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ScienceDirect
J. of Supercritical Fluids 43 (2008) 477–483
THE JOURNAL OF Supercritical Fluids
www.elsevier.com/locate/supflu

Static mixers as heat exchangers in supercritical fluid extraction processes

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Received 4 May 2007; received in revised form 4 July 2007; accepted 27 July 2007

Abstract

The performance of a Kenics static mixer as a heat-transfer device for supercritical carbon dioxide (CO_2) flow is studied and compared with conventional tube-in-tube heat exchangers. Measurements were carried out at pressures ranging from 8 to 21 MPa, temperatures from 283 to 323 K, and mass flowrates from 2 to 15 kg/h. The corresponding Reynolds and Prandtl numbers, at bulk conditions, ranged between 10^3 and 2×10^4 and between 2 and 7, respectively. The temperature increase experienced by the supercritical CO_2 stream varied between 10 and 35 K. The heat fluxes obtained with the static mixer are one order of magnitude higher than the ones observed with a tube-in-tube heat exchanger for the same set of operating conditions. The heat-transfer enhancement is caused by the cross-sectional mixing of the fluid and to a lesser extent by conduction across the metallic mixing elements. Heat-transfer is also affected by temperature-induced variation of physical properties, especially in the pseudocritical region of the fluid. From the experimental data, a correlation was developed for convective heat-transfer to supercritical CO_2 in terms of the Nusselt number.

Keywords: Static mixer; Heat exchanger; Supercritical carbon dioxide; Modelling

1. Introduction

Supercritical fluid extraction (SFE) is a process that uses fluids at supercritical conditions to selectively extract substances from solid or liquid mixtures. By changing pressure and temperature, the solvating power of the fluid (usually carbon dioxide) can be adjusted to obtain good solubilities, selectivities and transport properties. SFE technology has the potential to enhance product quality, while at the same time being an environmentally clean extraction technology. Heat-transfer to supercritical fluids (SCF) is important when dealing with technological applications of these fluids, especially for extraction, reaction or particle formation processes. Every SFE unit has several heat exchangers (HXs) in its flowsheet; their purpose can be, among others, to preheat the supercritical fluid before being fed to the high pressure vessel, to cool down the SCF before compression, or to change temperature conditions of the high pressure flow before separation of the solubilized solutes from the SCF solvent takes place. Conventional heat exchangers, such as double-pipe or shell-and-tube, have been used in SFE. They present important advantages (established design and manufacturing), but also show some undesirable features, such as relatively high surface areas to attain desired thermal exchange and heat-transfer inefficiencies due to non-negligible laminar film build-up on the tube walls.

Static mixers have been considered credible alternatives to conventional HXs, because they provide very high and uniform heat-transfer rates. They are currently being used in a wide range of applications, such as blending of gases or miscible liquids in laminar or turbulent flow, continuous co-current liquid/liquid or gas/liquid dispersions, heat exchangers, and interphase mass transfer between immiscible phases [1–3].

A static mixer consists of a contacting device with a series of internal stationary mixing elements of specific geometry, inserted into a pipe. The added effects of momentum reversal and flow division due to the internal elements of the mixer contribute to a maximization of mixing efficiency. The benefits of dispersion efficiency, short residence times, and low flow resistance, are advantages for the use of static mixers in mass and heat-transfer applications [4]. Recently, the use of static

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0896-8446/$ – see front matter
doi:10.1016/j.supflu.2007.07.015

Nomenclature

C_p	isobaric specific heat (J/K kg)
G	gas phase mass flowrate (kg/s)
Gr	Grashof number
h_G	heat-transfer coefficient in the gas phase (W/m^2 K)
H	specific enthalpy of carbon dioxide (J/kg)
k	thermal conductivity (W/m K)
Nu	Nusselt number
Pr	Prandtl number
Q	heat-transfer rate (W)
R_i	internal radius of the static mixer (m)
Re	Reynolds number
T	temperature (°C or K)
U	overall heat-transfer coefficient (W/m^2 K)
x_w	static mixer wall thickness (m)
Z	heated length of the static mixer (m)

Greek symbols

μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	residence time (s)

Subscripts

b	property evaluated at the bulk temperature
G	gas phase
in	carbon dioxide conditions at inlet of static mixer
out	carbon dioxide conditions at outlet of static mixer
pc	pseudo critical condition
w	property evaluated at the wall temperature

mixers in SFE processes has been proposed as, e.g., alternative contacting devices [5,6], equilibrium cells for high-pressure thermodynamic studies [7,8] and mixers of powder coatings and additives with SC-CO_2 to make fine, coated particles from gas-saturated solutions [9]. Static mixers have advantages over conventional equipment for use at SC conditions. These include lower capital costs at a large scale of operation, no possibility of flooding even if there is a low density difference between the phases, short residence times, and minimal space requirements for location in a SFE plant.

In this work, the performance of a Kenics static mixer to heat a SC-CO_2 stream is studied and compared with conventional tube-in-tube HXs. The Kenics mixer is comprised of a series of mixing elements aligned at 90°, each element consisting of a short helix of one and a half pipe diameters in length. Each helix has a twist of 180° with right-hand and left-hand elements being arranged alternatively in the pipe (Fig. 1a). The internal mixing elements direct the flow of material radially toward the pipe walls and back to the center. Additional velocity reversal and flow division results from combining alternating right- and left-hand elements, thus increasing mixing efficiency. All material is continuously and completely mixed, eliminating radial gradients in temperature in the bulk fluid. This in turn increases the thermal gradient near the hot wall and, consequently, the heat-transfer rate into the fluid.

Measurements are carried out at pressures ranging from 8 to 21 MPa, temperatures ranging from 288 to 323 K, and mass flowrates ranging from 2 to 15 kg/h. The effect of the density of the supercritical fluid, the heat flux, and the fluid flowrate, on the heat-transfer performance of the static mixer at high-pressure conditions is examined. Based on the experimental data, a correlation is developed for convective heat-transfer to SC-CO_2 on the basis of a Nusselt number.

The design and optimization of HXs for supercritical fluids have an additional difficulty when compared with normal liquids

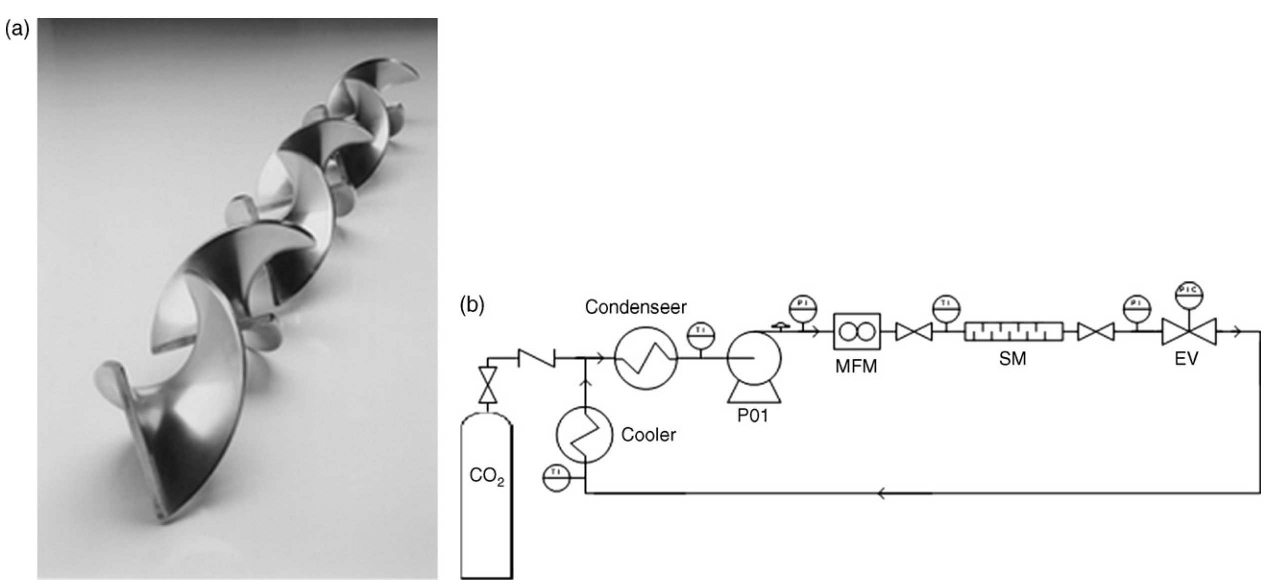

Fig. 1. (a) Mixing elements of the Kenics-type static mixer. (b) Schematic diagram of the experimental apparatus. SM: static mixer; P: pumps; MFM: mass flow meters; dP: differential pressure meter; EV: expansion valve; PI and TI: pressure and temperature indicators or controllers.