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# DETERMINATION OF RESIDENCE TIME DISTRIBUTION IN THIN FILM SCRAPED SURFACE HEAT EXCHANGER USING IMAGE ANALYSIS

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**Abstract:** Scraped surface heat exchangers are well established heating and cooling system for viscous and sticky products. Generally thin film has Scraped surface heat exchanger has short residence time compared to other heat exchangers which may be sometimes difficult to compute. In this study, a simple method for residence time distribution measurement was carried out using image analysis. Pulse input injection method was used to inoculate the tracer dye and colourimetric analysis of milk at SSHE outlet done by program developed in Scilab software. Mean residence time distribution for scraped surface heat exchanger was 41.46 s at 120 rpm scraper speed, 294 kPa steam pressure and 450 l/h milk feed rate. Determined RTD is helpful in context with thermal processing of milk in SSHE.
**Keywords:** Scraped surface heat exchanger, residence time distribution, milk, image analysis.

## Introduction

Scraped surface heat exchangers are widely used for processing of highly viscous or sticky fluids. In these heat exchangers, the product to be heated/cooled flows axially in an annular section between a stationary outer cylinder and a powered coaxial rotor. The inner wall of the outer cylinder is periodically scraped by blades attached to the rotor, while the heating or cooling fluid circulates into the external jacket, which is generally equipped with flow baffles [1]. SSHE have been used for number of applications like heating [2], cooling [3], concentration [4], crystallization [5], low grade heat recovery [6] etc.

Residence time distribution is an important parameter to understand extent of thermal treatment and flow behavior in a SSHE. An analysis of the experimental RTD data provides valuable information about the fluid flow behavior, the degree of radial and axial dispersion, and possible flow problems in the exchanger, such as stagnation or short-circuiting. It is therefore important to perform a RTD study, complemented with temperature profile measurements, in order to assess the influence of the operating conditions on the fluid flow

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behavior and on the efficiency of the thermal treatment applied to the product [7]. Study of residence time distribution (RTD) is required for design and the control of chemical processes [8]. RTD measurements constitute an efficient tool that can help better understand and determine different hydrodynamic parameters. The parameters identified allow for the modeling of many processes [9].

The residence time distribution (RTD) can be easily obtained for all unit operations in a continuous line with a tracer response experiment performed for each unit operation separately and for the mechanically integrated line as well. In this testing, a pulse or step change of tracer is added to the inlet of the continuous equipment being characterized, and the response of the tracer concentration profile at the outlet is measured. The concentration measurements can be recorded using online spectroscopy, or samples can be collected for off-line measurement. In either case, it is important that the tracer concentration be readily measureable by an analytical technique. Additionally, the presence of the tracer should not impact the flow properties of the bulk material for which the RTD measurements are being taken, because the RTD is highly dependent on the flow behavior of the material within the apparatus. Any significant changes to the flow behavior will cause the measured RTD not to be representative of the material [10].

There are number of methods used to determine residence time distribution. Dye tracer method is mostly commonly used method for residence time studies [11, 12, 13, 14]. RTD in a one-stage impinging streams reactor was investigated using coloured solution as the tracer and samples were analyzed by an UV–vis spectrophotometer to determine the concentration of the dye [15]. Method based on visible-near infrared spectroscopy using a fiber optic probe inserted in the extruder die to measure the concentration of red dye was studied [16]. Another popular method is use of salt or ionic compound as tracer and RTD is determined using electrical conductivity [17, 18]. RTD was indirectly computed by measuring magnetic susceptibility using iron powder as tracer [19]. Among all available method, colourimetric method is the most easy method to implement in heat exchangers for RTD measurement. In the present study effort was made to determine RTD of SSHE using image analysis.

**Material and methods**

**Scraped surface heat exchanger**

Experiments were carried out using a Scraped surface heat exchanger jacketed with mild steel having four SS blades (two for scraping and two for conveying) and cylinder diameter 340 mm with inner length of 1200 mm from feed end to exit end was used to concentrate the milk. Scraper was coupled with geared motor. To regulate the speed of scraper the motor was controlled using a variable frequency drive (Model: VLT Microdrive, Danfoss Drives Pvt. Ltd.). SSHE was provided with vapour vent, vapour vent cock, steam trap, pressure gauge, air vent and safety valve. The parameters were kept constant includes rotational speed of scraper and feed rate.

**Standardization of dye solution**

Tracer dye solution was prepared by adding 10 g of mixed dye sunset yellow FCF (Disodium 6-hydroxy-5-[(4-sulfophenyl) azo]-2-naphthalenesulfonate) and carmoisine (Di-sodium salt of 2-(4 sulpho -1-naphthylazo_1-naphthol-4-sulphonic acid) in 1000 ml of distilled water. Preliminary trials were conducted to determine the dye concentration required for visible colour change. As shown in **Figure 1.** The different percentage of dye solution (1-10%) was added to milk and images were analyzed using computer vision system. Average CIE Lab values were computed and colour difference (Δ E) was calculated using following equation:

$$\Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - bL_2)^2} \qquad (1)$$

Where,
$\Delta E$ = Colour difference
$L_1$ = L value for reference sample i.e. milk
$L_2$ = L value for milk + dye sample
$a_1$ = a value for reference sample i.e. milk
$a_2$ = a value for milk + dye sample
$b_1$ = b value for reference sample i.e. milk
$b_2$ = b value for milk + dye sample

**Image acquisition and analysis system**

To take images of milk at SSHE, an inclined distribution plate was attached at the SSHE outlet (**Figure 2**). The purpose of the distributor plate was to spread milk over the plate so that image of milk sample could be acquired. An LED (D65) light source was used to illuminate the distributor plate. Camera was fixed at an angle normal to the distributor plate. The video (mp4 format) was taken during the RTD experiment. The video was converted to digital images (1 frame per second) using DVD Video software (Version: 5.0.59.525). The digital images were processed using Scilab program to compute CIE Lab values.

**Determination of RTD**

Buffalo milk (6% fat and 9% SNF) was used as feed. Acidity of raw milk was 0.12% (lactic acid). Thin film scraped surface heat exchanger was used for heating milk and was operated in recirculation mode. The constant parameters during trials were scraper speed (120 rpm) and milk flow rate (450 l/h). Tracer was injected after system achieved steady scraper speed of 120 rpm. The RTD technique involved pulse injection of a small amount of dye tracer at the inlet port. CIE *a* value was used to measure the concentration of tracer in SSHE [11, 20]. Plotting of graph and RTD calculation was done using program developed in MATLAB R2016 trial version (MathWorks, Inc., MA, USA). The residence time distributions of material in the SSHE is described by the E(t) curve that shows the variation of tracer concentration at the exit and is given by:

$$E\ (t) = \frac{C\ (t)}{\int_0^{\infty} C\ (t)dt} \qquad (2)$$

Mean residence time was computed as:

$$E\ (t) = \int_0^{\infty} t\ E\ (t)dt \qquad (3)$$

**Results and discussion**

**Standardization of dye solution**

The standard curve was plotted to determine the exact quantity of tracer to be injected in the pulse input method. The visible colour change is an indication of the concentration change of tracer. Initially, the samples were placed on white background and colour (L*, a*, b*) was measured to plot a standard curve. It was done to predict the exact quantity of tracer to be injected during each step of operation. It was observed that 1% increase in the concentration of tracer dye resulted in visible colour change. Upto 5% dye concentration colour change ΔE value was more as compared to incremental increase in 6-10% dye concentration range.

**Residence time distribution**

The graphical representation of colour difference (ΔE) versus time indicates visible change in colour values at fixed interval of time 1 s (**Figure 3**). The graph shows chaotic trend which specifies that the colour difference changes initially from low to high and again low as response to pulse injection of dye solution. Taking ΔE as parameter for computing RTD was not feasible as definite RTD trend was not observed in ΔE - time plot. When inverted CIE a value was plotted against time, a definite RTD trend was observed (**Figure 4**). Inverted CIE a colour value was observed near 53 seconds.

E(t) plot was different from conventional plots having a bell curve with tail end. There may be number of reason for obtaining a non conventional E(t) plot for SSHE (**Figure 5**). One of the prime reasons could be high flow rate which resulted in short-circuiting and channelling at the bottom of horizontal SSHE. Another reason could be use of two conveying blades which immediately carries the milk from the inlet region towards the outlet of SSHE. Such phenomena results in very short residence time of milk in the SSHE as compared to other heat exchangers. The E(t) plot also indicates turbulent flow regime inside the SSHE. It Has been reported that residence time distribution based on the colour a* values shown a logarithmic trend for the extradites using laboratory extruder [20]. The mean residence time of milk in SSHE was calculated as 41.46 s from the area under the tE(t)-time curve (**Figure 6**).

**Conclusions**

Rapid and simple imaging method for RTD measurement was established. RTD measurement of SSHE gives information on the time spent by fluid particles in the apparatus and has been obtained using a new method to detect the pulse response. The images were successfully analyzed by the program developed in Scilab software and CIE Lab values were extracted. The method was found less time consuming as compared to RTD determination by concentration measurement using complex chemical analysis. Also this method does not alter the flow properties of milk.

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**Figure 1:** Threshold value (ΔE) for colour change at different dye concentration

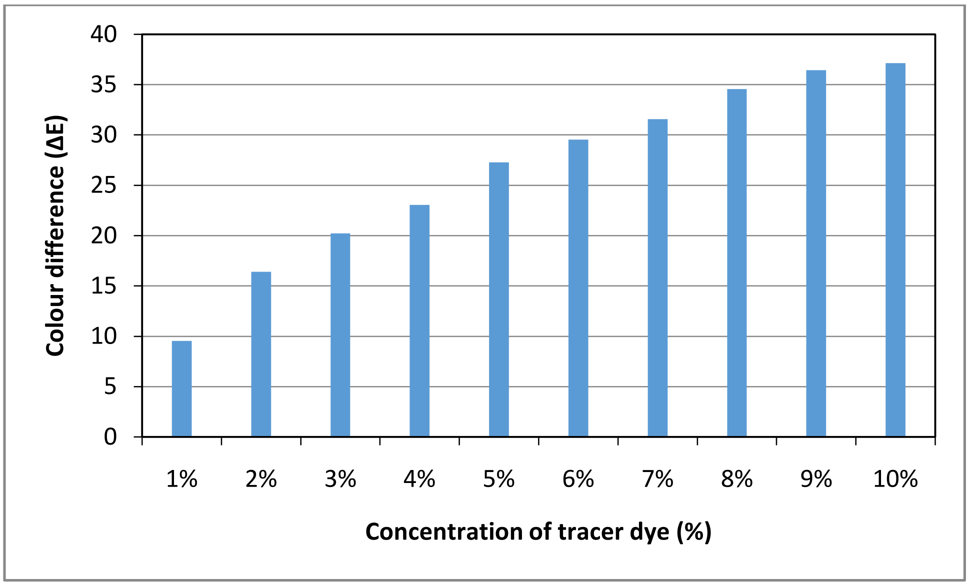


**Figure 2:** Experimental setup for RTD determination

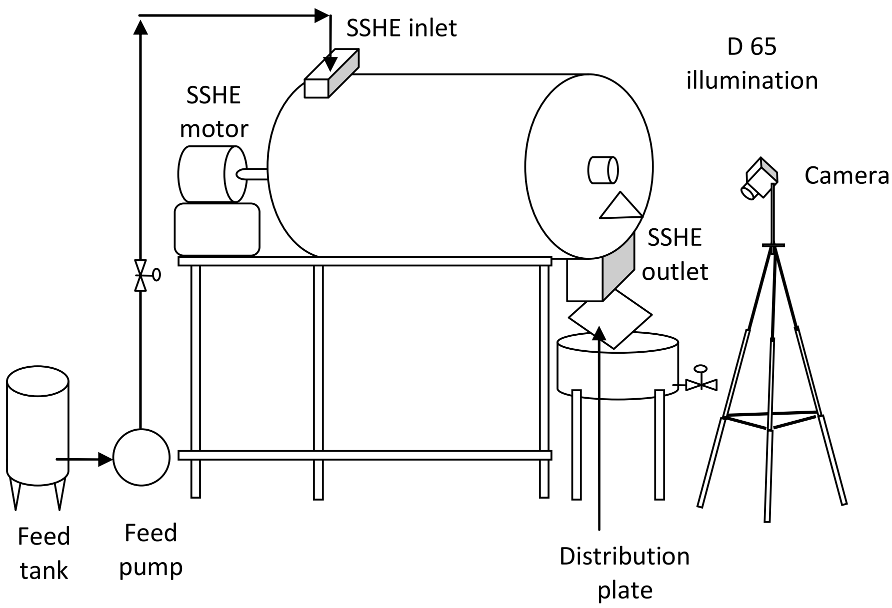

**Figure 3:** Change in colour difference (ΔE) with respect to time

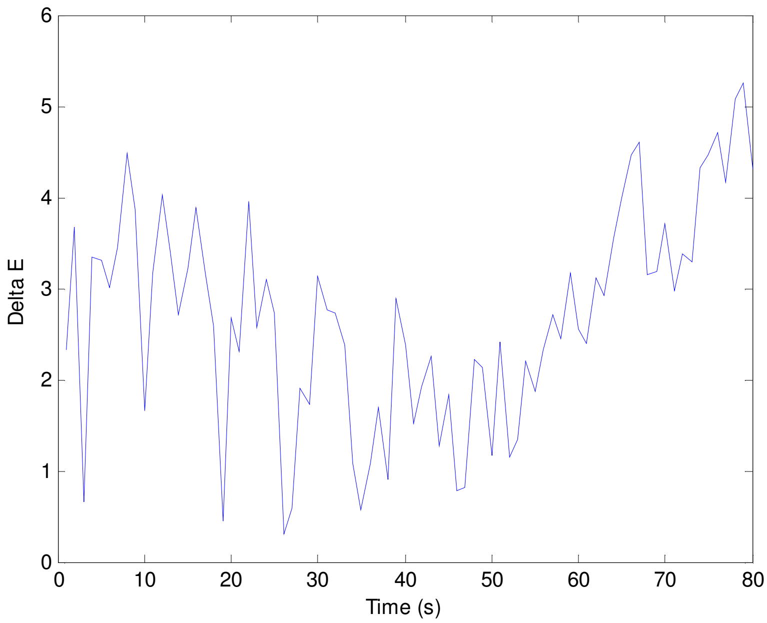


**Figure 4:** Change in inverted CIE a* value with time

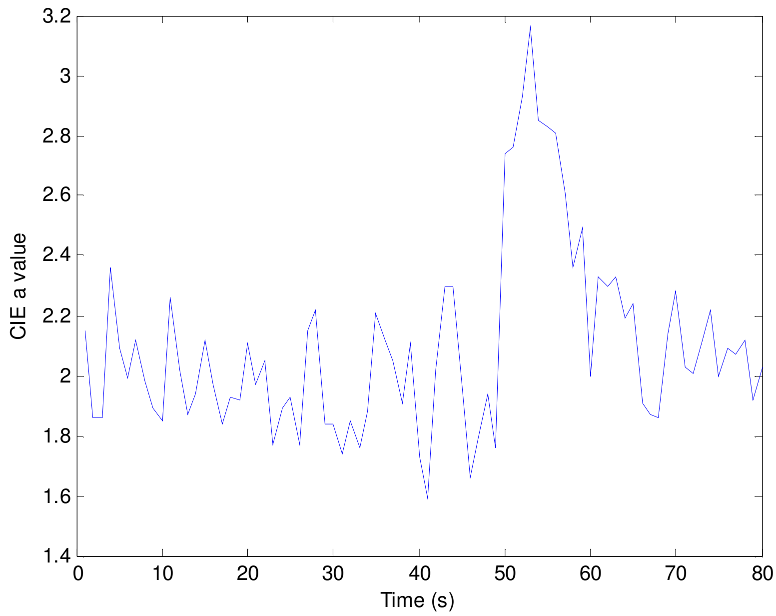

**Figure 5:** E(t) curve representing variation of tracer concentration at exit

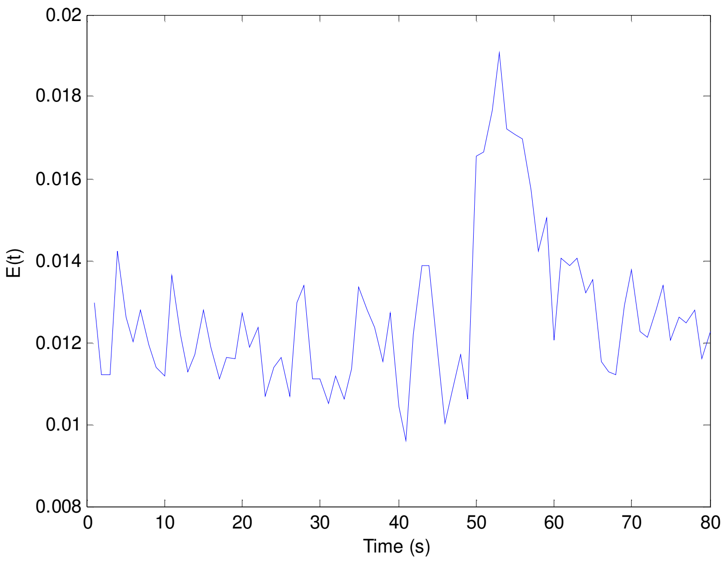


**Figure 6:** t.E(t) curve to calculate mean residence time