \delta_1}{\partial r} = \alpha \cdot 2 \cdot \Delta T$$

- derivative relative to the temperature changes ΔT :

$$\frac{\partial \Delta \delta_1}{\partial \Delta T} = \alpha \cdot 2 \cdot r$$

- derivative relative to the angle α :

$$\frac{\partial \Delta \delta_3}{\partial \alpha} = \alpha \cdot 2 \cdot r \cdot \Delta T \cdot \left(-\frac{\sin \alpha}{\cos^2 \alpha}\right)$$

- derivative relative to the angle β :

$$\frac{\partial \Delta \delta_4}{\partial \beta} = \alpha \cdot 2 \cdot r \cdot \Delta T \cdot \left(\frac{\sin \beta}{\cos^2 \beta}\right)$$

- derivative relative to the angle φ :

$$\frac{\partial \Delta \delta_5}{\partial \varphi} = \alpha \cdot 2 \cdot r \cdot \Delta T \cdot \left(\frac{\sin \varphi}{\cos^2 \varphi}\right)$$

The impact of individual quantities on the measurement results of piston thermal was shown in table no. 7

Table 7. The influence individual physical largeness on the result of measurements.

Physical Quantity	Symbol	Value	Uncertainty	Way to determine	Error
thermal expansion coefficient alpha	alfa	$2,32 \cdot 10^{-5}$ m/K	$\pm 1 \cdot 10^{-7}$ m/K	$\frac{\partial \Delta X^\circ}{\partial \text{alfa}} \cdot \Delta \text{alfa}$	5,72 μm
piston radius	r	0,0635 m	$\pm 0,0001$ m	$\frac{\partial \Delta X^\circ}{\partial r} \cdot \Delta r$	2,09 μm
temperature change	ΔT	450 K	± 5 K	$\frac{\partial \Delta X^\circ}{\partial \Delta T} \cdot \Delta \Delta T$	14,73 μm
tilt sensor	α	0°	$\pm 1^\circ$	$\frac{\partial \Delta X^\circ}{\partial \alpha} \cdot \Delta \alpha$	0,40 μm
tilt sensor	β	0°	$\pm 3^\circ$	$\frac{\partial \Delta X^\circ}{\partial \beta} \cdot \Delta \beta$	3,65 μm
inclination of the axis of the piston	φ	0°	$\pm 0,33^\circ$	$\frac{\partial \Delta X^\circ}{\partial \varphi} \cdot \Delta \varphi$	0,04 μm
Systematic error	Δ			Δ	19,61 μm

The biggest impact on the accuracy of the measurement is accurate to determine the temperature changes. Given the fact that as a result of preliminary measurements made on the described test rig the piston geometric dimensions changed approximately 700 μm , the systematic measurement error reached up to 3%.

4. Measurements

4.1 Test conditions

Modification of the test conditions can be achieved by changing:

- coolant temperature controller settings,
- position of the valve controled pressure of coolant,
- mixture of propane-butane with air by means of valves,

For research, the following settings were assumed:

- temperature below which the heater is attached $T = 60^\circ \text{C}$
- temperature above which the heater turns off $T = 62^\circ \text{C}$
- temperature above which the solenoid valve opens to supply cold water to the radiator $T = 63^\circ \text{C}$
- coolant pressure valve $p = 0.2$ bar
- pressure of propane-butane gas $p = 36$ mbar
- air pressure $p = 2$ atm

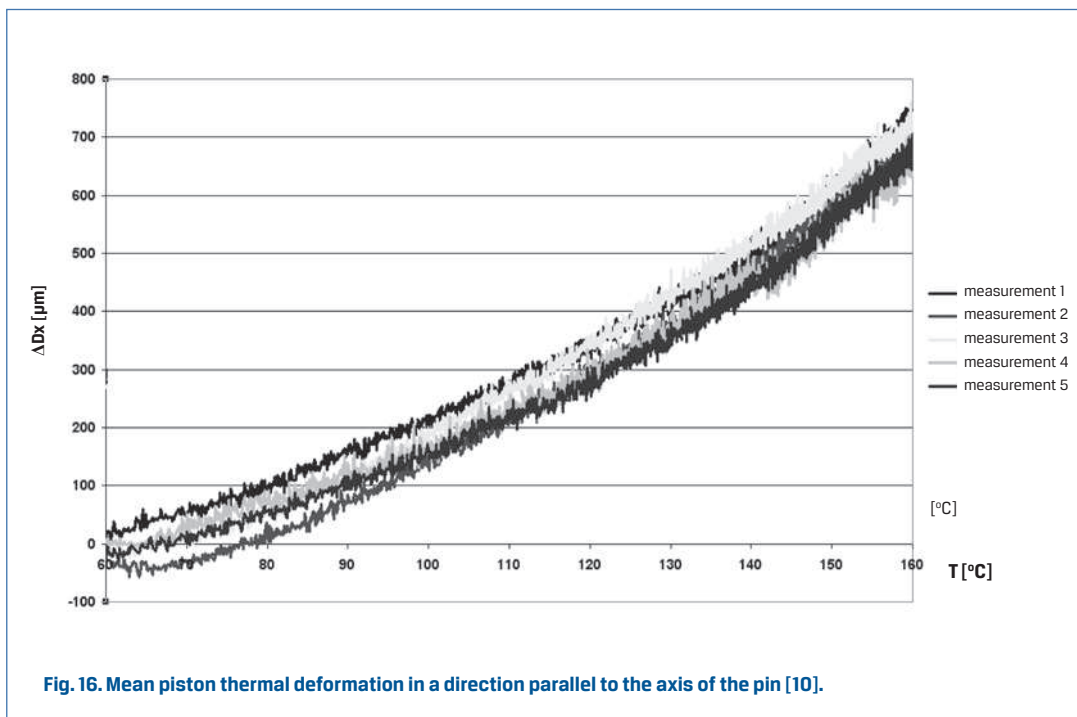
4.2 The course of study

Research methodology consisted of:

- test rig heated to 60 °C
- start the burner and start heating with simultaneous archiving of measurements results of four laser sensors and four temperature sensors,
- after 30 minutes of heating burner was switched of and left the test rig to achieve the input temperature,
- the measurements were repeated several times for each piston.

4.3 The measurement results and analysis

In Figures 16 and 17 shows the thermal deformation of the piston in a direction parallel and perpendicular to the axis of the pin obtained at the 5 measurements [10].



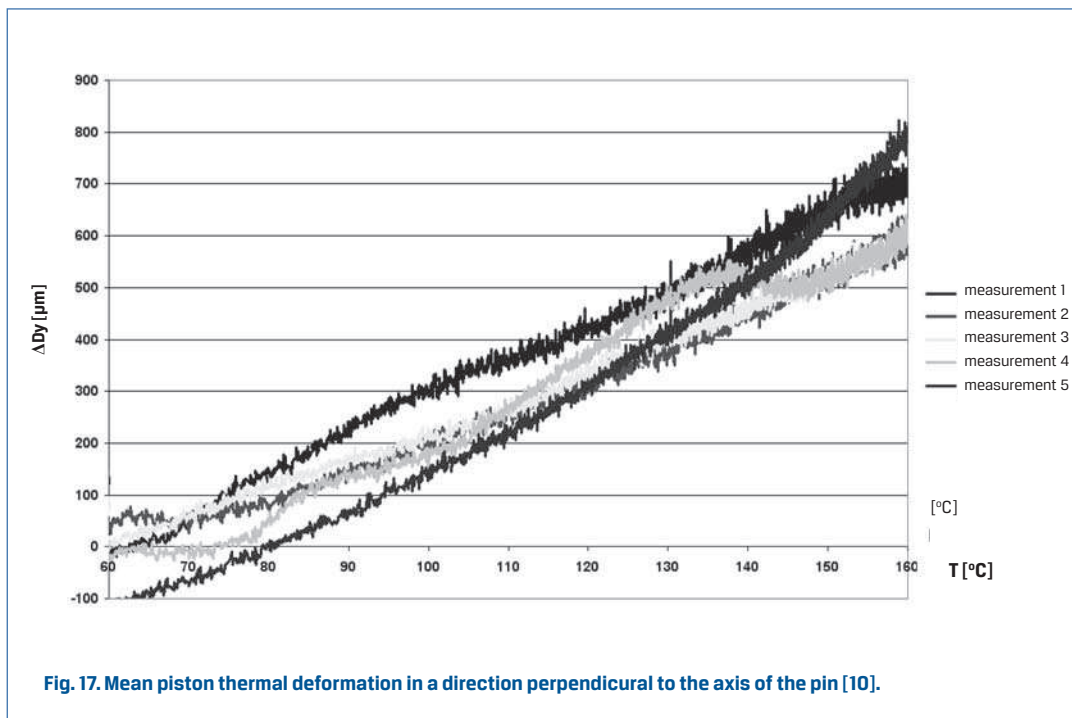


Fig. 17. Mean piston thermal deformation in a direction perpendicular to the axis of the pin [10].

Due to the number of repetitions (5 times) statistical treatment of results were performed according to Student's t-distribution for which:

- estimator of the expected value is the arithmetic mean:

$$\bar{x} = \frac{1}{n_p} \cdot \sum_{i=1}^n x_i, \quad (12)$$

- estimator of the standard deviation is the standard deviation for a small sample:

$$S_n = t_n \cdot \sqrt{\frac{1}{(n_p - 1)} \cdot \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (13)$$

- standard deviation of the arithmetic mean:

$$S_n^- = t_n \cdot \sqrt{\frac{1}{n_p \cdot (n_p - 1)} \cdot \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (14)$$

where:

n_p – number of measurements,

x_i – the result of a single measurement,

t_n – numerical factor, dependent on the number of measurements and the assumed level of confidence.

The confidence level value was assumed as 95%.

Middle curve illustrates the average change in geometrical dimensions of the piston and the outer curves are confidence limits.

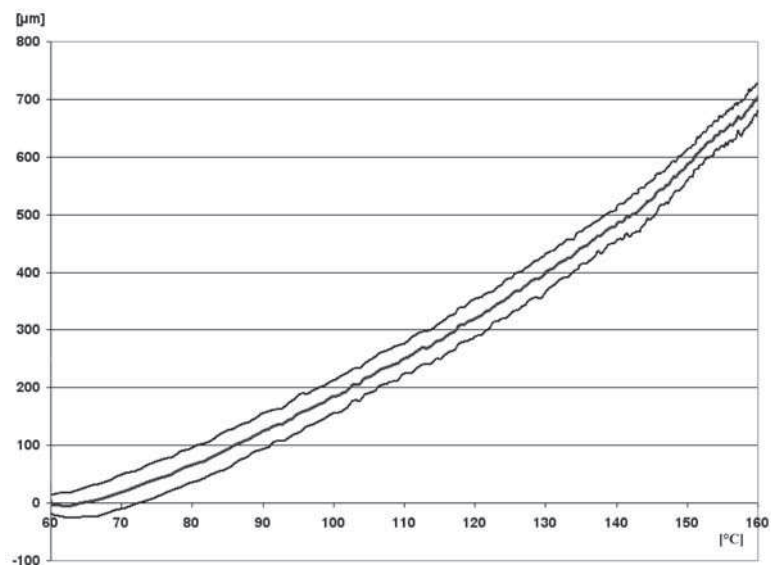


Fig. 18. Thermal deformation of the piston in a direction parallel to the axis of the pin [10]

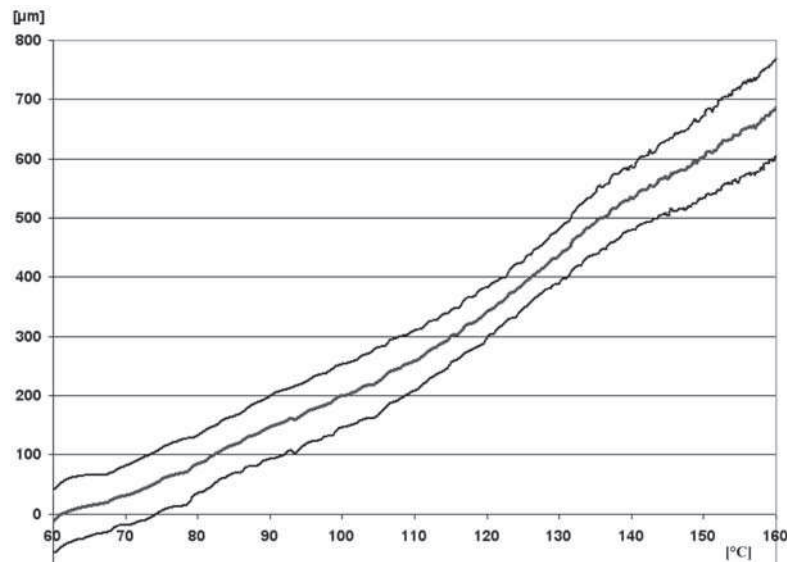


Fig. 19. Thermal deformation of the piston in a direction perpendicular to the axis of the pin [10].

After conducting a statistical analysis of measurement results turned out that the maximum thermal deformation are:

- along the axis of the pin 711 ± 28
- perpendicular to the axis of the pin 692 ± 78

and these values are consistent with simulation results [8,9]. It may be notice that the systematic error of the results obtained on this rig ($19.61 \mu\text{m}$) is smaller than the random error ($28\mu\text{m}$).

5. Conclusions

The analysis of measurement error on this test rig allows to formulate the following conclusions:

1. differential measurement method used during the measurements significantly increases the accuracy of the research. You can thus avoid the error of measuring the diameter of the piston and location of the measuring laser sensors. The directly measured quantity is the change of geometrical dimensions of the piston.
2. measurement method is satisfactory, since systematic measurement error is much less than the random error (statistical).

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