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Effect of physical properties of the liquid on the efficiency of a UV-C treatment in a coiled tube reactor

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ABSTRACT

In liquid foods, various given physical properties affect simultaneously the inactivation of microorganisms by UV-C treatment. Here, the effect of absorption, turbidity and viscosity on the efficiency of UV-C inactivation in a coiled tube reactor was investigated. Model solutions with *Escherichia coli* DH5α as biodosimeter were chosen. The Weibull fit was suitable to describe the inactivation behavior of *E. coli* DH5α in the liquids. Regarding the physical parameters, the absorption was identified as the main parameter affecting the inactivation performance. A considerably lower 5*D* value was observed for the inactivation kinetic at the highest concentration of cellulose particles compared to the absorptive liquids, indicating a minor effect of turbidity on the reduction rate. However, an underperformance of mixing caused by the high viscosity of 10 mPas was observed in absorptive liquids (40 cm^{-1}). In addition, the inactivation behavior of *E. coli* DH5α in juices was compared to the reduction in corresponding model juice. It was shown, that inactivation kinetics in model juice can provide first indications for the inactivation behavior of microorganisms in real juices.

Industrial relevance: Ultraviolet treatment is a promising non-thermal technology for enhancing shelf life of liquid food, where the various given physical properties affect simultaneously the inactivation of microorganisms. For accurate assessment of process design substantial knowledge of the influencing parameters is required in order to prevent an under- or overestimation of the inactivation efficiency.

1. Introduction

Regarding food preservation, the food industry focuses on the improvement of food safety while simultaneously minimizing the loss of quality. Since the commonly used heat processing has adverse effects on sensory and nutritional qualities, increasing consumer demands for fresh-like and minimal processed food products are observed (Henry, 1997; Manas & Pagan, 2005; Raso & Barbosa-Canovas, 2003). Therefore, contents of recent research are devoted to non-thermal technologies (Manas & Pagan, 2005; Raso & Barbosa-Canovas, 2003). Here, an emerging approach to enhance food safety is the application of ultraviolet (UV) light (Koutchma, Forney, & Moraru, 2009). Since DNA absorbs photons in the range of UV-C light, wavelength around 254 nm are reported to be most effective against microorganisms by inhibiting DNA replication (Koutchma et al., 2009). In food industry, UV-C light is already used for the disinfection of air, surfaces and drinking water (Bintsis, Litopoulou-Tzanetaki, & Robinson, 2000; Bolton, 2010; Hoyer, 2007; Koutchma et al., 2009; Shama, 1999). The application for liquid foods is limited by the penetration depth of UV-C energy, which depends on the presence of dissolved and suspended compounds (Koutchma et al., 2009; Shama, 1999). To overcome this limitation, an appropriate process technology is required in order to inactivate as many harmful microorganisms as possible (Müller, Stahl, Graef, Franz, & Huch, 2011). In 2000, the US Food and Drug Administration (FDA) approved the UV-C treatment as a suitable method for the pasteurization of fruit juices in the case of an obtained minimum 5 $\log_{10}$ reduction of pathogens at turbulent flow conditions (United States Food Drug Administration (USFDA) (2000)).

Classically, microbial survival for pasteurization and sterilization processes is described by first-order kinetics (Chen, 2007; Geeraerd, Herremans, & Van Impe, 2000; van Boekel, 2002). This mechanistic approach is based on the assumption that each microorganism in a population has the identical sensitivity to the germicidal agent (Cerf, 1977; Peleg & Cole, 1998; van Boekel, 2002). However, numerous deviations from linear kinetics have been reported, indicating the improbability of experimental artifacts (Chen, 2007; Peleg & Cole, 1998). Using the concept of first-order kinetics for the description of occurring shoulder

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or tailing phenomena, the inactivation efficiency may be under- or overestimated (Geeraerd, Valdramidis, & Van Impe, 2005; Peleg & Cole, 1998). In contrast, the basic idea of the vitealistic conception for the interpretation of microbial inactivation considers the distribution of sensitivities to the lethal event (Cerf, 1977; Peleg & Cole, 1998; van Boekel, 2002). For the description of non-linear inactivation kinetics numerous mathematical models are proposed in the scientific literature (Buzrul & Alpas, 2007; Cerf, 1977; Geeraerd, Valdramidis, & Van Impe, 2006; Geeraerd et al., 2000, 2005). Among the predictive models, the Weibull distribution can describe shoulder and tailing phenomena in addition to the linear regression, while it remains simple to handle (Mafart, Couvert, Gaillard, & Leguerinel, 2002; Peleg, 1999).

In liquid foods, various intrinsic physical properties affect simultaneously the inactivation of microorganisms by UV-C treatment. The objective of this study was to evaluate the effect of product parameters such as absorption coefficient, turbidity and viscosity on the UV-C delivery in absorptive liquids, as well as to assess their importance on the inactivation efficiency. In order to control the influencing parameters, inactivation kinetics of *Escherichia coli* DH5α were conducted in a model solution with adjusted absorption coefficient, turbidity and viscosity at 40 L h^{-1} and 30 L h^{-1}, respectively. To exclude effects of flow conditions on the reduction rate, the UV-C energy input was adjusted by the insertion of coverings between the lamp and the coiled tube. The actinometric UV-C dose was used as dose specification for the inactivation kinetics. Regarding the description of microbial survival, first-order kinetic and Weibull function were assessed for its suitability based on statistical parameters included in GInaFiT and Weibull fit was used to describe the inactivation kinetics of *E. coli* DH5α at the varied test settings. Based on the physical properties of apple and blood orange juice, similar physical parameters for inactivation were adjusted in a model system and the inactivation behavior of *E. coli* DH5α was compared.

2. Materials and methods

2.1. The coiled tube reactor

The MRIUV2010 coiled tube reactor was developed at Max Rubner-Institut (Karlsruhe, Germany). The main component is a module which consists of a FEP envelope (UV-C transmittance of 66 ± 1%) with an inner diameter of 3.7 mm (Adtech Polymer Engineering Ldt., Stroud, UK) which is wound around a 36 W low pressure mercury lamp with maximum peak radiation at 253.7 nm (UVN 30, uv technik Speziallampen GmbH, Wümbach, Germany). Liquids can be pumped through the device at flow rates between 10 and 40 L h^{-1} by a peristaltic pump (Pumpdrive Pd 5206, Heidolph, Schwabach, Germany). Coverings consisting of PVC, single or double wrapped sieve cloth (Spörl KG, Sigmaringendorf, Germany) can be inserted between lamp and coiled tube to reduce the incident UV-C intensity. The PVC covering can be used to shade the tube in 1/8 dividers. Whereas, the sieve cloths consist of stainless steel and decreases the transmittance to about 11% (single wrapped (SWSC)) and 1% (double wrapped (DWSC)), respectively.

To specify the flow conditions in the reactor for several viscosities and densities at 30 and 40 L h^{-1}, Reynolds numbers were calculated.

$$Re = \frac{u \times d}{\upsilon} = \frac{u \times d \times \rho}{\eta} \tag{1}$$

where d is the diameter of the tube, u is the velocity (m s^{-1}), υ is the kinematic viscosity (m^2 s^{-1}), η is the dynamic viscosity (Pa s) and ρ is the mass density (kg m^{-3}). Values of viscosity and density of the used liquids required for the calculation, as well as the resulting Reynolds numbers are given in Table 1.

2.2. Dosimetry

2.2.1. Calculated UV-C dose

The theoretical UV-C dose per liter (D_v in J L^{-1}) of treated liquid for the coiled tube reactor was calculated as the UV-C output of the lamp ($P_{\mathrm{lamp}} = 16$ W) per flow rate (R_{flow} in L s^{-1}) (Keyser, Müller, Cilliers, Nel, & Gouws, 2008) including the transmission of the coiled tube ($T_{\mathrm{tube}} = 0.66$). Depending on the test setting, in which PVC coverings were inserted between lamp and coiled tube, the additional factors for PVC coverings (0.125, 0.25, 0.375, 0.5, 0.625, 0.75, 0.875) were considered by multiplication of the Eq. (2).

$$D_v = \frac{P_{lamp}}{R_{flow}} \times T_{tube} \tag{2}$$

2.2.2. Dosimetry using a potassium iodide/iodate actinometer

In this study the UV-C energy at 254 nm was measured by the chemical iodide/iodate actinometer developed and described by Rahn (Kuhn, Braslavsky, & Schmidt, 2004; Rahn, 1997a, 1997b; Rahn & Echols, 2010; Rahn et al., 2003). The aqueous solution of 0.6 M potassium iodide and 0.1 M potassium iodate in 0.01 M borate buffer (pH 9.25) is optically opaque to light below 290 nm and absorbs all of the germicidal wavelengths. Irradiation results in the linear formation of triiodide, the reaction having the following stoichiometry:

$$8\,KI + KIO_3 + 3\,H_2O + h\nu \rightarrow 3\,I_3^- + 6\,OH^- + 9\,K^+ . \tag{3}$$

Through a regression it is possible to determine the absorbed UV-C dose as a function of formed triiodide, which can be determined

Table 1
Physical properties of the used liquids as well as resulting Reynolds numbers at 40 L h^{-1} and 30 L h^{-1}*.

Model solution	$\alpha_{254\ nm}$ in cm^{-1}	Turbidity in NTU	Viscosity in mPas	Density in g cm^{-3}	Reynolds number
0 cm^{-1} = 0 NTU	0	0	1.05 ± 0	1.005 ± 0.001	3360
9 cm^{-1}	9.3 ± 0.1	0	1.06 ± 0.01	1.005 ± 0.001	3625
20 cm^{-1}	20.4 ± 0.1	0	1.06 ± 0.01	1.005 ± 0.001	3625
40 cm^{-1}	39.6 ± 0.1	0	1.06 ± 0.01	1.005 ± 0.001	3625
60 cm^{-1}	60.9 ± 0.1	0	1.06 ± 0.01	1.005 ± 0.001	3625
1000 NTU	0	1132 ± 66	1.03 ± 0.02	1.001 ± 0.001	3716
10,000 NTU	0	9576 ± 175	1.06 ± 0.02	1.010 ± 0.001	3643
9 cm^{-1}; 10,000 NTU	9.0 ± 0.1	10,157 ± 162	1.05 ± 0.01	1.010 ± 0.001	3678
0 cm^{-1}; 10 mPas	0.2 ± 0.1	29 ± 1	9.68 ± 0.2	1.000 ± 0.010	296*
40 cm^{-1}; 1 mPas	39.6 ± 0.4	0	1.06 ± 0.01	1.005 ± 0.001	2719*
40 cm^{-1}; 10 mPas	39.7 ± 0.8	28 ± 1	10.19 ± 0.59	0.999 ± 0.001	281*
AJ	18.0 ± 0.2	590 ± 2	1.98 ± 0.02	1.050 ± 0.001	1941
Model AJ	18.3 ± 0.3	564 ± 3	1.75 ± 0.04	0.999 ± 0.001	2183
BOJ	53.51 ± 0.96	9973 ± 108	2.99 ± 0.01	1.050 ± 0.003	1007*
Model BOJ	52.83 ± 0.58	10,152 ± 326	2.65 ± 0.02	1.010 ± 0.001	1093*