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Intensification of heat and mass transfer by ultrasound: Application to heat exchangers and membrane separation processes

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ABSTRACT

This paper aims to illustrate the interest of ultrasound technology as an efficient technique for both heat and mass transfer intensification. It is demonstrated that the use of ultrasound results in an increase of heat exchanger performances and in a possible fouling monitoring in heat exchangers. Mass transfer intensification was observed in the case of cross-flow ultrafiltration. It is shown that the enhancement of the membrane separation process strongly depends on the physico-chemical properties of the filtered suspensions.

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1. General introduction

Ultrasound is well-known to be helpfully used to enhance equipment efficiencies in several engineering applications. Intensification of chemical reactions, of drying processes, welding, and cleaning are among the most famous applications of ultrasonic waves. For what concerns heat transfer processes that are omnipresent in the industry, one might wonder what could be the influence of ultrasound on the performances of heat transfer systems. As surprising as it can be, this has not been a research topic deeply investigated until the end of the 90's and it has gained of interest since 2000 and especially for the last five years. Owing to effects induced by ultrasound, it might be expected that limitations of heat transfer processes and fouling could be overcome by ultrasonic vibration of heat exchangers. In the case of membrane separation processes such as ultrafiltration, a lot of academic works have been published in the past. However; the understanding of the mechanisms by which ultrasound acts on the limiting phenomena has not been fully elucidated. Effect of ultrasonic irradiation especially on concentration profiles at the membrane/solution interface when concentration polarization and/or fouling occur has not been fully explained.

Therefore, this paper presents new experimental results from studies performed in our laboratory on these topics. It is divided into two main parts. The first one focuses on heat transfer intensification with application to heat exchangers. The second part is devoted to the enhancement of ultrafiltration.

2. Part 1: heat transfer intensification

2.1. Introduction

Heat transfer processes are widely used in a lot of industrial applications like oil, chemical, gas or food industries. Among the new emerging techniques that could be developed and optimized in order to improve heat transfer processes, the use of ultrasound seems to be one of these new sustainable technical solutions [1]. However, although the effect of ultrasonic vibrations on natural convection or phase-change heat transfer has already been largely illustrated by many previous fundamental studies [2], there are only a few publications focusing on the influence of ultrasound on heat exchanger performances [3,4]. These reasons already led us to develop three different heat exchanger configurations in

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Nomenclature

Latin and Greek symbols

A	area (m^2)
Cp	specific heat ($J\,kg^{-1}\,K^{-1}$)
E_{US}	enhancement factor thanks to ultrasound application (dimensionless)
J_{us}	permeate flux of ultrafiltration under ultrasound ($L\,h^{-1}\,m^{-2}$)
J_v	permeate flux of ultrafiltration, general term ($L\,h^{-1}\,m^{-2}$)
J_{vo}	permeate flux of ultrafiltration without ultrasound ($L\,h^{-1}\,m^{-2}$)
L_p	permeability of membrane ($L\,h^{-1}\,m^{-2}\,Pa^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
P	power (W)
q	heat flowrate (W)
Q_v	cross-flow rate ($L\,min^{-1}$)
R	thermal resistance ($K\,W^{-1}$)
t	time (s)
T	temperature (K)
TMP	transmembrane pressure (Pa)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
z	distance from the membrane surface (μm)
Φ_v	volume fraction of suspension (vol%)
ΔT	temperature difference (K)

Subscripts

c	cold side, cold water
env	environment
exc	exchanged
h	hot side, hot water
in	at the inlet
lm	log-mean
out	at the outlet
US	ultrasound, in the presence of ultrasound

order to study the influence of ultrasound in devices including two fluids, unlike most studies in the literature where only one fluid is usually involved. The first system of interest was a classical ultrasonic reactor containing hot water at rest into which was inserted a copper coil [5]. Cold water was flowing throughout this coil to chill out the reactor content. As previously reported, it was shown that the overall heat transfer coefficient can be increased up to two times in the presence of ultrasound, resulting in an enhancement of the cooling rate of the hot water volume even at low power supply [5]. The second system was a shell-and-tube heat exchanger where both hot and cold fluids were flowing [6]. It was designed and built upon a Sonitube® resulting in the first version of an acoustically-assisted heat exchanger (35 kHz). In this case, the overall heat transfer coefficient was enhanced up to 260% as detailed in a previous paper [6]. In this work, an “equivalent” liquid flowrate has been determined in the presence of ultrasound from convection heat transfer correlation at the cold side. It was then demonstrated that depending on hydrodynamic conditions, this “equivalent” liquid flowrate could be equal up to 60 times the real cold liquid flowrate [6]. Finally, the third configuration of interest is a double-tube heat exchanger. As mentioned here above, a thermal approach of a slightly different geometry has already been reported and improvements are of the same order than with the first version of the vibrating shell-and-tube heat exchanger [7]. On the other hand, since cleaning capability of ultrasound is extensively used in the industry, there is also an innovative challenge to adapt this technology to heat exchangers in order to propose a possible way for fouling monitoring in these equipments [8]. Preliminary experimental investigations of artificial fouling reduction have shown that ultrasound can be successfully applied to remove resistant paint layers leading to restore the initial performances of the heat exchanger [9].

Based on the above, the objective of this part I is to demonstrate that ultrasound could be a valuable technique for heat transfer enhancement in heat exchangers. Experimental results on heat transfer intensification observed with the latest version of a homemade vibrating heat exchanger at the pilot scale are given. New preliminary experimental results on the intensification of heat transfer of a commercial plate heat exchanger are also reported here for the first time. This paper then focuses on the possible use of ultrasound in a curative or preventive way to monitor natural fouling in the double-tube heat exchanger. Fouling was obtained from calcium carbonate precipitation.

2.2. Experimental

2.2.1. Heat exchangers

2.2.1.1. Double-tube heat exchanger. The double-tube heat exchanger that can be defined as a vibrating heat exchanger is shown in Fig. 1. As previously detailed [10], it was built using a Sonitube® (model SM35). Therefore, the shell side can be put into vibration at 35 kHz. Two non-vibrating elements were added at each extremity of the vibrating shell to ensure inlet and outlet of both hot and cold fluids. Hot water flows into the central pipe whereas cold water flows throughout the annular space in a counter-flow configuration.

2.2.1.2. Industrial plate heat exchanger. The ultrasonically-driven heat exchanger was built using a commercially available brazed plate heat exchanger supplied by Barriquand company. 3 ultrasonic transducers usually used for cleaning baths (24 kHz) were stuck on each side of this heat exchanger as shown in the picture given in Fig. 2.

2.2.1.3. Test loop. Investigations on heat transfer intensification for both heat exchangers described here above were performed using the same test loop as detailed in previous works [7,10]. This set-up is composed of two circuits corresponding to hot and cold fluid respectively. A specific acquisition system was developed for liquid flowrates and temperatures measurements at both sides of the tested heat exchanger. Ultrasonic power was estimated by calorimetric measurement in the dynamic mode. Investigations on fouling reduction were performed using the same set-up. The internal tube was previously submitted to the fouling protocol described in

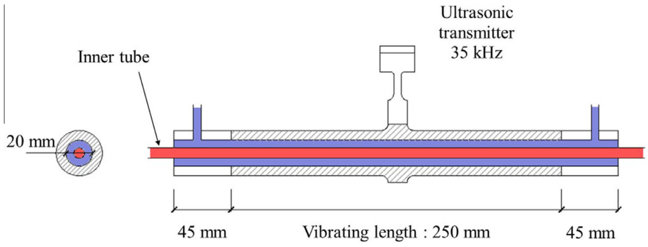

Fig. 1. Scheme of the double-tube vibrating heat exchanger.

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