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Supercritical CO_2 as heat transfer fluid: A review

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HIGHLIGHTS

- Comprehensive review of correlations of heat transfer coefficient of supercritical CO_2.
- Different applications of supercritical CO_2 are also reviewed and discussed.
- Correlations from experimental are presented for different geometries.
- There is a lack of a unique universal correlation for each geometry.

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ABSTRACT

This paper presents a comprehensive review of all correlations and experimental studies available in the literature to determine the heat transfer coefficient of supercritical CO_2 flowing in heat exchangers. The different applications in which it is used are also reviewed and discussed. The correlations obtained from extensive experimental measurements are presented for different geometries (horizontal, vertical and inclined tubes, closed-loop circular pipes, and mini-channels) and dimensions. The review shows that there is a lack of a unique universal correlation for each geometry, suggesting the need for more work in this area.

Contents

1. Introduction

Supercritical fluid is a fluid state where it is held at or above its critical temperature and critical pressure. Carbon dioxide behaves as a supercritical fluid above its critical temperature (304.25 K) and critical pressure (72.9 atm or 7.39 MPa), expanding to fill its container like a gas but with a density like that of a liquid (Fig. 1). When fluids and gases are heated above their critical temperature and compressed above their critical pressure they enter a supercritical phase where some properties, such as solvent power, can be dramatically changed. Fig. 2 shows in images how CO_2 goes

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Nomenclature

c_p	specific heat at constant pressure [J/kg·K]
$\overline{c_p}$	average specific heat at constant pressure [J/kg·K]
D	inner diameter [m]
f	friction factor [–]
G	mass flux [kg/m^2·s]
Gr	Grasshof number [–]
g	gravity acceleration [m^2/s]
h	specific enthalpy [J/kg]
k	thermal conductivity [W/m·K]
L	tube length [m]
Nu	Nusselt number [–]
p	pressure [Pa]
Pr	Prandtl number [–]
$\overline{Pr}$	average Prandtl number [–]
q	heat flux from tube wall to fluid [W/m^2]
Re	Reynolds number [–]
Rr	channel relative roughness
T	temperature [K]

Greek symbols

α	heat transfer coefficient [W/m^2·K]
β	thermal expansion coefficient [1/K]
Δ	Increment
ε	channel roughness [m]
μ	dynamic viscosity [Pa·s]
ρ	density [kg/m^3]

Subscripts

ac	acceleration
b	at fluid bulk temperature
exp	experimental
f	at film temperature
in	inlet
Iso	isothermal
Out	outlet
Pc	at pseudo-critical temperature
Pred	predicted
W	at inner wall temperature

through different phases from behaving as a sub-critical fluid to a supercritical fluid.

Okamoto et al. [3] in 2003 successfully visualized the variation of $scCO_2$ under forced convective heat transfer using schlieren and shadowgraph techniques as research towards the precise characterization of supercritical fluid behaviour. For example, Fig. 3 presents $scCO_2$ imaging by infrared laser and its translation to an instantaneous vector map and the average velocity distributions.

Supercritical CO_2 is becoming an important commercial and industrial solvent due to its role in chemical extraction in addition to its low toxicity and being environmental friendly solvent. The relatively low temperature of the process and the stability of CO_2 also allow most compounds to be extracted with little damage or denaturing. In addition, the solubility of many extracted compounds in CO_2 varies with pressure, permitting selective extractions. $scCO_2$ has been used for fluid extraction in areas such as food science, pharmaceuticals, chemical residues, biofuels, and polymers [4].

The aim of this review is to summarize the literature on the use of $scCO_2$ as a heat transfer fluid (HTF), however its wider application of extraction will also be summarized in this review.

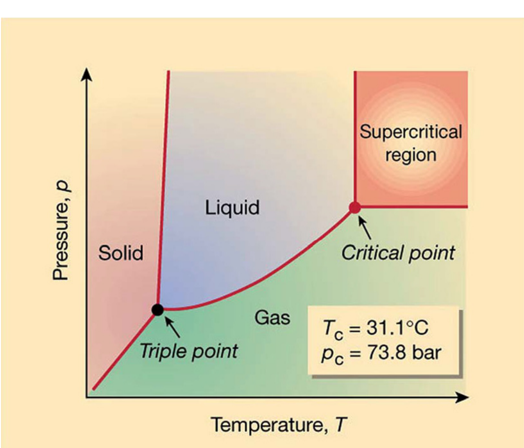

Fig. 1. Supercritical CO_2 p-T diagram [1]

2. Applications of supercritical CO_2

A short summary of supercritical CO_2 applications is presented here. Supercritical carbon dioxide ($scCO_2$) offers an acceptable combination of pressure and temperature to achieve supercritical conditions. $scCO_2$ is not a good solvent for most materials, which are $scCO_2$-phobic. However, both silicone and fluoro-products may be regarded as CO_2-philic and, therefore, potentially more soluble; such products are used in magnetic media production, one of the first applications of $scCO_2$ studied [5].

Another application investigated was supercritical extraction in petroleum refining and petrochemistry [6]. According to this publication, the advantages of carbon dioxide as solvent include; non-explosiveness and incombustibility; chemical inertness; absence of toxic wastes; sufficiently low critical parameters (pressure and temperature); low polarity; availability and low cost; high extraction rate due to high diffusing power.

The food industry is always looking for the best separation technology to obtain natural compounds of high purity, healthy products of excellent quality with several industrial applications. The conventional extraction process for those compounds has some limitations regarding the solvent toxicity, flammability and wastefulness. Supercritical carbon dioxide is ideal for the food processing industry because of its non-flammable, non-toxic, non-polluting and recoverable characteristics [7,8]. Examples of applications in the food industry are extraction of cholesterol and other lipids from egg yolk; milk fat fractioning; extraction of lipids and cholesterol from meat and meat products; from fish; extraction of natural colourings from several foodstuffs (such as carrots, leaf protein concentrates, sweet potatoes, tomato paste waste and tomato skin, and rape grape skin); extraction, refining and fractioning of oils and vegetable fats; extraction and fractioning of natural flavourings; extraction of antioxidants; decaffeinating of coffee and tea; extraction of hop; and the alcoholisation of drinks.

$scCO_2$ is also used in separation processes [9]. For example, Semenova and Ohya [10] studied the fractionation of SC CO_2/ethanol and $scCO_2$/iso-octane mixtures using an asymmetric Kapton membrane. The investigators concluded that CO_2 transfer across was predominantly by convection rather than diffusion. At approximately the same time, Hsu and Tan [11] proposed the use of