IChemE

www.icheme.org/journals
doi: 10.1205/fbp.04021

0960–3085/05/$30.00+0.00

Trans IChemE, Part C, March 2005
Food and Bioproducts Processing, 83(C1): 53–60

LOCAL WALL SHEAR STRESS VARIATIONS PREDICTED BY COMPUTATIONAL FLUID DYNAMICS FOR HYGIENIC DESIGN

B. B .B. JENSEN[1,*], A. FRIIS[1], Th. BÉNÉZECH[2], P. LEGENTILHOMME[3] and C. LELIÈVRE[3]

[1]*Food Process Engineering, BioCentrum-DTU, Lyngby, Denmark*
[2]*INRA-LGPTA, Villeneuve d'ascq, France*
[3]*GEPEA—UMR CNRS 6144, Université de Nantes, Sant-Nazaire, France*

Food producers depend to a great extent on the availability of easy-to-clean processing equipment. This paper presents initial work carried out to improve the application of commercially available computational fluid dynamics (CFD) programs as a tool to improve hygienic design of food processing equipment. In the present paper, previous work on using CFD to improve hygienic design are combined with work that shows the importance of measured local mean wall shear stresses and the fluctuations in these wall shear stresses with respect to cleaning effects of the flow. Results of wall shear stress and the fluctuations acquired by the measuring technique are difficult to apply directly for actual design optimization. Instead, steady-state CFD simulations using STAR-CD were applied to predict the fluctuation of equivalent mean wall shear stresses on the entire surface of pipes with various diameter changes (gradual and sudden expansions or contractions). Measured fluctuation rates of wall shear stress are shown to be analogous to the turbulence intensity in the near-wall region predicted by CFD simulations. The results are promising; hence, an important step has been taken towards setting up a method for evaluating cleanability by steady-state CFD simulations based on evaluation of the mean wall shear stresses and the turbulence intensity.

Keywords: cleaning-in-place; wall shear stress; turbulent flow fluctuations; computational fluid dynamics; hygienic design; local flow conditions; experimental.

INTRODUCTION

In many areas of the food industry, production lines are cleaned-in-place daily to maintain heat transfer characteristics, reduce the pressure drop in heat treatment units and maintain product quality of the product (microbial quality and safety). However, literature show that some level of bacterial contamination does remain on surfaces in equipment after standard cleaning-in-place (CIP) procedures (Stevens and Holah, 1993; Austin and Bergeron, 1995; Elevers *et al.*, 1999). Disinfection-in-line is an alternative; however, the costs of thermal disinfection and limitations on chemical disinfection (highly chemical-resistant bacteria) sets limits to these methods.

Cleaning is a complex operation, where the efficiency depends on many factors, e.g. the soil to be removed, cleaning time, temperature of the cleaning agent and the hydrodynamic effect of the moving liquid (Graßhoff, 1992; Lelieveld *et al.*, 2003). Shear forces imposed by the cleaning fluid at fluid–equipment interfaces are of importance for the cleaning mechanism. Shear forces can be controlled by either design of the equipment or volumetric flow rate, with the former being preferred due to the cost of increasing the flow rate. Since 1998, food processing equipment intended for the European market must meet the design criteria given by the EC (European Commission) Machinery Directive (98/37/CEE). This Directive includes a section on hygiene and design requirements. According to the Directive, machinery intended for preparation and processing of foods must be designed and constructed to avoid health risks. Hygiene rules that must be respected are present in amendments to the Directive.

Published work shows a correlation between removal of matter from a surface and wall shear stress on surfaces exposed to parallel, fully-developed laminar and turbulent flow (Visser, 1970; Graßhoff, 1988; Sharma *et al.*, 1992; Jensen and Friis, 2004a). Jensen and Friis (2004b) show that the correlation is not as clear for surfaces exposed to the chaotic flow present in most processing equipment. Lelièvre *et al.* (2002) studied the effect of different mean

Correspondence to: Dr B. B. B. Jensen, Food Process Engineering, BioCentrum-DTU, Soltotfts Plads build. 221, 2800 Lyngby, Denmark. E-mail: bbb@biocentrum.dtu.dk

local wall shear stresses and their associated time-dependent fluctuation rate on the removal of *Bacillus cereus* spores from pieces of closed equipment cleaned under turbulent flow conditions. They use an electrochemical method based on an analogy between mass and momentum transfer to measure the wall shear stress. An electrical current caused by the mass transfer is measured and correlated to the mean wall shear stress. The fluctuations of the measured current are correlated qualitatively to the wall shear stress fluctuations. These measurements are compared directly to the data from cleanability assessments. This work demonstrates the importance of both mean local values of wall shear stresses and their variations in sudden and gradual pipe diameter changes. Areas on the walls are found to be cleanable despite the presence of low mean wall shear stress values. This is because of the presence of high levels of fluctuation of the current (up to 25%) recorded in these areas. The presence of large wall shear stress fluctuations is because of the flow patterns and, hence, the geometry. *B. cereus* spores in areas of high fluctuations are exposed to high peaks of wall shear stress caused by the fluctuations. In addition, the shear stress fluctuations could influence the removal of *B. cereus* spores because of fatigue mechanisms (Hertzberg, 1996) in the bond between *B. cereus* spores and the surface. The above evidence suggests that a combination of the mean wall shear stress and the fluctuating part of the wall shear stress can be used for evaluating cleaning properties.

The technique used for measuring the mean and the fluctuating parts of wall shear stress has its shortcomings for use in actual design procedures with respect to hygiene. Measurements can only be performed in a predefined number of discrete points, and the equipment tested has to be specially designed to mount the measuring probes. An alternative approach for estimating the mean and fluctuating wall shear stress over the entire surface in a piece of equipment is to apply computational fluid dynamics (CFD) to predict the flow in the equipment. CFD is widely used with great success within other industries for prediction of flow patterns, quantitative hydrodynamic parameters, chemical processes, etc. Quantitative prediction of wall shear stress is a difficult exercise for CFD simulations (shown by Wilcox, 1998; Bouainouche *et al.*, 1997). However, models for representation of near-wall flow have recently been implemented in commercially available CFD codes, which have improved quantitative prediction of wall shear stress (Rodi, 1991). Qualitative prediction of wall shear stress was proven to be very good indeed (Chen and Patel, 1988; Wilcox, 1998). However, predicting the fluctuating part of wall shear stress using CFD is not straightforward. Transient simulations with a time step sufficiently small to resolve the time scale of the fluctuations are an option; however, this is extremely time-consuming.

The aim of this paper was to determine if CFD could be applied to predict the actual mean wall shear stress variations and the fluctuating component variations of the wall shear stress along the length of a pipe measured by Lelièvre *et al.* (2002). The turbulence intensity obtained from steady-state simulations was found to predict the trends of fluctuation rates of the wall shear stress. This should encourage further work in order to establish a platform for the use of CFD in hygienic design. The steady-state simulation was performed taking into account commonly used desktop computer power.

MATERIAL AND METHODS

Local Wall Shear Stress Measurements (Lelièvre *et al.*, 2002)

Measurements of wall shear stress and bacterial removal was conducted in two set-ups (Figure 1); one with a sudden expansion from 1 to 2 inch pipe followed by a gradual contraction from a 2 to a 1 inch pipe and one with a gradual expansion from 1 to 2 inch pipes followed by a sudden contraction from 2 to 1 inch pipe. The components were re-used for each set-up; only the configuration of the components was different. Detailed information on the test set-up is found in Lelièvre *et al.* (2002).

In order to measure the local wall shear stress, platinum microelectrodes were placed close to the geometrical changes (Figure 1 and Table 1). Each microelectrode consisted of cross-sectioned platinum wire of 1 mm diameter. The local

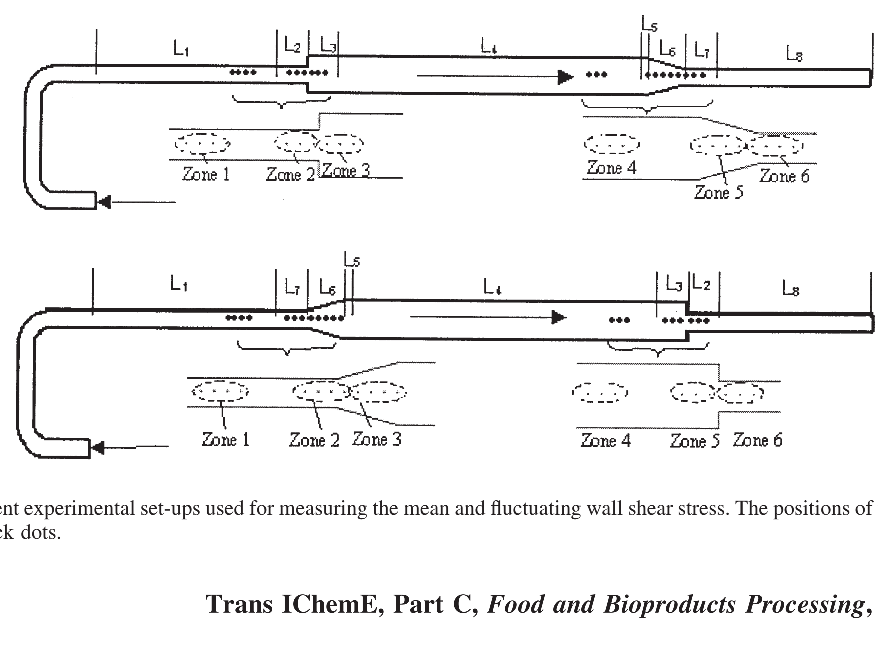

Figure 1. The two different experimental set-ups used for measuring the mean and fluctuating wall shear stress. The positions of the electrochemical sensors are indicated by the black dots.