

EXPERIMENTAL STUDY OF THE HEAT TRANSFER IN A FALLING FILM EVAPORATOR: INFLUENCE OF THE CO-FLOWING VAPOR

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ABSTRACT

A large number of industrial processes are based on the concentration of liquid products by means of falling-film evaporation. In the dehydration of dairy products, concentrating a fluid by evaporating represents one of the most important steps of the whole drying process. Among the advantages of this technology is that it is possible to operate within small temperature differences which results in low heat consumption. In this sense, it is necessary to increase the amount of removed water during the falling-film evaporation to reduce the energy cost of the overall process. However, reducing the fraction of the solvent leads to an increase in viscosity of the product which can show non-Newtonian features. This aspect significantly affects the heat transfer, that is to say, the higher the solid content, the lower the heat transfer coefficient. One of the possible solutions to this drawback consists in drawing maximum benefit from the interaction between the fluid film and the co-flow of the gaseous phase resulting from the evaporation process. Unfortunately, accurate studies of the effect of co-flow on evaporative falling films are very rare and difficult to perform because of the high costs of the implementation of a suitable experimental apparatus.

In this work, the experimental study of the influence of the co-flow on the heat transfer coefficient is presented as a function of both the solid content and the mass flow rate of the feed. The experimental set-up, consisting in a unique industrial pilot scale evaporator, provides the possibility to obtain results useful for realistic industrial conditions. Tests were conducted with varying dry solid content from 10 to 50%.

The results show that the co-flow has the effect to decrease the potential for fouling/poor wetting. Above this, the influence on the heat transfer is not as large as expected because of the dominant influence of the viscosity.

INTRODUCTION

The evaporation of falling film is a technology applied in various industrial fields, from the food to the pulping industry [1-4], with the aim to maximize the solid content of the feed product in detriment of the solvent (water in general). The advantages of this process, which have been presented several times in literature [5, 6], consist mainly in: short residence time of the product (3-20 s), since the falling-film is driven by the gravity that lead to high velocities of the fluid [2]; low process temperature results in gentle heat treatment preventing chemical or physical transformation of the product and relatively high overall heat transfer coefficient. Moreover, the overall efficiency can also be improved by reusing the removed vapour in cascade-coupled multi effect evaporation plants. The falling film evaporation represents one of the most important steps in the overall drying process of dairy products where the product is concentrated up to approximately 50% of dry solid content (*DC*), with the dry solid content defined as:

$$DC [\%] = \frac{\text{Dray powder}}{\text{Solvent+powder}} 100 \left[\frac{kg}{kg} \right] \quad (1)$$

In contrast, processes of dehydration that normally follow this stage are highly energy intensive. For these reasons, the amount of water removed during this phase of the process should be as large as possible: under specific conditions, it is theoretically possible to save about 10% of the energy consumption of an evaporator-dryer plant by increasing the total solid content of the concentrate from 48 to 54% [7]. Unfortunately, the higher the *DC* of the product is the higher its viscosity. Experimental studies have shown that up to about 37% of *DC*, the fluid behaves in agreement with the Newtonian law but with increasing *DC*, the rheological features fit well with the Power law model and at 48% *DC* or higher with the

Herschel-Bulkley yield stress model [8]. At constant mass flow rate, this increase in viscosity can generate instability in the falling-film that can lead to the breakdown of the film and eventually the formation of dry patches. This phenomenon is associated with a reduction of the heat transfer coefficient (h). The presence of a co-flow, has been identified as one of the main factor affecting the heat transfer coefficient [9, 10].

Mathematical models present in the literature are still immature or insufficient to describe this phenomenon. Furthermore, the lack of adequate experimental systems makes the collection of reliable data difficult since they are so far often taken from industrial installations with the intrinsic negative effects on the accuracy and on the required times resources.

In the present work, quantitative results concerning the influence of the co-flow on the heat transfer coefficient are presented in function of the dry solid content of the product that varies from 10 to 50% and in function of its mass flow rate. The experimental campaign has been performed using an industrial pilot scale falling film evaporator and results are supported by images of the falling fluid film obtained by a high speed image acquisition device.

NOMENCLATURE

A	$[m^2]$	Surface
DC	$[\%]$	Dry solid content
D	$[m]$	Characteristic diameter
f_i	$[-]$	Friction coefficient
g	$[ms^{-2}]$	Gravity acceleration
h	$[Wm^{-2}K^{-1}]$	Local heat transfer coefficient
L	$[m]$	Length
k	$[Wm^{-1}K^{-1}]$	Conductivity
K	$[Pas^n]$	Consistency factor
n	$[-]$	Power law index
P	$[Pa]$	Pressure
T	$[K]$	Temperature
Q	$[W]$	Heat flux
u	$[ms^{-1}]$	Velocity
U	$[Wm^{-2}K^{-1}]$	Overall heat transfer coefficient
A, b, c, d, f, g	$[-]$	Parameters
Nu	$[-]$	Nusselt number
Re	$[-]$	Reynolds number
Special characters		
ϕ	$[m]$	Diameter
δ	$[m]$	Thickness
ρ	$[kgm^{-3}]$	Density
ν	$[m^2s^{-1}]$	Kinematic viscosity
$\dot{\gamma}$	$[s^{-1}]$	Shear rate
τ	$[Pa]$	Shear stress
Γ	$[kgm^{-1}s^{-1}]$	Mass flow rate per unit width
μ	$[Pas]$	Dynamic viscosity
Subscripts		
Avg		Averaged
app		Apparent
CF		Co-flow
FF		Falling film
i		Inside
o		Outside
sat		Saturation
$Steam$		Steam inside of the tube
t		Tube
tot		Total
w		Wall
y		Yield stress
$\mu_{3450s-1}$		Measured viscosity at $\dot{\gamma} = 3450s^{-1}$

EXPERIMENTAL SET UP

The experimental set-up consists of a stainless steel tube of length $L = 4.5\text{ m}$, diameter $\phi = 60\text{ mm}$ and a thickness $\delta_t = 5\text{ mm}$, equipped with a series of thermocouples located on both the inner (T_i) and the outer surface (T_o). Differently from the most common falling film evaporators, our configuration allows the viewing of the falling film since the product flows in the outer surface of the tube (heat transfer surface $A = 0.85\text{ m}^2$). After being evenly spread by means of an overflow distributor located on the upper part of the tube, the film achieves rapidly the saturation conditions and starts to evaporate. The vapor produced is then condensed and reintroduced into the circuit to maintain the dry solid content (DC) constant. The end of the tube is provided with a special cup where the temperature of the processed product (T_{sat}) is measured with a thermocouple before it is finally collected. The mass flow rate, the density and the viscosity are measured in real time before the introduction of the product into the evaporator.

A source of saturated steam is positioned on the inside of the tube and distributed homogeneously over its entire length. That steam, condensing upon the wall, supplies the required heat for the evaporation process (see **Figure 1**).

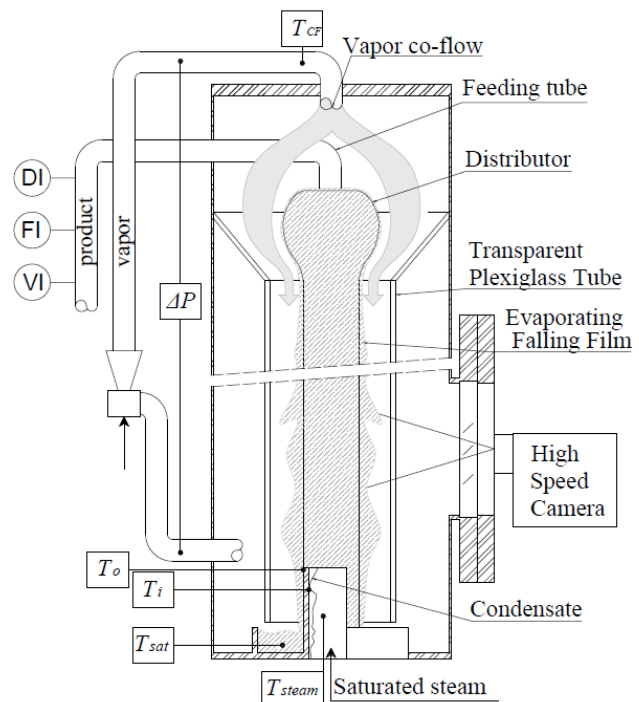


Figure 1. Schematic diagram of the evaporator: DI = density meter, FI =flow meter, VI =viscometer.

The volume of condensate produced per unit of time is used to characterize the heat flux (Q). A more detailed description of the experimental system, including the calibrations procedure of measurement systems, is available in [4, 11].

To study the influence of the co-flow on the falling film, an amount of steam is injected from the top of the evaporator (see

Figure 1). The largest part of the total vapor co-flowing (~70%) consists of vapor that has been released during the process and recycled by means a steam ejector. The remaining fraction is supplied from an external source. The steam is forced to flow in contact with the falling film by means of a transparent Plexiglas shell that has been fixed around the tube. The distance between the internal Plexiglas surface and the external tube surface is of 25mm.

METHOD

Samples

The feed material for the experiments is composed of a dairy powder and distilled water in several different mass fractions as shown in **table 1**. The product tested in this study is related to whole milk and its properties are similar to reconstituted whole milk. The dry solid content is obtained by drying a sample in an oven ($T = 105 \text{ }^\circ\text{C}$ for $t \geq 24h$), and comparing that to its original total wet mass. The measurement is done twice for each sample and an averaged value is reported. As already anticipated in the introduction, the viscosity of the feed depends on the dry solid content and both the hydrodynamics and the heat transfer mechanisms are obviously affected by this feature.

The dynamic viscosity has been measured by an online viscometer at constant shear rate (3450 s^{-1}). Values, reported in **Table 1**, demonstrate the increase of the viscosity as a function of the solid content.

Table 1: Dry solid content (DC), Density (ρ) and online measured viscosity ($\mu_{3450s^{-1}}$).

DC [%]	51,5	51	49	42	27,7	25,5	24	16	15	14	11
ρ [kg/m^3]	1120	1120	1115	1100	1057	1057	1055	1030	1025	1022	1016
$\mu_{3450s^{-1}}$ [$\text{mPa}\cdot\text{s}$]	221	172	82,9	46,5	6,7	4,6	4,3	1,2	0,9	1,6	1,4

This result has been further confirmed by an experimental rheological study performed by a rheometer *Rheoplus 32* equipped with a coaxial cylinder sensor kept at the same temperature of the evaporative process (55°C). These tests, carried out in function of the DC , provided the shear stress [Pa] evolution as a function of the shear rate varying from 0 to 1000 [s^{-1}]. The rheometer results reveal that our product can be identified, depending on its solid content, by three parameters typical of the Herschel-Bulkley model. This model is characteristic of yield-shear-thinning fluids according to the equation:

$$\tau = \tau_y + K\dot{\gamma}^n \quad (n < 1) \quad (2)$$

where τ_y [Pa] represents the yield stress which appears for $DC \geq 40\%$ (below this value, τ_y vanishes and the model takes the power law form). The parameter K [$\text{Pa}\cdot\text{s}^n$] is the consistency factor and it assumes the dimensions of a viscosity depending on the index n , which is <0 for shear-thinning fluids. In our case, the variation of these parameters fits very well with an exponential law of DC with the expressions:

$$\tau_y = ae^{b\cdot DC} \quad (3)$$

$$K = ce^{d\cdot DC} \quad (4)$$

where: $a=4\cdot 10^{-7}$, $b=30$, $c=6\cdot 10^{-5}$, $d=17,5$.

n (in our case $n \leq 1$) represents the non-linear feature of the correspondence between an applied shear stress and the response in terms of shear rate. This index, varying from value close to unity typical of Newtonian fluids, is reduced by increasing DC . A simple approximation, valid in the range of our interest ($16 \leq DC \leq 60\%$), has been obtained on the basis of the rheometer's data:

$$n = 1 - fDC^g \quad (5)$$

where: $f=3$ and $g=3,5$. The experimental results and the trend of these three parameters as a function of the solid content are shown in the graph of Figure 2.

Other types of similar approximations are present in the literature [8].

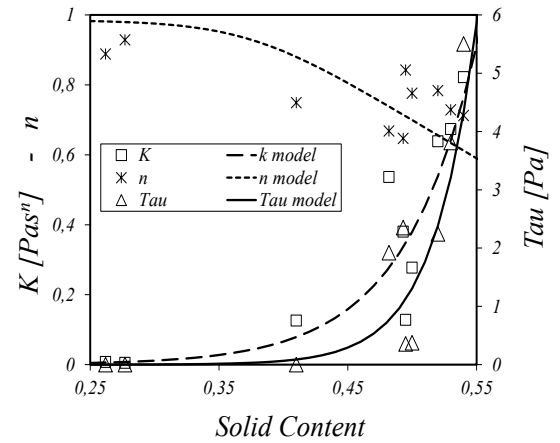


Figure 2: Experimental and fitted values of Yield stress, Consistency factor and n -index as a function of the solid content of the dairy product.

Other characteristic parameters of the product, such as thermal conductivity (k) and heat capacity (C_p), have been obtained, as a function of the temperature (T) and the solids content (DC), by means of correlations present in the literature [12].

Experimental Protocol

The goal of this research is to highlight the influence of the co-flow on the mechanism of heat transfer during the evaporation process of the fluid falling film. In order to achieve this, the system is preheated (at temperature close to 55°C) under vacuum conditions ($P_{abs} \sim 0.016 \text{ MPa}$) by means of steam. The product (c.a. 50kg), mixed in the suited proportions of solvent (water) and dry solid content, is pumped into the plant, forced to flow along the tube and heated by means of condensing steam on the inside of the tube. At this point a

difference of temperatures (ΔT) between the two fluids is applied and the evaporative process starts. When the operating conditions (flow rate and temperatures of the falling fluid and temperature of steam) are stable, data related to the heat transfer are recorded. The concentration of the product is kept constant thanks to the continuous recirculation of the condensate produced during the evaporation and a sample of product is extracted during the phase of the measurement for the analysis of the rheological characteristics and of the solid content. After the measurement has been obtained, a mass flow rate of $0,039\text{kg s}^{-1}$ of co-flowing steam with a density of $\rho_{steam}=0,11\text{kg m}^{-3}$ is circulated with an averaged velocity (u_{CF}) of 55m/s as shown in **Figure 1**. When the new stable conditions are achieved, values of heat transfer are recorded.

The same tests were carried out in non-evaporative conditions ($\Delta T=0$) with the objective to observe the effect of co-flowing steam on the appearance of falling-film hydrodynamic, by using a high speed image acquisition device (500fps^{-1}). The images capturing has been an important part of this work although their contribution is highly qualitative. The images have been acquired during the experimental tests when stable conditions were obtained and both with and without co-flowing vapor. The pictures have been taken at three different levels ($0,4 - 2 - 4\text{ m}$ from the distributor).

ANALYSIS

Heat transfer evaluation

To evaluate the influence of the co-flow on the heat transfer mechanism we choose to refer to the overall heat transfer coefficient (U) defined as

$$\frac{1}{UA_o} = \frac{1}{A_i h_i} + \frac{\delta_w}{A_{avg} k_w} + \frac{1}{A_o h_o} \quad (6)$$

where A_i represents the inside area of the tube and h_i is the inside heat transfer coefficient obtained by using the Schnabel & Palen relation for vertical falling film [13]. δ_w is the wall thickness, k_w is the conductivity of the tube wall and A_{avg} is the associated logarithmic averaged area. The only unknown parameter is the outside heat transfer coefficient h_o .

These values are calculated by using the total heat flux Q_{tot} , obtained by measuring the steam condensate flow, in agreement with the relation:

$$U = \frac{Q_{tot}}{A_o(T_{steam}-T_{sat})} \quad (7)$$

T_{steam} and T_{sat} represent respectively the steam temperature and the saturation temperature of the falling film.

Others tools such as the Nu and Re numbers are used to evaluate the convective exchange in the area of the product and the flow condition:

$$Nu = \frac{h_o l}{k} \quad (8)$$

$$Re = \frac{4\Gamma}{\mu} \quad (9)$$

l is the viscous characteristic length, defined by $l = \left(\frac{\nu^2}{k}\right)^{1/3}$.

When the co-flow is active, due to the sum of static head, kinetic energy of the steam and frictional losses, a pressure drop occurring all along the tube [6]. This pressure drop ΔP (measured as shown in **Figure 1**) results in a variation of the saturation temperatures (T_{sat}) of the product leading to a higher thermal driving force (ΔT) at the bottom of the evaporator compared to the upper side. Since in our system (as in every industrial plants) the value of the T_{sat} is collected in the lower part of the evaporator, it is necessary to make a correction to obtain a representative value of the thermal driving force for the entire evaporation process. Assuming that the pressure drop is linear, a saturation temperature profile was calculated and an average value of T_{sat} was determined.

To be able to compare the heat transfer measurements, it is necessary to define a viscosity that takes into account the non-Newtonian features of the film. We will call this the apparent viscosity (μ_{app}). To obtain this value the thickness of the fluid film must be evaluated (see **Figure 3**).

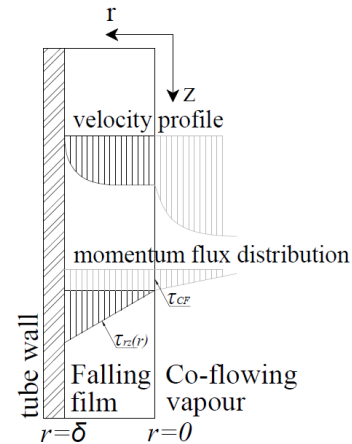


Figure 3. Qualitatively velocity profile of the falling film (black lines) and co-flowing vapor (gray lines).

Under the hypothesis of a laminar flow on a flat surface with small film thickness compared to the tube length, for a bi-dimensional case, we can integrate the momentum flux (τ_{rz}) considering the effect of the co-flowing vapor shear stress upon the interface as boundary condition:

$$\begin{cases} \frac{\partial \tau_{rz}}{\partial r} = \rho g \\ \tau_{rz} = \tau_{CF} \quad (r = 0) \end{cases} \quad (10)$$

where τ_{CF} represent the momentum flux of the co-flowing vapor acting on the free falling film surface defined by [14]:

$$\tau_{CF} = \frac{1}{2} f_i \rho_{CF} u_{CF}^2 \quad (11)$$

where f_i is the friction coefficient calculated by considering the ΔP

$$f_i = \frac{\Delta P D_{CF}}{2 \rho_{CF} L u_{CF}^2} \quad (12)$$

and u_{CF-FF} is the velocity of the co-flowing vapor relatively to the falling film velocity.

Substituting equation (2) on the momentum flux equation resulting from (10) it is possible to integrate the velocity profile over the film thickness from θ to δ and to obtain the specific mass flow rate (Γ) according to the equation:

$$\Gamma = \rho \frac{n}{n+1} \frac{K}{\rho g} \left[\left(\frac{\rho g \delta - \tau_y + \tau_{CF}}{K} \right)^{\frac{n+1}{n}} \delta - \frac{n}{2n+1} \frac{K}{\rho g} \left(\frac{\rho g \delta - \tau_y + \tau_{CF}}{K} \right)^{\frac{2n+1}{n}} \right] \quad (13)$$

In (13) the only unknown parameter is the film thickness (δ). The effect of τ_{CF} is negligible when co-flowing vapor is not applied ($u_{CF-FF} \approx 0$). With δ obtained from (13), in agreement with the classical Nusselt's theory, we can calculate an apparent viscosity (μ_{app}) of a Newtonian fluid without interfacial shear stress having equal film thickness:

$$\mu_{app} = \frac{\delta^3 \rho^2 g}{3\Gamma} \quad (14)$$

RESULTS

Images

It has been observed that, the "Wind Over Water" effect, shown by Jebson & Chen [10], generated by the momentum sheared between falling film and co-flow that should improve the convective heat transfer, it seems to be present only in the first section of the falling process close to the distributor. After this section, the flow does not appear to have any apparent effect. Moreover, the small difference observed seems to be typical of the case with low solid content: by increasing the DC , the surface effects seem to vanish gradually.

In **Figure 4**, two pictures with and without co-flow are presented with $DC=25.5\%$ and $\Gamma=0,16 \text{ kgm}^{-1} \text{ s}^{-1}$.

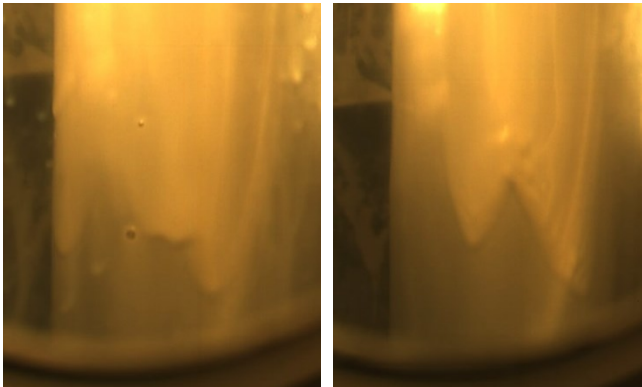


Figure 4. Image of a fluid with $DC=25,5\%$, flowing at mass flow rate of $\Gamma=0,16 \text{ kgm}^{-1} \text{ s}^{-1}$, without evaporation, respectively in reduced co-flow (right) and no-co-flow condition (left).

These images have been captured on the lowest optical access of the evaporator ($4m$ from the distributor) at the final section of the Plexiglas tube. As is observable, it seems that there is no difference in the appearance of the falling film. This result is also valid for product with higher solid content.

We are now able to show in the graph of **Figure 5** the variation of the heat transfer coefficient (h_o) as a function of the viscosity (μ_{app}). As can be observed, a drastic reduction of the heat transfer coefficient corresponds to an increase in viscosity. This trend is valid in both cases of co-flow and no-co-flow.

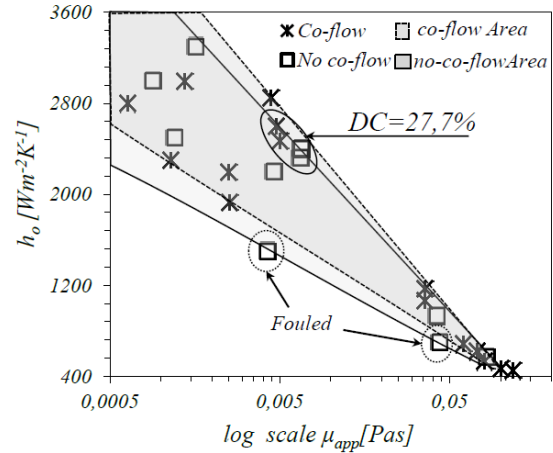


Figure 5. Experimental results of the heat transfer coefficient (h_o) Vs viscosity (μ_{app}) in co-flow and no-co-flow conditions.

The areas that contain the points obtained in the different conditions of co-flow and no-co-flow are almost overlapping: the trends of variation of h_o follow the same pattern. This means that there is not an obvious effect of the co-flow on the heat transfer coefficient above decreasing the apparent viscosity. As a matter of fact, points related to the case with co-flow are shifted toward lower values of the apparent viscosity if compared with the no-co-flow results. This aspect highlights that for a constant (DC), the action of τ_{CF} has the effect of reducing the contribution of the viscous forces acting on the fluid film promoting its fall. The points within the continuous circle in **Figure 5**, whose corresponding values are shown in **Table 2**, are eloquent of this aspect.

Table 2: Apparent viscosity (μ_{app}), film thickness (δ) obtained from (13), and heat transfer coefficient (h_o) at the same solid content (DC) for co-flowing and no-co-flowing conditions.

DC [%]	Condition	δ [mm]	μ_{app} [mPas]	h_o [$\text{Wm}^{-2} \text{k}^{-1}$]
27,7	Co-Flow	0,76	4,73	2600
	Co-Flow	0,98	5,02	2470
	No-Co-Flow	0,85	6,67	2400
	No-Co-Flow	1,11	6,63	2320

The effect of the co-flow was also investigated by analyzing the local difference in temperature (between the inner and the outer side of the tube) at different levels of the evaporator and observing the images acquired during the experimental tests. This analysis led to associate a more strict condition of poor wettability to the no-co-flow conditions. It means that higher specific mass flow rates (I) are required to assure the minimum wettability condition. The adverse consequence of this aspect mainly consists in the formation of dry spots on the external wall surface. In this condition, the heat transfer coefficient is affected by the drastic reduction. This aspect is observable in **Figure 6** where the variation of the local heat transfer coefficients, at different distance from the inlet distributor ($0,1 - 3 - 3,5$ and $4,1$ m), is reported versus time.

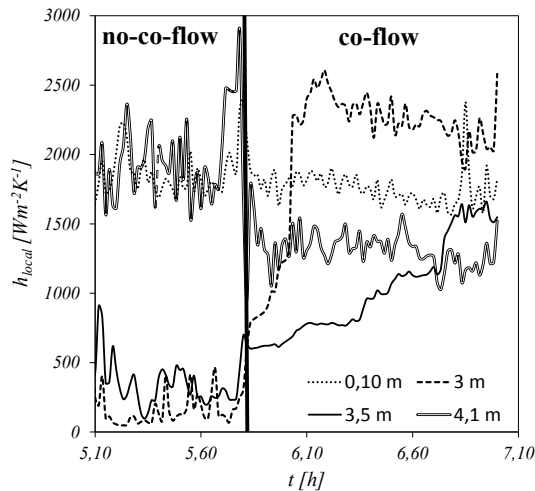


Figure 6. Variation of local heat transfer coefficients on the tube Vs time: effect of the co-flow on the wettability (the no-co-flow corresponds to the left point identified as *Fouled* in **Figure 5**).

As can be observed, the local heat transfer coefficient on the highest section of the evaporator ($0,1$ m) is not affected by the presence of the co-flow, since the flow is still evenly distributed around the tube. As a matter of fact, the most relevant results concern the variation of the local heat transfer coefficient on the lower sections of the tube ($3 - 3,5 - 4,1$ m), which are more sensible to the conditions of reduced wettability. For these cases, it is easy to notice that the co-flow condition is characterized by a drastic increasing of the heat transfer coefficient if compared with the no-co-flow conditions. This behavior underlines that the presence of dry spots on the outer surface of the evaporator is reduced when the co-flow is active.

This aspect can be highlighted by taking into account the dimensionless numbers of Nu and Re for the falling film as shown on the **Figure 7**.

The solution to this problem consists in increasing the specific mass flow rate that it is to say the minimum limit of wettability is shifted towards higher values. This could encourage some reflections whereas the positive effect of the

co-flow, previously attributed to the momentum traveling down the tube [9, 10], seem to show another nature.

Indeed, the images show not any obvious effects of the co-flow on the free surface of the film even if it is evident the positive effect on the reduction of fouling. In this sense, the evaluation of the apparent viscosity of the falling film highlights the role played by the co-flow on the increasing of the heat transfer coefficient.

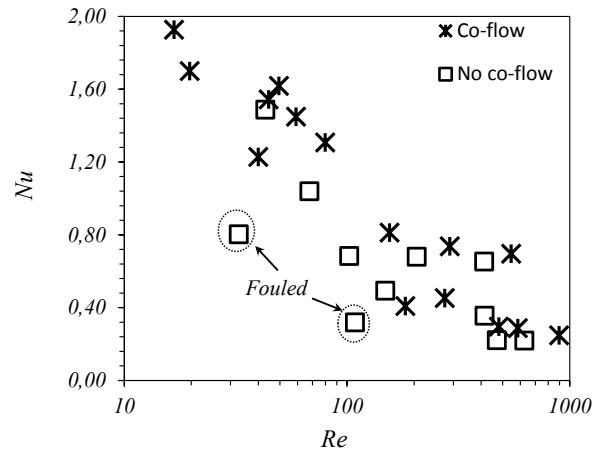


Figure 7. Nusselt Vs Reynolds numbers for co-flow and no-co-flow conditions.

This line of reasoning makes us think that the influence of the co-flow should be associated with variations in the surface tension forces (i.e. Marangoni) on a smaller scale of the film thickness. This assertion is reflected mathematically and experimentally in some studies [15, 16] in which have been highlighted that instabilities of the interface liquid-gas are amplified or damped by the combined action of the heat and the gas flow field.

CONCLUSIONS

In this paper, the experimental study of the influence of the co-flow on the overall heat transfer coefficient has been investigated. The work has been performed by means of an industrial falling film evaporator pilot plant. Several samples of a dairy product have been tested in function of the solid content (DC) varying from 11% to 51% . Results show that the increase in solid content leads to a dramatic increment of the viscosity of the feed.

Rheological measurements have shown that the fluid shows non-Newtonian characteristics in the cases of high solid content. This aspect heavily influences the heat transfer coefficient.

It has been shown that the co-flow has a positive impact on the heat transfer coefficient. This effect is reduced for increasing values of DC until it almost vanishes.

The positive effects of the co-flow is related to two facts: 1) it reduces the effects of fouling ensuring the wettability at low values of specific mass flow rate and 2) it reduces the apparent viscosity of the falling film under co-flowing condition (i.e.

lower apparent viscosity than in no-co-flow condition) which inherently increase heat transfer.

In perspective, it is desirable to further investigate the effects of the co-flow on the surface tension forces.

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