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A soft tubular model reactor based on the bionics of a small intestine – Starch hydrolysis

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ABSTRACT

The traditional reactors in industry are usually made of rigid material. The vessel walls do not actively engage in the mixing and reactions. Here, the fabrication of a new soft tubular reactor by mimicking the structure and physiological processes of an animal or human small intestine is presented. The reactor is made of silicone rubber, with good toughness yet being flexible. A peristalsis process was introduced externally and the mixing viscous materials in the soft reactor are investigated. The extent of starch hydrolysis with α-amylase under the peristaltic action has been studied. Experimental data showed that the peristaltic process was effective in mixing the viscous materials in the reactor and has enhanced the starch hydrolysis. The mixing effect can be regulated from the peristaltic frequency and the peristaltic amplitude. The degree of starch hydrolysis in the soft reactor has been measured and compared with a stirred tank reactor.

1. Introduction

In industry, the reactor is the heart of a chemical process, where chemical and/or physical conversions are carried out to transform feeds into products (Mann, 2009). Generally, mixing in a reactor greatly affects the reaction efficiently and the quality of products. The design and fabrication of the reactors are particularly important, including the aspects of mass transfer, heat transfer, material properties and cost etc. (Couper et al., 2012). The materials for constructing reactors in most cases are steel, resin or polymer, and graphite (Atsumi and Tauchi, 2003; Brunetti et al., 2007; Hayward et al., 2003; Uyanik et al., 2002). These materials are rigid and not flexible. The mixing inside the reactor depends on devices such as various kinds of impellers to induce agitation and increase the mixing efficiency (Visscher et al., 2013). However, there are some limitations for the conventional mixing methods, especially for mixing high viscosity fluids. Metzner and Taylore (1960), Dong et al. (1994), Kuncewicz (1992), Perng and Murthy (1993) found that segregated regions can occur in stirred tank rigid reactors for Reynolds numbers below 500 (Lamberto et al., 1996). The segregated regions represent the less effective mixing and are not conducive to mass transfer. The mixing method in a rigid tubular reactor also encounters similar problems. Static devices, such as mixing tee and insert mixers, provide an inexpensive way to continuously mix fluids in tubular

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reactors. However, the effective mixing length is relatively short (10–80 times of the pipe diameter) and the performances are limited by the viscosity, density and velocity of the fluids being mixed (Towler and Sinnott, 2013). The static inline mixer, which is widely used in tubular reactors, is not so effective when mixing highly viscous material in the case of laminar flow (Visscher et al., 2013). If the reactor walls are soft and elastic, the problems mentioned earlier might be avoided. If the reactor wall has motility, the mixing of materials could be achieved through the powerful contractions and peristalsis of the reactor wall. The reactors found in nature are soft in general, for instance, the 'reactors' in the digestion tract of animals and human, and indeed many innovations can be made from mimicking biological sources (Chen, 2015).

It has been reported that the viscosity of bolus/chyme in the gastrointestinal media is usually high (Dikeman et al., 2007; Dorota et al., 2012; Edmund et al., 2014; Pernille et al., 2013). Interestingly, for healthy individuals, the small intestine of human can handle high viscosity chyme efficiently. This is largely attributed to the unique physiological structure and the peristalsis of the small intestine. The presence of intestinal villi makes the small intestinal mucosal surface area increase significantly, reaching more than 400 m^2 (Campbell, 2012; Ingenbleek and Beckers, 1973; Klausner et al., 2003). There are many reports about in vitro models of gastrointestinal system, such as TIM developed by TNO (Kheadr et al., 2010), the large intestine simulation system developed by Minekus et al. (1999), and the small intestine model developed by Tharakan et al. (2007) etc., which have confirmed the contribution of peristalsis action on mass transfer and mixing. In a sense, the whole physiological process of digestion is akin to a highly efficient food processing, in which chemical reactions and physical transport processes are simultaneously achieved in the small intestine, hence the small intestine can be seen as a tubular reactor with very complex functions.

There have been modeling studies based on the assumption that the mammals' gastrointestinal tract is an ideal reactor (Penry and Jumars, 1987; Horn and Messer, 1992; Jumars, 2000). Here, we proposed a type of soft-reactor, based on a bionic concept of the human small intestine. The residence time distribution (RTD) performance in such a reactor has been investigated previously in our laboratory (Deng et al., 2014). To further understand the performance of the device truly as a reactor, starch hydrolysis involving a highly viscous material in the small intestine model reactor has been studied. The peristalsis process has been simulated and its effects on the mixing and the hydrolysis of starch with α-amylase have been investigated.

2. Materials and methods

2.1. The design and fabrication of the small intestine model reactor

The material used to make the small intestine model reactor (SIMR) is K-1001 A, B two-component plus liquid silicone rubber, which was purchased from Kuwart Silicone (Group) Co. Ltd. (China). Table 1 shows the relevant physical parameters of rubber-like form after the K-1001 A and B two-component plus liquid silicone rubber vulcanizing. The material obtained is soft, flexible and elastic after curing. Our work here focuses on the design and development of a new soft reactor based on the bio-inspired chemical engineering principles. We imitated the working mechanism of the small intestine, but not reconstructing it. The current work is expected to trigger more interesting works on developing industrially relevant soft reactors. Here, in the current work, a small reactor size is fabricated to facilitate the research in lab. The schematic diagram of the SIMR is shown in Fig. 1. The reactor is 600 mm long with an internal diameter of 25 mm and outer diameter of 31 mm. Uniform sized villous protrusions are made to distribute evenly on the inner wall of the reactor. The protrusion is a small cylindrical object with about 1.5 mm in diameter and 2.5 mm in length. The top of the cylinder is a roundish shape with a height of approximately 0.5 mm. The spacing between two adjacent protrusions is 5 mm (center to center distance). To facilitate a clear observation of the mixing and flow of materials in the soft reactor, another intestine model reactor with no villous protrusions was also made by using the same material, which has the same geometrical characteristics otherwise. The small intestine model reactor with villous protrusions was abbreviated as SIMR-1, and the one without villous protrusions was abbreviated as SIMR-2.

Table 1 – The relevant physical parameters of K-1001 A, B two-component plus liquid silicone rubber after curing (components A and B are uniformly mixed together with the mass ratio of 1:1, then vacuum dried at the temperature of 140 °C for about 10 min).

Physical parameter	Units	Data
Shore A hardness	Shore A	≈0
Tensile strength	MPa	2
Elongation at break	%	300
Tear strength	kN/m	2.7
Linear shrinkage rate	%	2.0
Compression set value	%	0.15

2.2. Simulation of the small intestinal peristalsis process on the SIMR

The peristalsis of the small intestine was mimicked on the SIMR using a homemade cross-shaped rotating device as shown in Fig. 2(a). The device was made from stainless steel. Only one device is used in this work. The shaft (1) was 15 cm long. The 'cross' (2) was about 10 cm long with an oval steel ball bearing (about 1 cm long) attached on the each end. When the device rotated at a certain frequency driven by a stepper motor (3), the oval ball bearings on each end of the stick would induce periodic impacts on SIMR under the pre-determined frequency.

Fig. 2(b) shows the schematic diagram of SIMR with the simulated peristalsis process. The SIMR was connected end to end by a glass connecting tube (4). There are two injection ports on the glass connecting tube for feeding. It was about 16 cm long from the closest injection port to the peristaltic center along SIMR in the experiments. The intestinal motility is actually the results of synergistic effect of the mixing contractions and propulsive contractions. The mixing contractions (segmentation contraction) occur when a portion of the small intestine becomes filled with digesta and causes a localized concentric contraction, spaced at intervals along the intestine. The propulsive contractions are responsible for propelling the digesta through the small intestine and are known as peristalsis (Tharakan et al., 2010). The peristalsis speed is about 1–2 cm s^{-1}, and each peristaltic wave disappears after propelling the chyme about 3–5 cm in distance (Tharakan et al., 2007). Therefore, the peristalsis action could