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Transient analysis of subcritical/supercritical carbon dioxide based natural circulation loops with end heat exchangers: Numerical studies

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ABSTRACT

Transient analysis of carbon dioxide based natural circulation loop (NCL) with end heat exchangers has been carried out. Subcritical and supercritical phases of CO_2 are considered with operating pressures in the range of 50–100 bar for an operating temperature range of 323 K to 363 K. Studies are carried out for various loop tilt angles, different initial conditions, and different water mass flow rates.

Results are obtained for various inlet temperatures of water in the hot heat exchanger while keeping the inlet temperature of cooling water in the cold heat exchanger fixed. Effect of tilting the loop in *XY* and *YZ* planes on transient as well as steady state behaviour of loop are also studied. Validation of simulation results against experimental and numerical results reported in the literature in terms of modified Grashof number (Gr_m) and Reynolds number (Re) show good agreement.

1. Introduction

In recent years, a growing popularity of carbon dioxide as secondary fluid has been witnessed in forced as well as natural circulation loops [1–3]. This may be attributed to the favourable thermo-physical properties of CO_2 in addition to its environment friendliness. Studies show that any fluid operating near its critical point offers thermophysical properties that are favourable to natural circulation loops (NCLs). Operating temperatures of many engineering applications lie around the critical temperature of CO_2 (31.2 °C), which makes CO_2 one of the best working fluids for NCLs. However, high critical pressure of CO_2 (73.8 bar) is one of the demerits. NCLs offer certain advantages over forced circulation loops, particularly in small to medium capacity systems; they are preferred where safety is of foremost concern, for example, in nuclear power plants. NCLs are also widely used in applications such as refrigeration and air conditioning systems, solar collectors, and nuclear reactors. Studies show that for low temperature refrigeration and air conditioning applications, use of CO_2 in place of conventional secondary fluids results in very compact loops [2]. CO_2 based NCLs have also been proposed for various heat transfer applications such as new generation nuclear reactors [4], in chemical extraction [5,6], cryogenic refrigeration [7], heat pump [8], electronic cooling systems [9], geothermal applications [10,11], etc. However, detailed modelling and analyses of CO_2 based NCLs are relatively sparse in the literature. Kiran Kumar and Ram Gopal [12] reported a one-dimensional steady-state analysis of a rectangular NCL with end heat exchangers for low temperature applications. Recently Zhang et al. [13] and Chen et al. [14] reported studies on the effects of heat transfer and the instabilities of supercritical CO_2 flow in a 2-D NCL at a fixed operating pressure of 90 bar operating over a large heat source temperature range. It was concluded that using supercritical CO_2 as the loop fluid, a temperature difference as small as 25 K between heating and cooling sources can yield a Reynolds number as high as 6×10^4, resulting in high heat transfer rates. Most of the studies available for CO_2 based NCLs are for isothermal heat source and sink, which has less practical significance than NCLs with end heat exchangers.

In addition, to account for the strong local buoyancy effects near pseudo critical zone, and the effect of bends in pipe, etc., it becomes essential to consider a three-dimensional (3-D) model for greater accuracy. Recently, Yadav et al. [15,16] have reported a three-dimensional steady state analysis on CO_2 based NCLs. Review of literature shows that transient analysis of CO_2 based NCLs employing 3-D models are not available in the open literature. To fill in that void, this study presents a CFD analysis of a three-dimensional model of subcritical/supercritical CO_2 based NCL with end heat exchangers. Results are presented on the transient behaviour of the loop at various operating pressures and temperatures. The operating parameter range is chosen such that the loop fluid (CO_2) exists as a subcritical or supercritical single-phase fluid.

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Nomenclature

A	area
C_μ $C_{1\varepsilon}$ $C_{2\varepsilon}$ $C_{3\varepsilon}$	parameters in RNG model equations
c_p	specific heat capacity
C_v	constant
D	diameter of outer pipe of CHX and HHX
d	diameter of inner pipe or loop diameter
E	energy
f	friction factor
g	gravitational acceleration
G_b	turbulent kinetic energy due to buoyancy
G_k	turbulent kinetic energy due to mean velocity gradient
Gr	Grashof number
Gr_m	modified Grashof number
h	heat transfer coefficient
H_0	total height of vertical pipes
k	turbulent kinetic energy
L	length of CHX (sink) and HHX (source)
L_0	total length of a horizontal pipe
L_1	adiabatic pipe length on horizontal pipe
L_c	characteristic length
L_t	total length of the loop
m	mass flow rate
Nu	Nusselt number
p P	pressure of fluid
Pr	Prandtl number
Pr_t	turbulent Prandtl number
Q	heat transfer rate
r	radius of loop
R	radius of curvature for bends
Ra	Rayleigh number
Re	Reynolds number
R_ε	parameters in RNG model equations
S	strain tensor
T	temperature
t	time
u v V	velocity
x	x-coordinate location

Greek letters

α α_0	thermal diffusivity
α_k α_ε	parameters in RNG model equations
β	volumetric expansion coefficient
ΔT	temperature difference across the CHX/HHX
ε	turbulence dissipation rate
λ	thermal conductivity
μ	dynamic viscosity
μ_t μ_{eff}	viscosity parameters in RNG model
η	parameter in RNG model
ρ	density of fluid
$\bar{\bar{\tau}}$	stress tensor

Subscripts

avg	average
c	critical
C	cold heat exchanger, sink
CO_2	carbon dioxide
eff	effective
f	fluid
H	hot heat exchanger, source
i	x-direction/internal
j	y-direction
m	modified, bulk mean
max	maximum
o	external
ref	reference
r	radial direction
s	pseudocritical/optimum/solid
θ	azimuthal direction
w	water, wall
z	axial direction

2. Physical model and mathematical formulations

2.1. Physical model

A three dimensional geometry shown in Fig. 1a is prepared in ANSYS 14.0 using Design Modeler. Figure shows the schematic of a rectangular NCL comprising a cold heat exchanger (CHX), a hot heat exchanger (HHX), a riser and a downcomer. The loop fluid is heated sensibly by extracting heat from the external fluid (hot water) in HHX and is cooled sensibly by rejecting heat to the external fluid (cold water) in the CHX. Circulation of the loop fluid is maintained due to the buoyancy effect caused by heating at the bottom and cooling at the top. Flow in the clockwise direction is considered positive. Based on commercial availability of stainless steel and copper tubes, diameter of the pipes are chosen for the simulation and the entire geometric and material specification of the model is listed in Table 1.

Studies are carried out at different tilt angles of the loop in XY and YZ planes. Fig. 1b shows the rotation of the loop in XY plane in clockwise direction. The loop is considered to be vertical at a tilt angle of 0°. The loop is also tilted in the YZ plane from vertical position in counter clockwise direction as depicted in Fig. 1c. During simulation, most of the transient analysis results have been taken at the cross section in the middle of the left leg pipe.

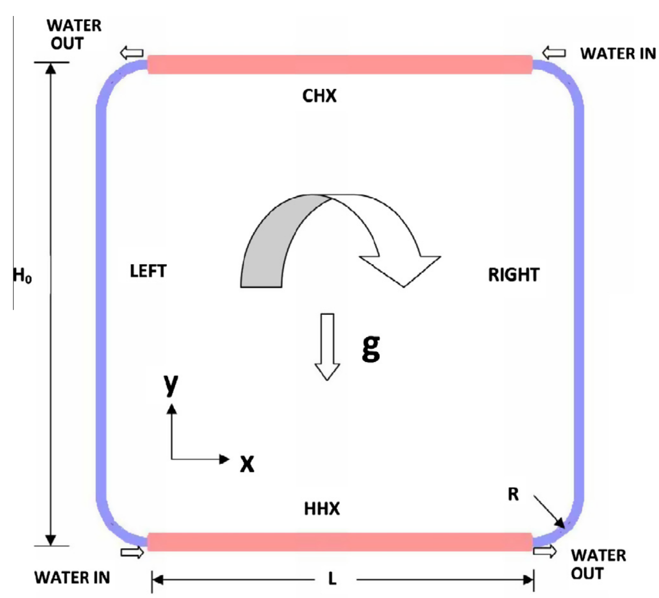

Fig. 1a. Schematic of the NCL with end heat exchangers.