Wear 289 (2012) 138–144

Contents lists available at SciVerse ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Abrasion in high-pressure homogenization orifices: A new method to quantify the erosivity of particle loaded liquids

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ARTICLE INFO

Article history:
Received 20 September 2011
Received in revised form
25 March 2012
Accepted 13 April 2012
Available online 6 May 2012

Keywords:
Solid particle erosion
Cavitation erosion
Abrasion
Orifice
High-pressure homogenization

ABSTRACT

Solid particles present in high-pressure homogenization processes damage the equipment, especially the orifices. So far the orifices have to be exchanged frequently causing increase of cost and decrease of efficiency. Modifications in orifice geometry or material as well as in the composition of the fluid may help to reduce abrasion. Therefore, a method to quantify wear in a homogenization orifice in a fast and cheap way is required. This method also has to be applicable if the particles are nano-sized. In this work an abrasion quotient Q_A is presented as a quantitative measure for erosion. It is calculated by the volume flow rate of water through the orifice before and after the passage of an abrasive fluid consisting of nanoparticles suspended in a fluid. The reproducibility and sensitivity of this method is investigated. The effect of the properties of particles suspended freely or encapsulated in water on the abrasion quotient has been measured. The new method shows that results are consistent with literature. These results give an interesting starting point to improve the durability of high-pressure homogenization equipment.

1. Introduction

1.1. Motivation

High-pressure homogenization is a common method used to break up emulsion droplets, e.g. in food, cosmetic or pharmaceutical industry. In the dairy industry, high pressure homogenization is an essential processing step. It is crucial for improving product properties by decreasing fat globule sizes below 1 μm in order to prevent creaming and improve the color as well as the feel of the product in the mouth [1, p. 106]. High pressure homogenizers in dairy process lines run at capacities of up to several tens of thousands of litres/h.

One challenge in high-pressure homogenization is the durability of the equipment. In general, there are two mechanisms that cause wear in high-pressure processes. The first is cavitation, the formation of cavities and their subsequent implosion, and the second is abrasion caused by particles present in the homogenized fluid. Whereas cavitation is a well investigated phenomenon in high-pressure homogenization, little is known about the effects of particles, especially nanoparticles, on the equipment. Specifically the orifices are reported to be extremely affected by nanoparticles [2]. Therefore lifetime is shortened and manufacturing costs of the product increase. Nevertheless, the knowledge about abrasion quantity and mechanism in high-pressure homogenization is limited. This is astonishing, especially as there are many applications of high-pressure homogenization involving particles. In food industry, cocoa particles for e.g. chocolate flavored milk or dairy products are pumped through the disruption unit and are known to lead to massive reduction of lifetimes [3, p. 37]. Also in the homogenization of fruit juices, the fibers of the fruits are known to lead to the same effect. Furthermore, high-pressure homogenization is proposed for the production of new products based on nano-sized particle structures, e.g. the break-up of nanoparticle agglomerates [2,4,5], or the preparation of nanoparticle loaded miniemulsions for polymerization processes [6,7]. A nanoparticle is defined as an object with all dimensions below 100 nm [8].

Modifications in orifice geometry or material as well as in the composition of the fluid may help to reduce abrasion and hence production costs. For a target approach in modifying material or geometries, a method to quantify wear in a homogenization orifice in a fast and cheap way is required.

In this article a literature overview on the possibilities to measure wear is given. We then present a new method for quantifying the abrasive effect on high-pressure homogenization orifices. With this method we investigate the effect of several product and process related parameters. First results concerning the influence of particle characteristics on the abrasion are shown

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http://dx.doi.org/10.1016/j.wear.2012.04.003

and compared with published data on abrasion in high pressure homogenization.

1.2. Wear caused by cavitation

Caused by high velocities and subsequent low static pressure, cavities can form if the vapor pressure of the liquid homogenized is higher than the static pressure. Dissolved gases may also evaporate and form small bubbles. These cavities implode when the static pressure increases above the vapor pressure. Resulting pressure fluctuations and micro-jets may cause abrasion to material being close to the imploding cavities [9,10]. This not only damages process units but also the product itself as the eroded material contaminates the products which is especially critical in food production.

Cavitation, however, also has positive aspects. It may help in comminution, dispersion, the break-up of agglomerates, or emulsification: it has been suggested to enhance the fragmentation of droplets or particle agglomerates [11,12,13, p. 95f,14, p. 48ff]. Thus, it is a challenge to make use of this positive effect without enhancing the erosion and its effect on the process unit and the product.

1.3. Wear caused by particles

The basic mechanisms of wear caused by particles have not been understood completely to date. Several parameters affect the erosion rate (e.g., impact angle and speed, shape and size, concentration, physical properties) [15]. As the parameters influence each other a clear allocation is not always possible [16]. In the following paragraph tendencies will be given.

Only particles, which interact with the surface of the equipment, cause abrasion. The dimensionless Stokes-number *Sto* describes the ability of a particle to follow the flow of the fluid it is dispersed in. Crowe et al. [17] define *Sto* for a plug flow as

$$Sto = \frac{\rho_p x^2 u}{18 \eta d}, \tag{1}$$

with ρ_p being the particle density, x the particle diameter, u the fluid viscosity, η the dynamic viscosity of the fluid and d the pipe diameter. If *Sto* is smaller than 1 the particles follow the flow and should cause no abrasion [18]. Despite the flow conditions in high pressure homogenizers being turbulent, we calculated the Stokes-number as first approximation.

1.3.1. Solid concentration

In general higher solid concentrations lead to higher abrasion as more particles strike the surface of the target material [19–22]. Sometimes even a disproportionate increase could be found [23] meaning that the same amount of particles causes more abrasion if the particles pass the target material in a higher concentration.

1.3.2. Particle size

Several authors report an increase in wear with an increase in particle size [10,19,21,24,25]. Clark [16] showed that large particles cause more erosion than smaller ones for the dissipation of a given amount of kinetic energy of impact. Gandhi and Borse [19] specified that smaller particles show less abrasion. Even an addition of a small amount of smaller particles (15% of the size) leads to a decrease in total abrasion. They propose that the fine particles form a thin layer over the target surface through which the bigger particles have to penetrate before striking the surface. Another possibility given by the authors is an increase in viscosity induced by the small particles and a decrease in turbulent flow fields.

1.3.3. Mechanical properties of particles and target material

Concerning the material impacted by particles, a distinction is made in the literature between hard-brittle and soft-ductile mechanisms of wear. Hard-brittle materials show mostly sliding wear and low angle impact fatigue cracking; soft-ductile materials are characterized by a combination of sliding wear, low impact angle wear through microscale deforming, cutting, plowing and work hardening [15,25]. Both types of material show an increasing erosion rate for increasing ratio of particle to target hardness [10,21,26–30]. In general hard-brittle materials show better resistance against particle erosion [31].

1.3.4. Impact angle

The impact angle is defined as the angle between the direction of the particle and the surface. Concerning the impact angle hard-brittle and soft ductile materials show different behaviors: whereas for ductile materials the highest erosion rates are measured for an angle of approx. 30°, brittle materials show the lowest resistance against erosion at an impact angle of about 90° [31]. But erosion can also occur at very low impact angles as reported in [32] and [33]. When the particle contacts the surface with only little kinetic energy, no rebound occurs, but the particle is trapped in a liquid film near the surface and starts sliding. Especially when the particles are irregular in shape a tumbling movement of the particle starts which leads to abrasion wear.

1.3.5. Velocity of solid particles

The velocity of the carrier fluid and the velocity of the particle significantly affect erosion with higher velocities causing a higher erosion rate [20,21,23,24]. John Rajesh et al. [34] used silica particles in air to test the influence of particle velocity and impact angle on polyamides. Although the amount of erosion is higher at an impact angle of 90° they found a more significant influence of velocity on erosion rate at small impact angles. Depending on the target material an increase of erosion rate of up to 240% at a velocity increase from 80 to 140 m/s could be found at an oblique angle of impact.

1.3.6. Properties of suspending liquid

The viscosity of the suspending liquid is also reported to have an influence on abrasion. Shah et al. [20] showed in simulations that increasing fluid viscosity reduces the erosion rate as viscous fluids impede the particle velocity resulting in a decrease in erosion rate. This result fits with the experimental results of Clark [16].

1.4. Interaction of particles and cavitation

Zhao et al. [35] concentrated on the combined action of abrasion and cavitation on different steels in a rotating disk equipment. They found that wear caused by simultaneous cavitation and particles is higher than the simple arithmetic sum of the wear caused by cavitation alone and particle abrasion alone. Madadnia and Owen [36] discovered a similar effect in a fluidic valve controlling sand-laden water. They arranged two identical fluidic valves in series with each valve handling the same flow, but cavitation only happening in the second valve. The presence of cavitation and particles increased the wear rate disproportionately in comparison to the individual effects of cavitation and particles. The explanations given in [35] and [36] are as follows:

- The sand particles in the water act as cavitation nuclei and the critical cavitation pressure of the fluid is thus higher than that of pure water and therefore more cavitation occurs.