Real time monitoring of food cooking using *in situ* autofluorescence measurements: case reports

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Abstract:

Fluorescence studies are one of the methods which can potentially be used for *in situ* monitoring cooking foods or off line understanding changes occurring during cooking process. Most of the time, fluorescence experiments are conducted using laboratory equipment like laser sources, monochromators and more or less integrated optical spectrometers. This allows developing classification algorithms based on various statistical analyzes. However, the use of laboratory equipment prohibits the direct transposition of fluorescence monitoring to application in industrial or domestic kitchens. In this communication, we present an *in situ*, integrated and low-cost fluorescence monitoring sensor based on synchronous detection of the autofluorescence emitted by several food products. Experiments were conducted with beef, chicken, veal, pork, trout, cod and salmon. Results show that the evolution of the emitted fluorescence can be used to assess the core temperature during the cooking process.

Key words:

Food cooking monitoring, autofluorescence, *in situ* measurements

1- Introduction.

Cooking induces microscopic and macroscopic changes due to effects of temperature on foods. Temperature induced variations concern chemical and physicochemical reactions. This also results in modification of foods texture, color and flavor. Among techniques used to assess food transformation during cooking process, optical methods like fluorescence spectroscopy offer the potential of accurate and contact-less investigations. Fluorescence has been used extensively to qualify foods. Just to give some examples, fluorescence has been applied on various food products like dairy products [1-3], eggs [4, 5], honey [6], olive oil [7], fish [8], chicken [9], pork [10] and beef [11].

Fluorescence spectra of food products result from contributions of a large number of chemical and physicochemical components. For example, fluorescence spectroscopy with excitation at 280 nm was used to observe oxidation of tryptophan residues [12, 13]. Excitation at higher wavelengths (325 nm) allows targeting collagen crosslinks and degradation [14]. Because mechanisms responsible for the shape of autofluorescence spectra are complex, classification methods have been developed in order to better understand them [15-16]. Review papers concerning food classification methods have been proposed [17]. They are based on principal component analyzes used to reduce the number of variables, followed by multivariate classifications for either qualitative or quantitative analyzes.

Although optical spectroscopic techniques can potentially be adapted for *in situ* monitoring, experiments were principally performed at the laboratory level. In this communication, we report the use of a reduced size autofluorescence sensor which has been integrated in a domestic oven. It is based on synchronous detection. This allows enhancing the detection sensitivity. Therefore, the sensor can be placed far away from the food sample, *i.e.* outside the oven enclosure, which prevent it from damages due to high temperatures. Also, synchronous detection makes the sensor independent from spurious signals due to the ambient light. Autofluorescence is excited at 405 nm and observed in the visible region. Here, we do not record the autofluorescence spectra but we simply monitor the fluorescence intensity. Both the excitation source and the detection unit (including the signal processing electronics) are centimeter size. *In situ* measurement were performed on various food products. These case reports show that the evolution of the autofluorescence during food cooking is related to the evolution of the core temperature. Note that we compare the autofluorescence signal to the core temperature because the latter is considered as a gold standard in food cooking industry.

2- Experimental set-up and results.

2.1- Experimental set-up.

Figure 1 shows the experimental set-up together with the signal processing electronics. Figure 1(a) shows the domestic oven equipped with the autofluorescence unit. The first experimental version we set-up was equipped with a high power LED (200 mW) emitting at 405 nm wavelength. This excitation wavelength was used because of the availability of cost effective and powerful sources and because most of the proteins present in food exhibit optical absorption at this wavelength. In this first experimental set-up, two amplified photodiodes (30 dB gain) were used. Each was equipped with band-pass emission filters. They were used to analyze the fluorescence signal in two different emission windows. Also, a CMOS camera was installed for image processing purpose (not discussed in this communication). Experiments conducted with this first version showed that measuring the fluorescence signal over the whole visible range was performant enough to monitor cooking and provided a much better signal to noise ratio than reduced emission windows. The second experimental version was therefore much simpler and cheaper (figure 1(b) showing the top part of the oven). Here, only 1 photodiode was used and was equipped with a high-pass optical filter with a cut-on wavelength at 435 nm.

Amplification of the photodiode signal was performed in a specifically designed electronic circuit (figure 1(c)). Indeed, we used a synchronous detection scheme, not only to improve the signal to noise ratio but also to make the sensor independent from the ambient light (square modulation frequency at 1 kHz). The electronic unit consisted of three main parts. The first one concerns the synchronous detection and photodiode signal amplification. Amplification gain up to 70 dB can be manually adjusted. The second one constitutes the 1 A LED driver. The last one contains the analog to digital converter and the microcontroller used to transform optical data to the RS485 format compatible with the master electronic board of the oven. The core temperature was measured *in situ* using a conventional temperature probe inserted in the center of the food samples.

The whole optical system and driving electronics are situated outside the oven and are protected by a glass window inserted in the oven's top wall through which optical beams can propagate. Therefore, the optical reading and the electronic information processing were not compromised by the high temperature of the oven cavity.

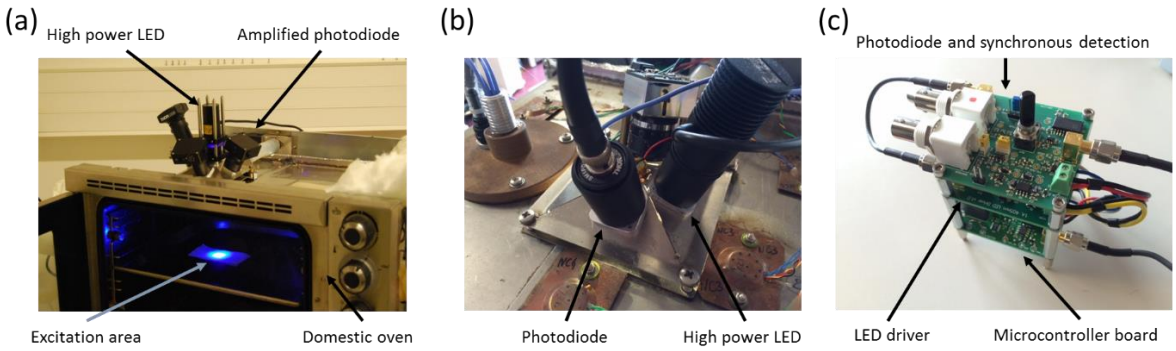

Figure 1: Experimental set-up for *in situ* monitoring of food product cooking. (a) First set-up used for multiple detection protocols: domestic oven equipped with a high power LED and amplified photodiodes. (b) Second set-up employing a simplified version of the first set-up: only one photodiode is used. (c) Embedded electronic units: from top to bottom, photodiode electronic and synchronous detection unit, high power LED driver, microcontroller and communication unit.

2.2- Food products and cooking protocols.

As above mentioned, experiments have been conducted with both meat and fish samples. Samples were thawed in air at room temperature. The oven was pre-heated according to the cooking protocol used for each food product. Once the inner temperature of the oven was stabilized, food was put into the oven and cooking started.

Three different cooking protocols were used: “hot air”, “steam mode” and mixed “hot air / steam mode”. In all cases, the air convection mode was turned on. In the case where the steam mode was selected, steam was injected in the oven according to on/off sequences with a 100 s period. Table 1 summarizes the cooking protocols for each food product and the number of samples in each case.

Food product	Oven temperature (°C)	Cooking mode	Number
Beef	200	hot air	3
Chicken breast	100	steam	2
Chicken leg	200	hot air	2
Veal	130	hot air + steam	2
Pork	200	hot air + steam	2
Salmon	200	hot air	2
Trout	200	hot air	2
Cod	100	steam	2

Table 1: Cooking protocols according to food type.

2.3- Experimental results and discussion.

Figure 2 shows the fluorescence signal collected as a function of the core temperature for the different food products. Only 1 record per sample type is given for clarity. Samples from the same food type behave the same way. In the figure, we also reported the cooking mode employed in each case.

The first thing to be observed from the figure is the fact that, in each cases, the fluorescence intensity tends to increase with the core temperature. However, the increase in fluorescence signal differs from one sample to another one. The maximum increase is observed for the chicken legs with Δsignal = 700 mV. Salmon also exhibits a relatively large increase with Δsignal = 650 mV. Previous experience in measuring tissue fluorescence led us to observe that fat is highly fluorescent. Indeed, both the skin of chicken legs and salmon are quite fat. During cooking migration of fat compounds to the surface of the sample is probably responsible for this large increase in the fluorescent signals.

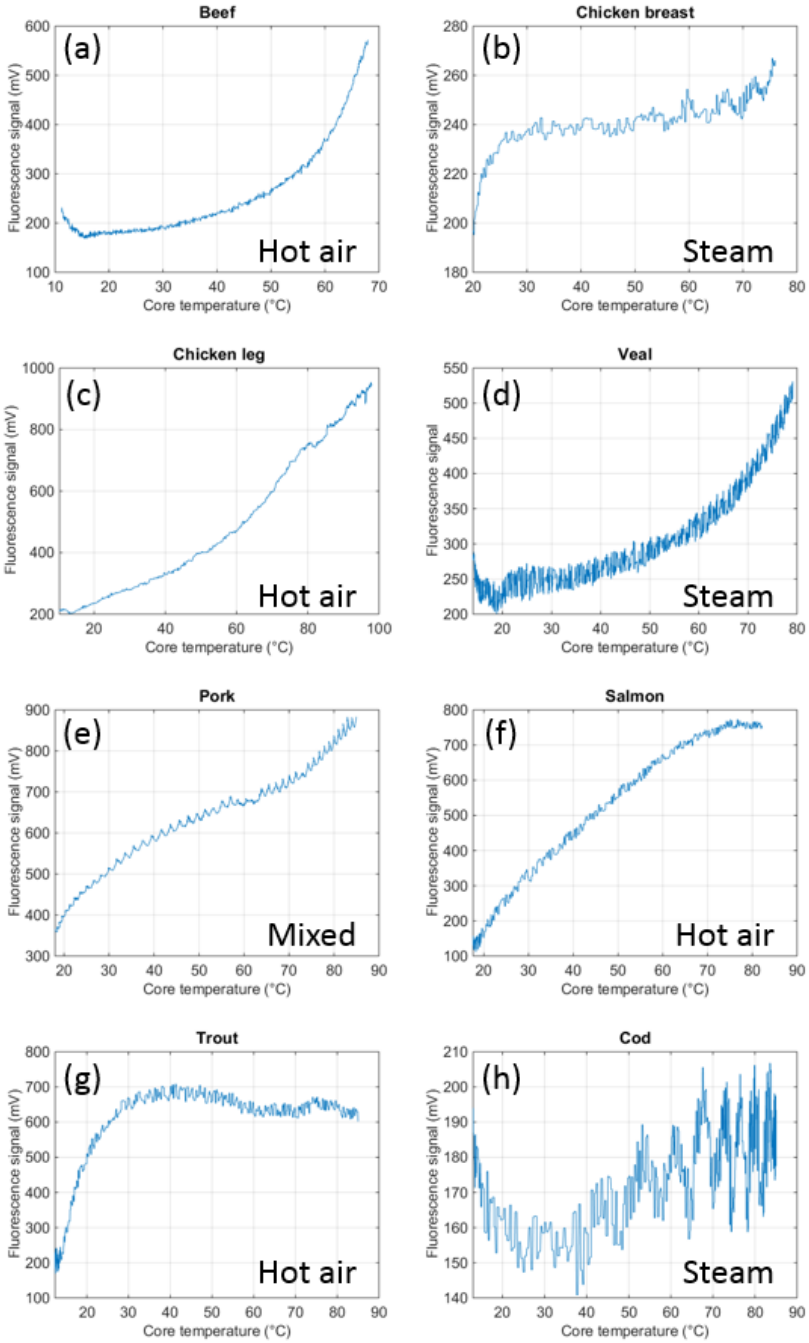

Figure 2: Fluorescence signal *versus* core temperature for the different food products and cooking modes. (a) beef / hot air, (b) chicken breast / steam, (c) chicken legs / hot air, (d) veal / steam, (e) pork / mixed, (f) salmon / hot air, (g) trout / hot air and (h) cod / steam.

Slightly lower increases are observed with the pork (Δsignal = 550 mV) and the trout (Δsignal = 500 mV). For the trout however, the increase in fluorescence signal stops after the core temperature reaches 40 °C. This is probably due to the fact that the thin skin of the trout is fully transformed a short time after cooking started. No evolution in terms of fluorescence can be observed after this moment. This suggests that it is unlikely to use fluorescence to monitor the entire cooking process of trout. Even lower increases are observed for the beef (Δsignal = 350 mV) and the veal (Δsignal = 300 mV). Note that in the case of the veal, the fluorescence signal is noisy. The lowest increases are observed for the chicken breast (Δsignal = 50 mV) and the cod (Δsignal = 50 mV). Indeed, for those two samples, the fluorescence signal is extremely noisy. This noise in addition to the fact that the fluorescence signal remains almost constant during cooking show that fluorescence monitoring is not an option for these products.

Signals evolutions can likely be used to monitor the core temperature in the case of beef, chicken legs, veal, pork and salmon. For these products, the increase of the fluorescence signal allows monitoring the core temperature, despite the fact that the signal obtained with the veal is relatively noisy. The noise is always observed when the steam mode is employed. In fact, the steam mode does not only induce noise but produces a spurious optical signal due to the composition of the oven atmosphere as it will be specified in the next section. In the case of veal however, the signal increase is large enough to allow monitoring the core temperature. Also, it should be noted that the shape of the fluorescence signal slightly differs from one product to another one. For beef, chicken and veal the evolution of the signal is convex while it is concave for the salmon and a mix of both for the pork. However, the variations in shape do not seem to be discriminative enough to automatically detect the product being cooked. For practical use, models of the evolution of the fluorescence intensity for each product should be included in the driving electronic circuit for proper monitoring.

To summarize, these very early results show that fluorescence measurement could be used to *in situ* monitor the core temperature of beef, chicken legs, veal, pork and salmon. Concerning cod and chicken breast, the use of the steam mode compromises the measurement. Also, the rapid evolution of the trout's skin makes the measurement only valid at the beginning of the cooking process. The resolution with which the core temperature can be deduced from the evolution of the autofluorescence signal depends on the signal to noise ratio. It can be estimated between 1 °C for the chicken legs to 10 °C for the veal. However, current results obtained using fluorescence spectroscopy seems to offer a better core temperature determination as it should be presented soon.

2.4- Remarks concerning the steam mode.

The temperature in the oven cavity is not constant. It is controlled in an "on" and "off" manner which leads to periodic changes of the cavity temperature. Measurements (not shown here) indicate that the temperature oscillates between 195 and 203 °C in the hot air mode, between 127 and 137 °C in the mixed mode (steam + hot air) and between 93 and 96 °C in the steam mode. This is not directly variations in the oven cavity which produces the above mentioned spurious signal. Looking at the cavity temperature in the steam mode, we observe that it never exceeds 100 °C. This means that the atmosphere is never saturated in water. Consequently, micro droplets of liquid water exist and diffuse the fluorescence signal.

This can be observed in figure 3 where we show the temporal evolution of the fluorescence signal. In figure 3(a) left part, we show this evolution for cod cooked using the steam mode. Periodic oscillations

of the signal are clearly visible. The left part of figure 3(a) shows a zoom of the recorded signal over an 800 s period together with the steam control signal. It is clear that when steam is injected in the cavity, diffusion of the fluorescence light leads to a decrease of the detected optical signal. When the steam control is switched off, the diffusion decreases and the optical signal increases accordingly.

Figure 3(a) should be compared to figure 3(b) where the same records are presented with pork cooked in the mixed mode over a 600 s period. Here, the temperature of the cavity is well above 100 °C and the amplitude of the spurious signal due to diffusion is greatly reduced. When only hot air is used, there is no spurious signal and only detection noise is observed.

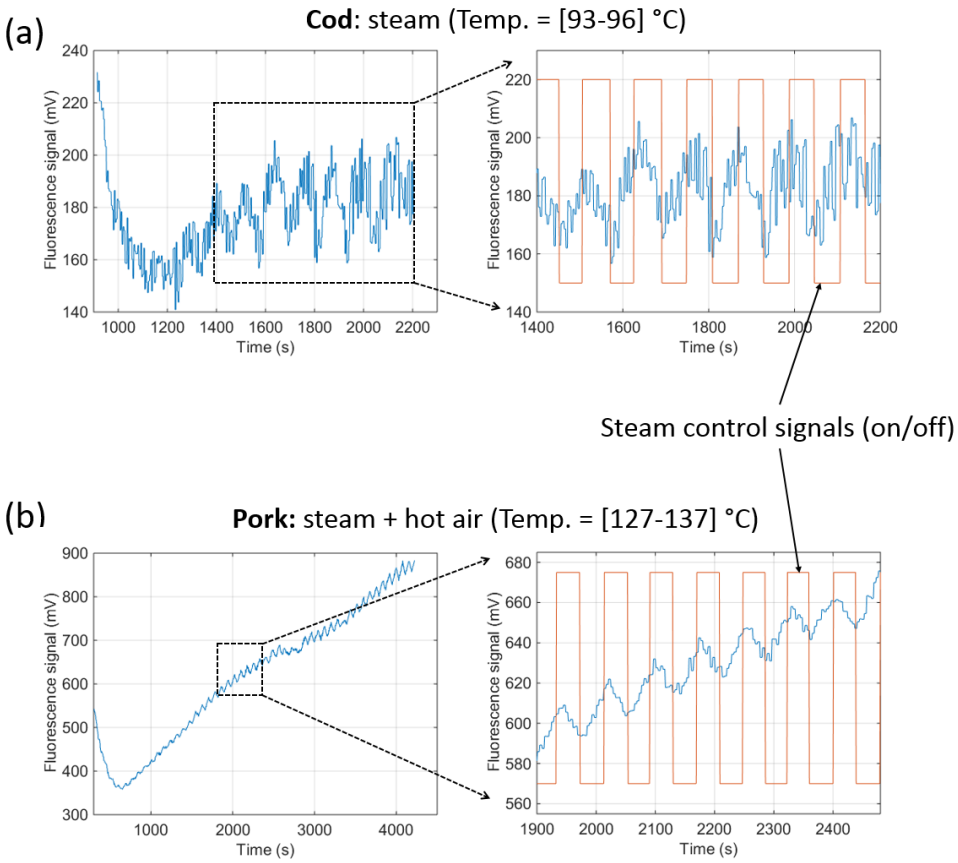

Figure 3: Spurious optical signals due to the steam mode. (a) Cod using steam mode: temperature between 93 and 96 °C, no water saturation in the oven cavity, diffusion of the fluorescence signal, decrease of the signal when the steam is injected in the cavity. (b) Pork using both steam and hot air: temperature between 127 and 137 °C, water saturation in the cavity, much less diffusion of the fluorescence signal.

3- Conclusion.

To conclude, we have briefly presented early results concerning the possibility to *in situ* monitor the core temperature of various food products during the cooking process. The method is based on the measurement of the variation of the autofluorescence intensity emitted by the food when excited at 405 nm wavelength. This optical technique offers a contactless solution for cooking monitoring and can potentially be adapted to industrial oven in its present form and in domestic oven in a more integrated and simplified version. The cost of this extra oven equipment being indeed an issue for domestic use. This method seems to be difficult to apply to some food products like cod and chicken

breasts. The resolution of the core temperature determination is of the order of a few degree Celsius. However, current experimentations using *in situ* fluorescence spectroscopy coupled to statistical analyzes seems to provide better core temperature determination resolutions to the expense of a more complex equipment. This, we believe, should be the subject of a shortly coming communication.

Acknowledgement

This work was part of the Open Food System (http://www.openfoodsystem.fr/) supported by BPI France in the frame of the "Programme Investissement d'Avenir" under the grant number OFS-RA EC3-160928.

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