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The influence of variable physical properties and buoyancy on heat exchanger design for near- and supercritical conditions

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Abstract

Computational fluid dynamics simulations were done on heated supercritical carbon dioxide flowing up or down in a vertical pipe. The impairment or enhancement of heat transfer caused by the temperature-induced variation of physical properties was investigated, as well as the effect of buoyancy. The simulations show, for non-buoyant flow, that for pressures above 120 bar, the effect of variation in physical properties is small and a constant-property Nusselt relation can be used for a heat exchanger design. For pressures below 120 bar, the variation in physical properties has to be taken into account for a correct heat exchanger design. For non-buoyancy conditions the Krasnoshchekov–Protopopov equation can be used to calculate heat transfer coefficients. It was observed that buoyancy can enhance heat transfer coefficients up to a factor 3. When buoyancy is active, the highest heat transfer coefficients are realized when the fluid flows downward. The Jackson and Hall correction factor for the calculation of heat transfer coefficients under buoyancy was confirmed by the simulations.

Keywords: Supercritical fluid; Heat transfer; Variable physical properties; Buoyancy

1. Introduction

In designing heat exchangers for supercritical fluids a complication arises that is not encountered when dealing with liquids or gases. The strong variation of the fluid physical properties with temperature around the critical point influences heat transfer strongly.

This problem has led to a great deal of research and many publications are to be found in which Nusselt relations for the calculation of heat transfer coefficients have been constructed and fitted to experimental work, as is reviewed by Pitla et al. [1]. The present work is an investigation into the phenomena around the critical point and into the buoyancy phenomenon, i.e. free convection caused by temperature-induced density differences. Computational fluid dynamics simulations of heated supercritical carbon dioxide flows through vertical pipes are carried out.

The objective is to study when and how the variable properties and the buoyancy must be taken into account in the Nusselt-relation for heating. For buoyancy conditions in a heated flow, it is investigated what the position of a pipe and the direction of the flow should be.

The importance of having information on tube-side heat transfer coefficients in supercritical fluid heat transfer can be illustrated by regarding the individual heat transfer resistances of shell-side, wall and tube-side. The overall heat transfer coefficient for a steel pipe is calculated with:

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{d_o \ln(d_o/d_i)}{2k_{steel}} + \frac{d_o}{d_i h_i} \tag{1}$$

where U_o is the overall heat transfer coefficient corresponding with the outside area of the tube, h_o and h_i are the outside and inside film coefficients, d_o and d_i are the outside and inside tube diameters and k_{steel} is the thermal conductivity of the steel tube wall. As an example is taken here supercritical carbon dioxide ($scCO_2$) being heated with steam in a pipe

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Nomenclature

a	constant
b	constant
c	constant
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
d	pipe diameter (m)
e	constant
g	gravitational acceleration (ms^{-2})
Gr	Grashof number, $Gr = gd^3\rho(\rho_b$-$\rho_w)/\mu^2$
h	heat transfer coefficient (Wm^{-2} K^{-1})
H	enthalpy (J kg^{-1})
k	thermal conductivity (Wm^{-1} K^{-1})
Nu	Nusselt number, $Nu = hd/\mathrm{k}$
p	pressure (bar)
Pr	Prandtl number, $Pr = \mu c_p/\mathrm{k}$
q	heat flow (Js^{-1})
Re	Reynolds number, $Re = \omega d/\mu$
T	temperature (K and °C)
U_o	overall heat transfer coefficient (Wm^{-2} K^{-1})
Greek letters	
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)
ω	mass flux (kg m^{-2} s^{-1})
Φ_m	mass flow (kg s^{-1})
Subscripts	
b	at bulk conditions
c	critical
cp	at constant properties
i	inside of pipe
o	outside of pipe
pc	at pseudo-critical temperature
vp	at variable properties
w	at wall conditions

with $d_o = 16$ mm, $d_i = 13$ mm and $k_{steel} = 16$ Wm^{-1}K^{-1} so that $2k_{steel}/(d_o \ln(d_o/d_i)) = 10{,}000$ Wm^{-2}K^{-1}. The heat transfer coefficient for condensing steam is $h_o = 8000$ Wm^{-2}K^{-1}. It can be seen in several publications [1–7] that, without the influence of variable properties or buoyancy, the tube-side heat transfer coefficient for scCO$_2$ is in the order of $h_i = 6000$ Wm^{-2}K^{-1}. All three contributions of Eq. (1) have the same order of magnitude, so it is important to take into account enhancement or impairment of tube-side heat transfer caused by variations in physical properties or buoyancy.

2. Nusselt-relations

For fluids with physical properties that can be regarded as temperature-independent, the generally applied Nusselt-relation for the calculation of the tube-side heat transfer coefficient is, according to Jackson and Hall [2,3]:

$$Nu_{cp} = \frac{h_{cp} d_i}{k_b} = 0.0183 Re_b^{0.82} Pr_b^{0.5} \tag{2}$$

or

$$h_{cp} = 0.0183 d_i^{-0.17} \omega^{0.82} k_b^{0.5} \mu_b^{-0.33} c_{p,b}^{0.5} \tag{3}$$

where Nu_{cp} is the Nusselt number in case of constant properties, evaluated at bulk conditions, h_{cp} is the corresponding tube-side heat transfer coefficient, k_b is the thermal conductivity of the fluid at bulk conditions, Re_b and Pr_b are the Reynolds and Prandtl numbers at bulk conditions, ω is the mass flux and μ_b and $c_{p,b}$ are the dynamic viscosity and the specific heat at constant pressure at bulk conditions. In Eq. (2), the physical properties are assumed constant in radial direction. In the longitudonal direction of a pipe, the bulk temperature and therefore the physical properties do change. Eq. (2) delivers the local heat transfer coefficient.

Around the pseudo-critical point, thermal conductivity, viscosity and specific heat vary strongly. It should be noted here that this temperature is higher than the critical temperature (31 °C) when the pressure is above its critical value (74 bar). As is shown in Fig. 1 for 80 bar (pseudo-critical temperature $T_{pc} = 34$ °C), the variation in the factor $c_{p,b}^{0.5}$ is much larger than the change in the factor $k_b^{0.5}\mu_b^{-0.33}$, so that it can be expected that the heat transfer coefficient from Eq. (3) will follow the trend of the specific heat, i.e. showing peaks at the pseudo-critical temperature. Indeed, these peaks were observed in the experiments of Swenson et al. [4] for water.

Eq. (2) can be used to predict the heat transfer coefficient at supercritical conditions only at low temperature differences between wall and bulk because then the physical properties can be regarded as constant in radial direction.

At higher wall-to-bulk temperature differences, specific heat, viscosity, thermal conductivity and density will show radial gradients and Eq. (2) is no longer valid. Instead, the variable properties have to be taken into account. This is mostly

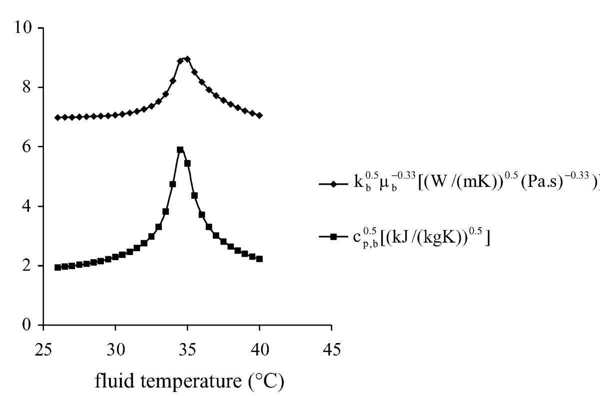

Fig. 1. Influence of the variation of carbon dioxide physical properties around the pseudo-critical temperature at 80 bar on the constant-property heat transfer coefficient of Eq. (3).