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Flow regimes in the emptying of pipes filled with a Herschel–Bulkley fluid

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ABSTRACT

The emptying of pipework from fluids of high viscosity is a significant multiphase flow problem in many food and personal care industries. Maximising product recovery whilst minimising cleaning time and effluent volume is important in minimising the environmental footprint of the plant. The cleaning of pipework fully filled by toothpaste by water under different process conditions has been studied and monitored by weighing pipes at intervals. Three flow regimes have been identified; a short *core removal* stage of product recovery, before water breaks through the filled pipe, and two in subsequent cleaning, *film removal* when there is a continuous wavy annular film on the wall, and *patch removal* in which the material is present as patches on the wall. The amount of product recovered in core removal is here not a function of flow conditions; however, conditions during core removal significantly affect the overall cleaning time. Overall cleaning time can be reduced by at least 25% by selecting the best removal conditions in the different stages. It is hypothesised that this is due to changes in the wall layer induced during core removal, with a very wavy wall layer leading to rapid subsequent removal. If this effect could be understood and scaled up it may be possible to improve commercial cleaning processes.

Keywords: Fluid mechanics; Cleaning; Optimisation; Waste minimisation

1. Introduction

Fouling of processing equipment is a severe industrial problem. In petrochemical processing, fouling is slow, and equipment is cleaned once or twice a year. However, in the food and personal product industries, more frequent cleaning, often daily, is needed. Fouling deposit can endanger hygienic operation as well as lowering the efficiency of the plant. Cleaning is also necessary at plant changeover to remove one product before processing of another starts.

Generally, food and consumer products industry operate cleaning-in-place (CIP) processes; these are automated systems that rinse and recirculate cleaning fluids through the equipment (Tamime, 2008). However, regular cleaning has considerable economic impact in terms of energy used and production time lost. The need to minimise waste and energy during cleaning is becoming increasingly crucial as the need to minimise the environmental impact of processes becomes more important.

Cleaning involves both physical and chemical processes (Fryer et al., 2006). Fryer and Asteriadou (2009) categorised cleaning problems in terms of soil types and removal mechanism, and identified 3 types of soils that are most difficult to clean. They are:

- Type 1 soil: residue of very viscous or viscoplastic fluids that can be cleaned by the action of water alone;
- Type 2 soil: biofilms which needs biocides to kill adhered organisms as well as fluid action for removal;
- Type 3 soil: deposits which required hot cleaning chemical to effect removal.

This classification allows different experiments to be compared and will hopefully lead to greater understanding of the problem. A number of studies have looked at Type 3 deposits, such as milk-based soils (Gillham et al., 1999, 2000; Tuladhar et al., 2002) and egg albumin (Liu et al., 2007) and extensive work has been done on biofilm removal (such as Blel et al.,

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2009; Burfoot et al., 2009; Lelievre et al., 2001; Lelièvre et al., 2002).

Commonly, both Type 2 and 3 soils form thin films of mm-scale deposit. However, in the cleaning of Type 1 deposits the soil can consist essentially of product that forms cm-thick layers on the surfaces of tanks and vessels and can completely fill pipework. Many food and personal care products can be involved, such as milk chocolate, mustard, mayonnaise, yoghurt, creams, and toothpastes. The problem in these soils is thus one of liquid–liquid displacement; of ensuring that pipes and tanks can be emptied as efficiently as possible by removing product with water.

In the removal of material from fully filled pipework, the first stage, here called *core removal*, is one of product recovery, in which water is used to push product out. This stage is rapid (of duration comparable to the residence time of the water in the pipe) and leaves a thick annular layer of product on the pipe wall. In the next *cleaning stage* this annular film of product is removed completely. It is common to attempt to recover as much product as possible; the technical problem is thus:

(i) to maximise the amount of product recovered in the first stages of the cleaning process, and
(ii) to minimise the cleaning time for total removal of material from the plant.

The removal of viscous fluids from pipework has not been studied in any detail. Generally, attention has been given only either to the way the core removed or how the residue is removed (such as Gabard and Hulin, 2003; Kuang et al., 2003; Park et al., 2003) thus interaction between these stages has not been investigated. Some work has been done on gas–liquid flows (such as Huzyak and Koelling, 1997; Kamisli and Ryan, 2001; Poslinski et al., 1995). The effect of the product recovery stage on cleaning has not been studied in any detail. However, some displacement studies with Herschel–Bulkley fluids have revealed the importance of product recovery. Displacement of laponite solutions by water (Gabard and Hulin, 2003) and carbopol solutions by gas (de Souza Mendes et al., 2007) was observed to be a perfect plug-like displacement which did not leave any remaining fluid behind at very low velocities. Wiklund et al. (2010) used ultrasound to identify the interface between two fluids in pipe flow, and show that this method can be used to identify the displacement of fluids. Cole et al. (2010) present preliminary data for the cleaning of toothpaste from pipework, and show that the overall cleaning time correlates with wall shear stress. Taghavi et al. (2012a,b) present experiments on a related problem, the displacement of a yield stress fluid by a Newtonian fluid in nearly horizontal pipes, and identify a number of flow regimes.

Conditions in the core removal stage will determine the structure of the thin film which remains after water has swept through. Wavy (unstable) films may enhance the cleaning performance. A number of modelling studies (including Ó Náraigh and Spelt, 2010; Sahu et al., 2007, 2009) have been conducted to examine the stability of the thin film after the displacement process. Taghavi et al. (2012b) generate some models, but both flows are laminar, unlike the cleaning case in which the water phase is turbulent.

If the pipe emptying process were better understood it might be possible to optimise both product removal and cleaning. The aims of this work were thus:

(i) to study the cleaning of material that behaves as a Hershel–Bulkley fluid from a tube systematically, for the first time separating the conditions for product recovery and cleaning;
(ii) to identify the regimes which are found and the factors that control the overall cleaning time; and
(iii) thus to identify whether it is possible to optimise these two stages.

To do this a simple experiment has been used in which the weight of toothpaste in a pipe is measured as a function of time when the system is cleaned with water.

2. Materials and methods

2.1. Experimental fluid

Toothpaste is a high phase volume suspension of many ingredients. The toothpaste used was supplied by GSK (Brentford, UK) and behaves as a Herschel–Bulkley type of fluid with an apparent yield stress of 92 Pa (based on a model fit) and is shear thinning (Cole et al., 2010) according to:

$$\sigma = 92 + 0.55(\dot{\gamma})^{0.78} \quad (1)$$

where σ and γ are shear stress and shear rate, respectively. The temperature dependence of the apparent viscosity is shown in Fig. 1, again from Cole et al. (2010).

The core of the method is the use of a tube full of toothpaste that can be weighed during the experiment. The pipe section, with or without toothpaste was weighed on an electronic scale EK5055 (Camry); this system could weigh to an accuracy of 0.5 g.

2.2. Experimental protocol

Fig. 2 shows the experimental rig which comprised of a 1 m long stainless steel pipe with an internal diameter of 0.0254 m, a water tank, a heat exchanger and a centrifugal pump (Alfa Laval, Denmark) used to supply water of desired temperature and velocity to the system. The pipe section, with or without toothpaste was weighed on an electronic scale EK5055 (Camry); empty it weighed 1088 g.

The experimental procedure was as follows:

- the pipe was first filled manually with toothpaste and placed into the rig; the toothpaste weighed 486 ± 5 g;
- water was pumped from the water tank through the bypass loop to ensure the temperature stability;
- water flow was then diverted to the test section; the valve was closed manually immediately after seeing water at the outlet of the test section, i.e. at the end of the core removal phase;
- the test section was then removed from the rig and water drained carefully;
- after weighing, the test section was placed in the rig. By adjusting the water temperature and flowrate cleaning could be performed using water *potentially at a different temperature and flow velocity*. After reconnection it took less than 5 s for the flow to become stable.
- The same dismantling and weighing procedure was applied at intervals throughout film and patch removal until a