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Contactless measurement of PET bottles' thickness

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***Abstract* – The tuning of Injection Stretch Blow Molding (ISBM) process for PET bottles is crucial to lower the production costs, reduce the environmental impact and assure a sufficient quality of the final product. Among the parameters defining PET bottles quality, the thickness is of primary importance for the appearance and mechanical resistance of the final product. Up to date, tuning of the process is demanded to the operator skills through a trial and error process, iterated until the wanted configuration is achieved. Moreover, the process is not controllable because the PET bottles characteristics are not currently measured. This work describes a method for PET bottles thickness measurement; the method could be implemented as part of an active control of the ISBM process. A non-contact method based on infrared transmittance measurement has been developed to evaluate the wall thickness of PET bottles. The method uncertainty is 6% when the nominal thickness ranges between 0.2 and 0.5 mm. A prototype of the measurement system has been developed and validated testing PET specimens with different geometry, pigmentation and composition.**

I. INTRODUCTION

Injection Stretch Blow Molding is one of the main technologies used in the PET bottles industry [1]. The process requires a pre-warming of the semi-finished PET product, named preform, and its subsequent shaping in a proper mold. The bottle reaches its final shape thanks to a combination of stretching action and air pressure. The quality of the product is related to the capability of the process to distribute a homogenous material layer in the mold, limiting shapes errors or defects, like opacity or pearlascence. The process is quite complex since the final result depends on the viscoelastic properties of the PET, determined by the pre-warming temperature distribution, the timing of stretching phase, the environmental condition and the insufflation air pressure. All these parameters are difficult to be controlled and optimized, because they interact in a complex way, as already shown in different studies [2-3]. Thus, tuning of the machine parameters is a critical task, generally performed by operators who exploit their experience and skills. Moreover, since no measurement systems are today used to control the ISBM, once the process is not fulfilling the quality requirements, new setting of the machine is required. This leads to wastes, possible line-stops and eventually an increase of the production costs.

Thus, it would be welcome the development of methods to measure on-line the bottles quality parameters (such as internal folding in the neck area, excessive material at the base, wall thicknesses, pearlescence, etc. etc.), and among these, the bottle thickness.

This work aims to design a non-contact measurement system capable of identifying the thickness distribution of PET bottles after the ISBM process. Our idea is to measure the thickness by measuring the infrared radiation transmitted through the bottle. The non-contact measurement of the thickness allows a short measurement time, that could be compatible with inline measurement and would provide for a feedback signal to be used in the development of an ISBM automatic control.

The proposed method and the experimental setup are descried in section II; experimental results are presented in section III and discussed in section IV. Paper conclusions are drawn in section V.

II. MATERIAL AND METHODS

A. Background

The principle exploited in this work is based on the measurement of the transmitted electromagnetic radiation through the observed material. A sketch of measurement principle is shown in Fig. 1.

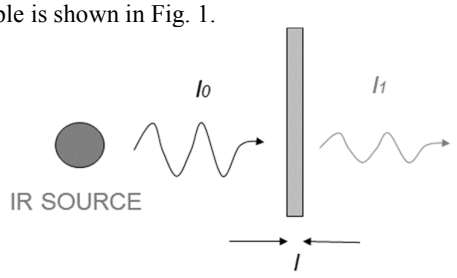

Figure 1 Measurement principle for the proposed method

Knowing the radiation emitted by a source I_0 and the one measured after the transmission I_1, the Lambert-Beer equation allows evaluation of the specimen thickness:

$$\frac{I_1}{I_0} = e^{-k_\lambda l} \quad (1)$$

The ratio between I_0 and I_1 is function of k_λ the extinction coefficient (a characteristic of the material variable with the wavelength) and l, which is the thickness of the observed material. Reversing Eq. 1, it is possible to obtain the thickness of the observed sample:

$$l = -\frac{\ln(\frac{I_1}{I_0})}{k_\lambda} \quad (2)$$

Nevertheless, in equation (1) the two intensities should be measured inside the specimen to avoid the influence of the reflections at the interfaces of the specimen with the air. In practice, the measurable quantities are the incident intensity and the transmitted one. Hence, a correction has to be applied to Eq. 1 in order to account for reflections. Moreover, in case the beam is not a collimated one and/or is non incident perpendicularly to the material surface, the actual optical path within the material will be variable and the incidence angle will have to be accounted for. This happens in our case study, since bottles have some inclined shapes and curvature.

The correction procedure requires the identification of a factor C (dependent on the incidence angle α) to be used for the determination of the thickness l_c:

$$l_c = -\frac{\ln(\frac{I_1}{I_0})}{k_\lambda} C(\alpha) \quad (3)$$

The correction factor can be derived knowing the reflectivity [4] and the inclination of the observed object with respect to the IR beam. The latter allows correction of the optical path of the radiation through the observed material sample, using Snell equation and the knowledge of the PET refractive index. The correction requires the knowledge of the bottles curvature combined with the thickness measurement. The curvature can be measured by means of imaging technique or correlating the IR beam position with the bottle shape information.

B. Amorphous PET samples

Amorphous PET flat samples have been used as specimens for the method initial validation. Two rectangular samples with nominal thickness of 0.2 and 0.5 mm were tested. These are in a range near to what expected for the final PET bottles. Fig. 2 shows tested samples.

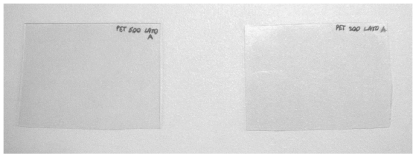

Figure 2 PET specimens with thickness 0.5mm (left) and 0.2 mm (right).

Material optical properties are necessary to identify spectral regions that can be used for the measurement. In fact, either high transmissivity spectral regions or high absorptivity ones must be avoided since the method requires to measure some radiation after the sample transmission. Thus, significant absorption should be present. Existing studies show that with a 0.2 mm thickness two regions can be used, i.e. between 2 and 5 µm and between 15 and 17 µm. In these regions the average transmittance is between 0.4 and 0.6. The measured transmissivity for the 0.5 mm sample is expected to be lowered as consequence of the larger thickness t.

C. Measurement system design

The designed measurement system comprises an IR source and a detector placed respectively inside and outside the measured bottle. The source and the detector are mounted over a fixed support whereas the bottle is over a slide, in order to allow the thickness measurement for the entire length.

The IR detector was chosen as a tradeoff between expected performances within found spectral bands and the cost. PbSe BXT1-18T type has been eventually selected for the intended application. Measurement range is up to 4.7 µm and provided specific detectivity D* is between 1.9 and 3.83 10^9 cm $Hz^{-1/2}$ W^{-1}. The detector is actively cooled by a thermoelectric cooler that has been equipped with a PID controller to stabilize its temperature during the measurement activity. Both sensitivity and zero signal depend on the temperature accurate control is therefore mandatory. The obtained RMS temperature variation with final PID configuration was 23 m°C. The detector signal has been measured using circuit suggested by the manufacturer, i.e. with a bias resistor (1MΩ) in series to the detector used in photoconductive mode. In order to maximize incoming radiation from the IR source and to reduce the areas over which the thickness is averaged, a focusing lens (focal distance 20 mm, 15.2 mm diameter) was added to the optical layout. The detector holding system is shown in Fig. 3.

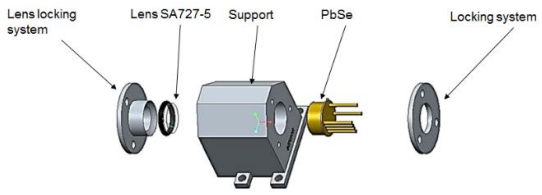

Figure 3 Detector holding system.

The IR source is a lamp SA727-5 (nickel-chromium) providing nominal black body temperature of 1170 K. Finally, in order to know the position along the bottle axis, a potentiometer (Celesco SP-12 type, range between 5 and 100 mm, linearity uncertainty of about 0.54% after calibration) has been connected to the slide. Moreover, knowing the relative position between the measurement

system and the bottle, once that the bottle geometry has been measured, it is possible to compensate for the incidence angle. An example of the bottle curvature retrieving is shown in Fig. 4. The prototype of the measurement system is described in Fig. 5.

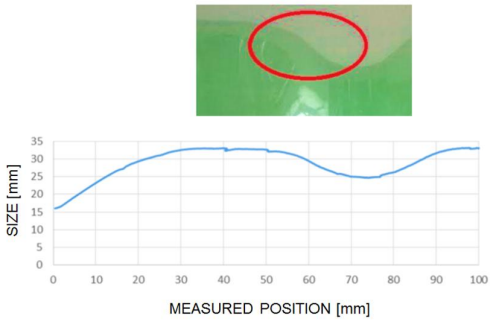

Figure 4 Bottle geometry definition. In the circle, highlighting of the curvature is evidenced.

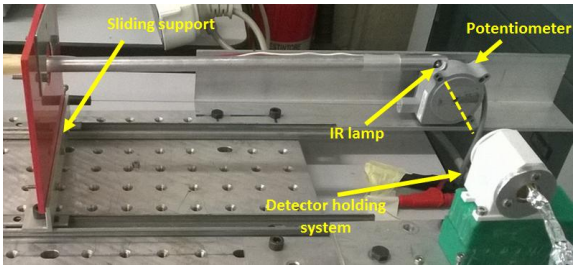

Figure 5 Prototype of the designed measurement system.

D. Measurement procedure and uncertainty budget

In order to measure the bottle thickness, k_λ has to be obtained by calibration performed in three steps:

- An opaque shied is placed between the detector and the sensor; measured voltage V_b is related to the dark resistance of the detector and is subtracted in the following steps to get the measured signal only due to the incoming radiation;
- IR source is measured by the detector without any material between them; measured voltage V_I provides the total input radiance of the source;
- PET material sample is placed between the detector and the sensor; V_O is the output radiance after attenuation thorough the sample thickness.

Measured attenuation coefficient $k_{\lambda c}$ during calibration is therefore obtained as follows:

$$k_{\lambda c} = -\frac{\ln\left(\frac{V_O - V_b}{V_I - V_b}\right)}{l_s} \qquad (4)$$

l_s is the known thickness of the PET samples and the correction of the reflection can be obtained using two different specimens of different thickness. During the measurement of the bottle thickness, Eq. 4 is used to derive the unknown thickness corrected in case of non-perpendicular incidence:

$$l_c = -\frac{\ln\left(\frac{V_O - V_b}{V_I - V_b}\right)}{k_{\lambda c}} C(\alpha) \qquad (5)$$

In order to assess the method performances, we have evaluated the measurement uncertainty, that accounts for the contributions of:

- AD conversion uncertainty of about 8.8 10^{-5} V and uncertainty of the measured voltages of Eq. 4;
- 5°C temperature variation of the shunt resistance used for the signal measurement (uncertainty of 5.4 % of the nominal value with calibration in thermal bath between 0 and 40 °C);
- Samples' thicknesses measured by means of a micrometer Mitutoyo 293-521-30 (resolution 0.002 mm);

The propagation using the GUM approach [5] lead to a relative uncertainty of about 6%, for the nominal thickness of 0.2 mm. The main uncertainty contribution is related to the temperature stability of the shunt resistance. In particular, strong improvement is expected in the final measurement uncertainty if an active thermal active control is implemented.

III. EXPERIMENTAL ACTIVITY

A. Method calibration

Calibration of the method has been performed following the procedure defined before. The PET samples have been used to measure the attenuation coefficients. Measured signals during calibration are shown in Fig. 6 and Fig. 7.

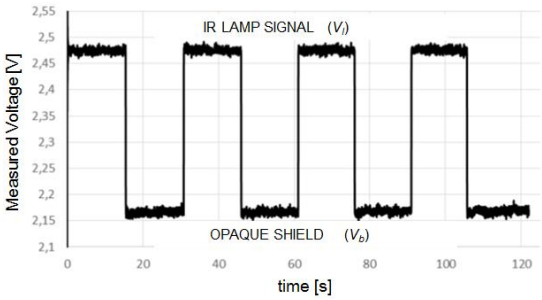

Figure 6 IR lamp and opaque shielding measured signals during calibration.

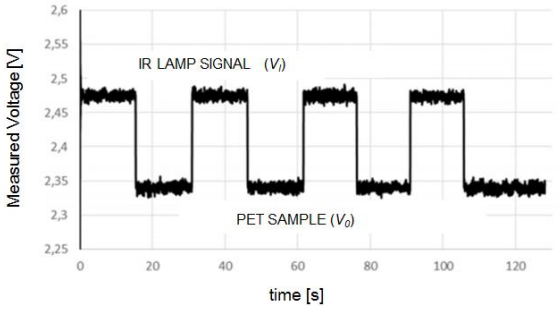

Figure 7 IR lamp and PET sample (nominal thickness 0.2 mm) measured signals during calibration.

The repeatability of the measured attenuation coefficients has been evaluated with multiple measurements (14 times for each sample). Results for the 0.2 mm PET sample are summarized in Table I.

Table I Method calibration: evaluation of the attenuation coefficients for the 0.2 mm PET sample.

Trial	***k_λ [mm^{-1}]***
1	2.497
2	2.529
3	2.569
4	2.534
5	2.509
6	2.521
7	2.529
8	2.548
9	2.518
10	2.540
11	2.561
12	2.536
13	2.521
14	2.524

B. Static testing

In order to validate the proposed method, we have measured the thickness of three different samples of PET bottles, as shown in Fig. 8. Bottles have different materials and thicknesses. Four different areas have been identified on the PET bottles and in each position, the acquisition duration was 10 s. Correction of the thickness for the reflections and incidence angle was implemented, after having defined the geometry of the bottle. Bottles have been tested in static and dynamic conditions, i.e. manually positioning the bottle at the identified areas or scanning the entire length with one continuous acquisition. The scanning speed was obtained by deriving the displacement measured by means of the potentiometer. Average speed during the dynamic testing was 4 mm/s with standard deviation of 1.9 mm/s.

After conclusion of the testing activity, bottles were cut and the previously selected areas were measured using the Mitutoyo 293-521-30 micrometer. This was done to compare the measurement results with another method and allow the validation of the proposed method.

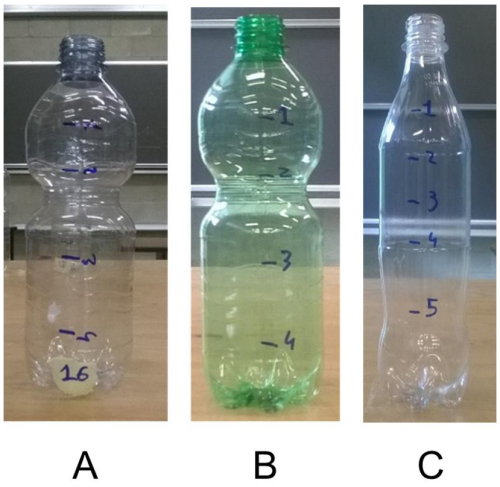

Figure 8 Bottles for static and dynamic testing

Measured thicknesses in static condition are described in Fig. 9. Table II summarizes the ratio (in percentage) between the measured thicknesses using the proposed method and the micrometer. Dynamic measurements are provided in Fig. 10.

Table II Differences between measured thicknesses by the proposed method and the reference one.

Sample	***1***	***2***	***3***	***4***
A	24%	24%	20%	21%
B	29%	24%	23%	27%
C	4%	8%	8%	-1%

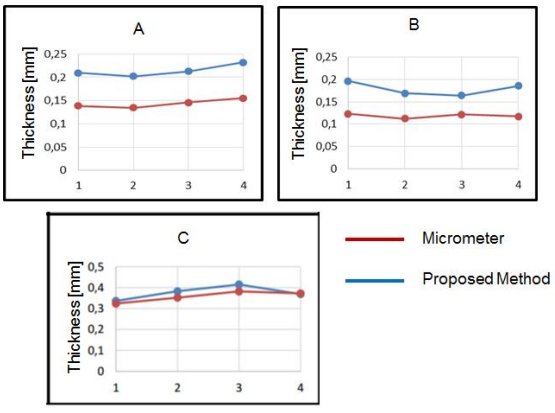

Figure 9 Static testing results.

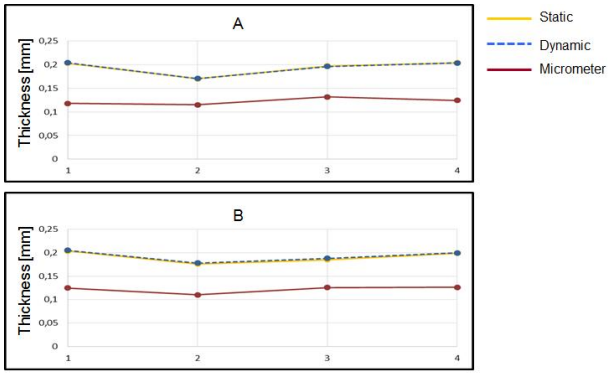

Figure 10 Dynamic testing results: static (yellow) vs dynamic (dashed blue) measurements.

IV. DISCUSSION

The method calibration evidenced a high repeatability, as shown in Table I. Average $k_{\lambda c}$ is 2.531 mm^{-1} with standard deviation of 0.019 mm^{-1}. The latter is less than 1% of the average value. The comparison of the measured thicknesses by the methods evidences that for cases A and B, the proposed approach leads to an overestimation of the measured thicknesses. Moreover, considering the uncertainties of the methods (1% for the proposed technique and 0.3% using the micrometer), the measurements are not compatible. As shown in Table II, the overestimation is between 20 and 30%. This behaviour is confirmed with C type bottle, even if the overestimation is much reduced in most of the areas. This result has been explained by the difference between the composition of the PET samples and the tested bottles. In fact, calibration of the method has been done with amorphous PET whereas some of the tested bottles were manufactured with a fraction of recycled material, whose optical properties are unknown. Anyway, this is not a strong limitation. In fact, since the measurements are nearly constant in the analysed areas, the effect can be removed using one representative sample of the bottle material to calibrate the method before starting the measurement. This can be easily obtained after that the machine tuning is completed. In this view, a "good" bottle becomes the reference to be used to calibrate the measurement system.

Finally, comparison between static and dynamic measurements evidenced full compatibility of the measured thicknesses. Maximum deviation between obtained values (as shown in Fig. 10) is comparable to the method repeatability. Thus, the proposed method is definitely suitable to be used for a continuous monitoring of the bottle thickness during ISBM production.

V. CONCLUSIONS

A contactless method to measure the thickness of PET bottles in ISBM process has been developed and validated. The method uncertainty was found to be about 6% of the nominal thickness. Performance improvement is expected with proper thermal stabilization of the circuit for reading the IR detector signal.

The method repeatability was 1% and the preliminary experimental activity, performed with bottles made of recycled PET, evidenced an overestimation of the measured thickness between 20 and 30%. The result depends on slight different optical properties of materials used in bottles production, and the error can be compensated with a direct calibration, i.e. by knowing the bottle material. Finally, it was demonstrated that the method can be effectively used to monitor on-line the bottles thicknesses, thanks to the fully compatibility between performed static and dynamic testing.

VI. REFERENCES

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