**Fouling sensor based on thermal excitation in bioprocess: investigation of sensor structures on responses and sensitivity.**

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**Highlights**

* Three thermal fouling sensors (MEMS structures) are compared
* Hot wire method in steady thermal regime and linearized responses were applied
* Metrological limits (accuracy and upper LOD) are reported

**1. Introduction**

Food and bioprocess efficiency is impacted by (bio)fouling [1, 2]. Monitoring and quantification of deposit through *in-situ* and local sensors constitute technological and scientific challenges. In present work, three fouling sensors based on a thermal excitation (steady thermal regime) with different technology (Macro and MicroElectroMechanical Systems MEMS), geometry (intrusive cylindrical, flush plan) and packaging (nude and encapsulated structure) are compared. Thermal responses are discussed versus heat transfer theory. Performances with model deposit are reported to deduce accuracy to monitor fouling and to determine metrological limitations.

**2. Methods**

Prototype sensors are based on the hot wire method [1] with powered and regulated Joule effect. Hot wire and fluid temperatures are continuously recorded. According to heat conduction’s law in steady thermal regime (equations), the temperature difference () evolves as a linear function of heat flux () and thermal resistance ().

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| --- | --- | --- | --- |
| Ref | Temperature difference | Local heat transfer  | Deposit thermal resistance |
| TS1 |  |  |  |
| TS2 |
| TS3 |  |  |  |

Three different structures are compared (Figure 1). TS1 is composed of a flat square MEMS structure (red line, 250µm) between a printed circuit board (PCB, green line, 800µm) and a protective packaging (stainless steel and resin layers, grey line, 450µm) in contact with bulk. TS2 is equivalent to TS1 without protective packaging. TS3 is based on a macroscopic cylindrical structure including a central heat wire and a wall temperature measurement (thermocouple). Sensors were tested in a 5L reactor (fluid: water, *Re*=2.6x106 and 20±1°C). Multiple layers of PVC scotch (TESA® 53948, *th*=130 µm, and *ρd*=1300 kg.m-3 [3]) were used to mitigate fouling. Thermal conductivity and heat capacity were measured at *λd*=0.115 W.m-1.K-1, *Cpd*=1025 J.K-1.kg-1 (Neotim FP2C). Experiments were performed in clean (reference) and fouled (up to 5 layers) conditions. Five successive heat flux steps were applied (from 0.2 to 7.5 kW.m-2, 30 min/step). The efficiency was indicated by the evolution of theoretical and experimental thermal resistances.

**3. Results and discussion**

Considering nominal flux (Figure 2), a non-linear response is observed for all sensors. Strong differences are noticeable and can be attributed to different structures and to heat loss contribution. For plan sensors, TS1 and TS2 inflection inform about the balance between efficient flux and back side and edge heat loss. As expected, the absence of front side packaging improves sensor response (TS2). Initial slope (*Rth*=0) informs about the ratio between efficient and nominal flux equal to 7.8, 29 and 80% for TS1, TS2 and TS3 respectively.

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| **Figure 1:** Schemes of TS1, TS2 and TS3 structures | **Figure 2:** Estimated versus theoretical thermal resistances considering nominal (continuous line) and efficient (dotted line) heat flux.  |

Considering efficient flux, estimated thermal resistance is consistent with theoretical values even if inflexion is noticeable for all structures with increasing fouling. Under clean condition, heat convection coefficient is highly superior to 1000 W.m-2.K-1 and for TS1, thermal resistance of front side packaging (stainless steel and resin layers) is close to 2.8E-03 K.m²/W. For food and bioprocess, it is assumed that a deviation of 30% between estimated and real fouling heat resistance is acceptable to control and regulate the process. In present case, the experimental upper LODs are equal to 3.4, 3.6 and 4.0E-03 K.m²/W for TS1, TS2 and TS3 respectively. Considering a dense biofouling (*λd*=0.6 W.K-1.m-1), it enables to estimate a thickness close to 2mm.

**4. Conclusions**

Three fouling sensors based on a thermal excitation have been compared and their metrological performances reported. Considering nominal heat flux, intrusive cylindrical structure should be preferred. However, an accurate estimation of efficient flux demonstrates that cylindrical or plan structures exhibit similar performances and upper LOD, which fulfill specifications. Further work will investigate periodic thermal excitation to qualify and quantify deposit.

**References**

1. J. Crattelet, Journal of Food Engineering 119 (2013) 72 – 83.
2. K.A. Hamilton, Water Research 134 (2018) 261 – 279.
3. Titow, PVC Technology (1984), p. 857