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**Infrared Heating of Foodstuff:
Measurement Method of IR Penetration
Depth and Effect of Process Parameters**

Tesi in
Principi di Ingegneria Chimica

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Riassunto

La radiazione ad infrarosso (IR) è uno dei metodi più antichi di trattamento con calore degli alimenti. Un metodo, volto a ridurre l'attività dell'acqua e che consente lunghi periodi di magazzinaggio con requisiti minimi di imballaggio, è stato l'esposizione dei prodotti alimentari alla luce solare intensa. È noto che la radiazione ad infrarosso ha dei vantaggi sul riscaldamento per convezione. I coefficienti di trasferimento di calore sono alti, il tempo di processo è breve e i costi energetici sono bassi. In questo lavoro sono stati utilizzati raggi NIR, prodotti da un forno ad infrarossi, allo scopo di verificare come cambiano i loro effetti su campioni di pane aventi caratteristiche diverse.

È stato migliorato un metodo, precedentemente messo a punto nei laboratori del SIK- the Swedish Institute for Food and Biotechnology- presso il quale è stato svolto questo lavoro di tesi, per misurare il flusso di calore, o meglio la profondità di penetrazione, attraverso il campione di pane. E' stato costruito uno strumento che può ridurre i raggi NIR riflessi dai corpi presenti all'interno del forno, cambiando la temperatura misurata dalla termocoppia posta nel black body.

La profondità di penetrazione dipende dalle caratteristiche del pane e in particolare dalla luminosità, infatti per il pane brown, che ha il valore più basso della luminosità, è stato misurato il valore più alto.

Infine sono stati applicati alle lampade diversi livelli energetici e più precisamente 100%, 75%, 50% e 25% del loro valore nominale; il valore della profondità di penetrazione misurata per valori compresi tra 100% e 50% del valore nominale è praticamente costante, quindi operando in queste condizioni si realizza un riscaldamento superficiale senza essiccamento significativo.

I risultati del lavoro possono essere riassunti come segue:

- Il metodo per misurare il flusso di calore attraverso il pane è stato ottimizzato mediante una opportuna schermatura del campione.
 - La proprietà più importante è la luminosità, essa influenza la profondità di penetrazione durante il trattamento ad infrarossi.
 - La profondità di penetrazione è più alta con valori più bassi dell'umidità iniziale e tenendo invece invariate tutte le altre proprietà.
 - Si può ipotizzare che c'è diretta proporzionalità tra l'energia assorbita e l'energia trasmessa nel campione.
 - Quando si cambia il livello energetico delle lampade tra 100% e 50%, la variazione del flusso di calore trasmesso attraverso il campione non è elevato, mentre questa differenza è più sensibile quando il livello energetico passa dal 50% al 25%.
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References

1. Nowak D. and Lewicki P. P. *Infrared drying of apple slices*. Innovative Food Science and Emerging Technologies 5, 353–360 (2004).
2. Jun S. *Selective far infrared heating of food systems*. Ph.D. dissertation, the Pennsylvania State University (2002).
3. Jun S., Krishnamurthy K., Irudayaraj J., Demirci A. *Fundamentals and Theory of Infrared Radiation*, Chap. 1 in *Infrared Heating for Food and Agricultural Processing*, edited by Pan Z. and Atungulu G.G., CRC Press, Boca Raton (2011) .
4. Sakai N. Hanzawa T. *Trend in Food Science and Technology* 5. The European Federation of Food Science and Technology, 357-362 (1994).
5. Molin G. Ostlund K. *Dry Heat inactivation of bacillus subtilis spores by means of IR Heating* Chap 11 in *Infrared Heating for Food and Agricultural Processing*, edited by Pan Z. and Atungulu G.G., CRC Press, Boca Raton (2011) .
6. Sawai J. Sakara K. Hashimoto A. Igarashi H. Shimizu M. *Inactivation characteristics shown by enzymes and bacteria treated with far-infrared radiative heating*, Int. J. Food Sci. Tech. 38:661-667(2003).
7. Jun S. Irudayaraj J., *A dynamic fungal inactivation approach using selective infrared heating*. Trans. ASAE 46(5):1407–1412 (2003).
8. Hamanaka D. Uchino T. Furuse N. Han W. Tanaka S. *Effect of the wavelength of infrared heaters on the inactivation of bacterial spores at various water activities*. Int J. Food Microbiol. 108:281–285 (2006).
9. Hashimoto A. Sawai J. Igarashi H. Shimizu M., *Effect of far-infrared radiation on pasteurization of bacteria suspended in phosphate-buffered saline*. Kagaku Kogaku Ronbunshu 17:627–633 (1991).

10. Sawai J. Kojima H. Igarashi H. Hashimoto A. Fujisawa M. Kokugan T. Dhimuze M., *Pasteurization of bacterial spores in liquids medium by far-infrared irradiation*, J. Chem. Eng. Japan 30:170–172 (1997).
 11. Hashimoto A. Sawai J. Igarashi H. Shimizu M., *Effect of far-infrared irradiation on pasteurization of bacteria suspended in liquid medium below lethal temperature*. J. Chem. Eng. Japan 25(3):275–281 (1992a).
 12. Krishnamurthy K. Jun S. Irudayaraj J. Demirci A., *Infrared Radiation Heating for Food Safety Improvement* Chap. 11 in *Infrared Heating for Food and Agricultural Processing*, edited by Pan Z. and Atungulu G.G., CRC Press, Boca Raton (2011).
 13. Patel B.K. Waniska R.D. Seetharaman K., *Impact of different baking processes on bread firmness and starch characteristics in breadcrumb*. Journal of Cereal Science 42 (2), 173–184 (2005).
 14. Sumnu G. Datta A. Sahin S., Keskin S., Rakesh V., *Transport and related properties of breads baked using various heating modes*. Journal of Food Engineering 78 (4), 1382–1387 (2007).
 15. Ginzburg, A.S., *Application of Infra-red Radiation in Food Processing*. Chemical and Process Engineering Series. Leonard Hill Books, London (1969).
 16. Il'yasov S.G. Krasnikov V.V., *Physical principles of infrared irradiation of foodstuffs*. Hemisphere, Washington DC (1991).
 17. Datta A.K., Ni H. . *Infrared and hot-air-assisted microwave heating of foods for control of surface moisture*. Journal of Food Engineering 54, 355–364 (2002).
 18. Skjöldebrand C. Andersson C.G. *Baking using short infrared radiation, Cereals in a European Context*. In: Morton, I.D. (Ed.), *Proceedings of the 1st European Conference on Food Science and technology*. Horwood, Chichester, pp. 364–376 (1987).
 19. Skjöldebrand C. Ellbjär C. Anderson C.G. Eriksson, T., *Optical properties of bread in the near infrared range*. Journal of Food Engineering 8, 129–139 (1988).
 20. Lentz R. Pesheck P. Anderson G. De Mars J. Peck T., US patent 5382441 in (1995).
 21. Cavada L. Noriega A. (2008). US patent 7323663 (2008).
 22. Salagnac P. Glouannec P. Lecharpentier D., *Numerical modeling of heat and mass transfer in porous medium during combined hot air, infrared and microwave heating*. International Journal of heat and mass transfer (47), 4479–4489 (2004).
 23. Skjöldebrand C. Van den hark S. Janestad H. and Andersson C. G, *Radiative and convective heat transfer when baking dough products*. Proceedings from the Fourth Bath Food Engineering Conference, University of Bath, UK 19–21 September (1994).
-

24. Parroufe J.M. Dostie M., Mujumder A.S. Poulin A., *Convective transport in infrared drying*. In: Mujumder, A.S. (Ed.), *Drying'92*. Elsevier, The Netherlands, pp. 695–703 (1992).
 25. Fasina O.O. Tyler R.T. Pickard M.D.. *Modeling the infrared radiative heating of agricultural crops*. *Drying Technology* 16 (9&10), 2065–2082 (1998).
 26. Dagerskok M. Osterstrom L., *Infrared radiation for food processing I. A study of a fundamental properties of infrared radiation* in *Journal of Food Engineering* 12, 237-242 (1979).
 27. Perry's Chemical Engineers' Handbook 7th Edition, McGraw-Hill (1998).
 28. Master thesis made by Daniel Eder (2010).
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