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Pressure drop in dairy evaporators: Experimental study and friction factor modelling

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ABSTRACT

The pressure drop that occurs during the falling film evaporation of dairy products is related to the downward co-flowing vapour and directly affects the saturation temperature of the product, resulting in a non-constant thermal driving force of the process along the evaporator. Frictional forces are the major contributor to the pressure drop, and the friction factor is a crucial parameter in reliably estimating the pressure drop. In the present study, the absolute vapour flow pressure losses during falling film evaporation of dairy products were measured using an experimental internal tube evaporator set-up. To simulate real industrial conditions, experiments were conducted by varying the co-flow inlet velocity (from *0* to *37* ms^{-1}) over a wide range of product dry solid content *DC* (from *DC* = *0%–50%*). Results obtained at *DC* = *0%* show that the experimental approach is consistent when measurements are compared to the well-known Wallis correlation. A large number of experimental data has been obtained for *DC* between *13* and *40%* for which the pressure losses have a strong dependence from the co-flowing vapour rate; in some specific cases, the influence of the surface bubbling phenomena has been put in evidence. The presented results, have been used to calibrate a new accurate correlation for the friction factor ($4f_{lv}$) coefficient showing a squared residual of $R^2 = 0.93$.

1. Introduction

In the dairy industry, the dehydration process includes falling film evaporation, followed by spray drying. The goal of these processes is to increase the solid content of feed (Valentas et al., 1997; Bylund and Tetra Pak, 2003). The energy efficiency of a dehydration unit is strictly related to the amount of solvent extracted during the falling film step (Bouman et al., 1993). Given the large difference in energy efficiency between spray dryers and evaporators, maximizing water removal by falling film evaporation while minimizing water removal by spray drying is optimal. The evaporation plants are usually multistage. Energy efficiency is further improved by thermal vapour recompression (TVR) and mechanical vapour recompression (MVR). In MVR, the vapour produced is compressed using an electrical compressor. The saturation temperature is increased to allow the vapour to be reused as a heating medium in the evaporator. The compressor consequently must increase the pressure to compensate for any pressure drop in the evaporator while creating the desired temperature difference of *3–7* °C. This pressure drop is related to the downward co-flowing vapour and directly affects the saturation temperature of the product, resulting in a non-constant thermal driving force of the process along the evaporator (Bouman et al., 1993; Mura et al., 2016). Consequently, accurately predicting pressure losses is critical when designing an evaporation plant. Previous studies have focused on the evaluation of the pressure drop (Bouman et al., 1993; Fu and Klausner, 1997; Hewitt and Hall-Taylor, 1970; Müller-Steinhagen and Heck, 1986; Henstock and Hanratty, 1976; Belt et al., 2009), and an accurate correlation for dairy products is not available. Experimental studies of the actual pressure drop are rare or are limited to a specific range of conditions. Bouman (Bouman et al., 1993) proposed and developed two correlations for the heat transfer and friction factor based on experimental results, but the pressure losses were evaluated indirectly by considering the temperature differences between the inlet and outlet of the product.

The pressure drop (ΔP) in an evaporative falling film tube comprises three terms: the friction contribution, the effect of acceleration, and gravitational head (Bouman et al., 1993). Analytical and numerical models are available to predict simultaneously

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pressure drop and heat transfer for two-phase annular flow (Hewitt and Hall-Taylor, 1970). The limitation of these approaches consists in the fact that empirical correlations are often required to define parameters such as the friction factor relative to the interaction between the free surface of the falling film and the co-flowing vapour (Fu and Klausner, 1997; Hewitt and Hall-Taylor, 1970; Müller-Steinhagen and Heck, 1986). Although several options for this correlations have been presented (Müller-Steinhagen and Heck, 1986; Henstock and Hanratty, 1976; Belt et al., 2009; Berna et al., 2014), they are mostly adapted to water/air or refrigerant flowing in geometric conditions quite different from those used in typical dairy processes. Moreover, few are applicable under evaporation conditions. Evaporation leads to a continuous increase in the co-flowing velocity because of the continuous production of vapour. Different approaches have been used to account for the evaporation process (Fu and Klausner, 1997; Chisholm, 1973), but these approaches have considered evaporation only in the convective regime and neglected the effects of bubbles, which are often present (Gourdon et al., 2015).

An important feature of dairy products is the variation of viscosity as a function of the dry solid content (*DC*). In general, the viscosity at low *DC* is similar to that of water at the same temperature. However, the viscosity increases by orders of magnitude as *DC* increases. The viscosity changes from Newtonian to non-Newtonian above approximately $DC = 35\%$ and transforms into a shear thinning fluid. Above approximately $DC = 40\%$, a yield stress factor appears and increases with *DC* (Mura et al., 2016; Ang, 2011).

Here, an experimental study of the process of falling film evaporation of dairy product is presented. The pressure drop generated by the co-flowing vapour is evaluated using an industrial scale experimental set-up. A correlation for the friction factor is presented for a large range of conditions relevant to industrial requirements. Substantial attention has been focused on the conditions of $DC \leq 40\%$, for which the pressure drop can be substantial under industrial conditions. In cases of higher solid content, the increase in vapour velocity inside the evaporator is less important, and the influence on the saturation temperature of the fluid film is negligible. The focus of this work was to provide a correlation modelled using parameters relevant to the design stage of evaporators that is applicable to industry and highly accurate.

2. Experimental method

2.1. Experimental setup

The apparatus (see Fig. 1) was an experimental industrial-scale vertical falling film evaporator provided with a stainless steel tube with the following dimensions: external diameter $D_{tube} = 51$ mm, wall thickness $\delta_{wall} = 1.2$ mm, total length $L_{tube} = 4125$ m, and outside heat transfer area $A_{out} = 0.66$ m^2. An extensive description of the overall experimental plant is presented in references (Mura et al., 2016; Gourdon et al., 2015).

The dairy product was fed at the top and evenly spread over the inlet using a suitable distributor to ensure a homogeneous film falling on the inner side of the tube. The inlet temperature (T_i) and the mass flow rate ($\dot{m}_i$) of the product were measured by a thermocouple and a flowmeter, respectively. Once the falling product reached saturation conditions, it began to evaporate. The heat for the evaporative process was provided by the condensation of saturated steam on the external surface of the tube. The condensate rate ($\dot{m}_{cond}$), which is a measure of the total heat load (Q_{tot}), was measured (Table 1).

The temperature difference (ΔT) between the steam (T_{steam}) and the falling film (T_{sat}) represents the thermal driving force of the evaporative process.

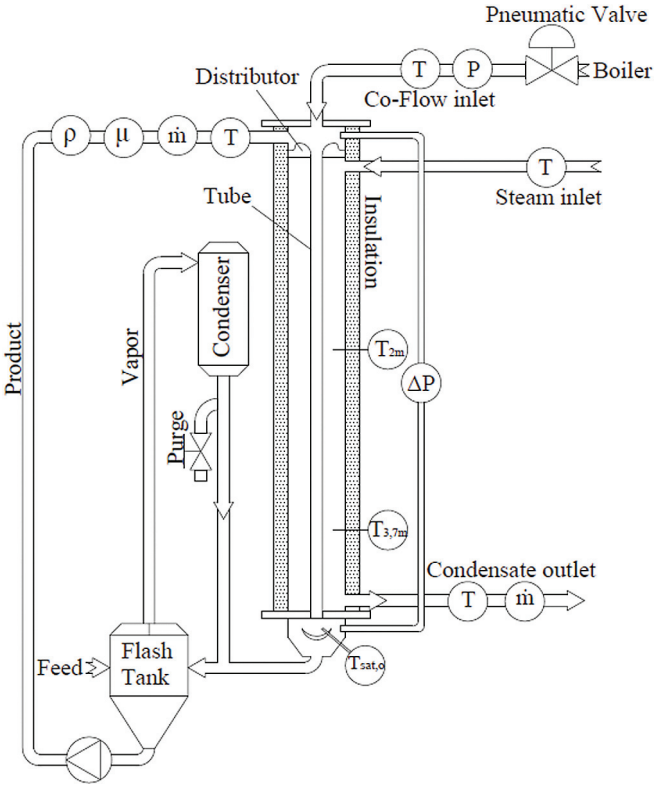

Fig. 1. Experimental setup. Experimental setup with the inline measurement devices for: the local temperature T, pressure P, mass rate ṁ, dynamic viscosity μ (at $3450\ s^{-1}$), density ρ.

The steam temperature (T_{steam}) in the evaporator was measured at several points along the steam side of the tube: 1) the inlet at the top of the evaporator; 2) *2* m below the top (T_{2m}); 3) *3.7* m below the top ($T_{3,7m}$); and 4) at the condensate outlet. The average of the values measured at the inlet and outlet was used in this work.

At the tube outlet, a portion of the product was constantly collected in a cup, and the saturation temperature of the outgoing product ($T_{sat,o}$) was measured by a PT-100. From the bottom of the evaporator, the product was directed towards the flash tank, where the vapour was separated. The vapour was condensed and reinjected into the product cycle to maintain constant *DC* during the experiment. The product was continuously recirculated from the top of the evaporator (see Fig. 1).

Under real industrial conditions, the vapour velocity increases constantly from the tube inlet to the outlet. To simulate these conditions, a specific amount of saturated vapour was injected at the top of the evaporator into two symmetrical inlets. A steam distributor equipped with a set of *8* fins ensured a homogenous distribution of the steam flow at the distributor level. This vapour was provided by an external steam boiler and flowed simultaneously with the falling film. The co-flow inlet velocity (v_i) at the distributor level was accurately modulated by varying the aperture of a pneumatic valve in the steam circuit.

The absolute pressure drop (ΔP) at the product side was continuously measured using a differential pressure measurement device. Other measurement devices, such as a density meter and the viscosity meter at a fixed shear rate ($3450\ s^{-1}$), were present at the product side of the experimental apparatus. Table 1 lists the measurement devices used (for a more detailed, list see Mura et al., 2016).