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1-D transient numerical modeling of counter-current two-phase stratified flow inside a medium temperature solar linear collector

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ABSTRACT

Two-phase gravity-driven and gravity-stratified flow regime inside a pipe, which is present in many engineering applications, is an attractive option for solar cooling/heating/power production using Rankine cycles, absorption cycles or any other thermodynamic application by means of vapor as working fluid. This paper offers a numerical model of this flow configuration that copes with transient phenomena, like unsteadiness of solar radiation, among others. The mathematical model consists of 1-D balance equations for mass and momentum for both fluids and energy for both fluids and the wall of the pipe that absorbs the solar radiation. The model is characterized by the fact that the area (or height) of the liquid layer is treated as a dependent variable forming part of the solution. The numerical method consists in a finite volume staggered grid discretization of the governing equations. Mass flow and liquid area are calculated with a semi-implicit pressure based method and the transient terms are treated with the explicit first stage singly implicit Runge-Kutta (ESDIRK) method. The calculation of the mass transfer rate from liquid to vapor is calculated iteratively by a guess-and-correct mass transfer algorithm, specially developed for stratified flows. The results show the applicability and benefits of this model for the not so well known counter-current stratified two-phase with evaporation/boiling. Additionally, the performance of the mass transfer algorithm is discussed showing that it is monotonic decreasing and linearly convergent.

1. Introduction

Solar energy is the most abundant energy resource, its advantages over other energy sources are clear, no polluting emissions, renewable, widely available and no fuel cost. All that makes this kind of source a very interesting choice in the years to come. Solar energy systems are encountered in many different applications, such as power generation, heating, hot sanitary water preparation and refrigeration applications only to mention a few. Many are the available technologies for solar thermal energy production. Among these technologies, thermal concentrated solar technology stands out for its high flexibility, high thermal efficiency, and low cost, Jebasingh and Joselin Herbert [1]. Either parabolic trough or Fresnel type linear solar collectors are the most common. They work on the same principle and their layout is similar for our purposes. The working principle is simple, a straight absorber pipe is located along the focal line of either a single or a group of large area mirrors that concentrate solar radiation from below on its external surface, tracking the sun, Fig. 1. With the resulting high radiation flux, a fluid stream that flows inside the straight pipe is heated. This fluid can be a pure substance, like water or thermal oil, or can be a mixture, depending on the application and operating conditions required.

Nowadays with the applications mentioned above, the liquid occupies entirely the straight pipe, which is normally horizontal; however in some other applications such as petroleum transport, steam generation equipment, chemical processes, distillation and nuclear reactors the simultaneous flow of liquid and vapor is used, e. g. Newton and Behnia [2] and the pipe can be inclined. If the vapor velocity is high enough an annular stratification can be established owing to the prevalence of shear stresses over gravity force, Rohsenow, Hammet and Cho [3], Wallis [4] and Friedel [5] among others, with the so-called liquid holdup. This flow layout has been much studied because it happens in vertical pipes and also in horizontal and inclined setups. Usually, the pipe is completely filled with liquid at its inlet side and it is subjected to intense heating, releasing so much vapor that the vapor velocity increases also very much downstream, especially at low pressures, driving the liquid flow by shear stresses. In those layouts, a complete transformation of liquid into vapor is pursued. This is not the present case, where the velocities involved are low, making gravity predominant. This type of regime is a gravity stratified flow, which

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Nomenclature

A	cross section area
a	butcher table of coefficient matrix
B	discretised linear system coefficient vector
b	source term vector
c	butcher tabl of quadrature point location
D	pipe diameter
G	mass flux
h	enthalpy
h_{lv}	phase change enthalpy
K	mass transfer coefficient
$\dot{m}$	mass flow rate
N	number of finite volumes
$\hat{n}$	unitary normal vector
Nu	Nusselt number ($= \alpha D_h/\lambda$)
P	perimeter
Pr	Prandtl number ($= Cp\mu/\lambda$)
p	pressure
r	radius
Re	Reynolds number ($= GD_h/\nu$)
S	surface area
T	temperature
t	time
u	velocity
x	quality ($=(h_l - h_l^{sat})/h_{lv}^{sat}$)
z	axial coordinate

Greeks

β	pipe tilting angle
ρ	density
δ	flow vein cross height
ε	fluid zone integer function
φ	liquid cross angle
θ	angle coordinate
ω	pointing vector
τ	shear stress
λ	thermal conductivity
α	convective heat transfer coefficient
μ	dynamic viscosity
ν	kinematic viscosity
Δ	finite difference

Subscripts

h	hydraulic
l	liquid
v	vapor
i	inner
ip	interphase
k	zone index
o	output, outer
wall	wall
0	at $z = 0$
w,e,Ee,W,P,E	cardinal coordinate system location index

Superscripts

	per unit length symbol, correction
$''$	per unit area symbol
$*$	correction
sat	saturation condition
T	transposed
(n)	time level
(s)	stage level

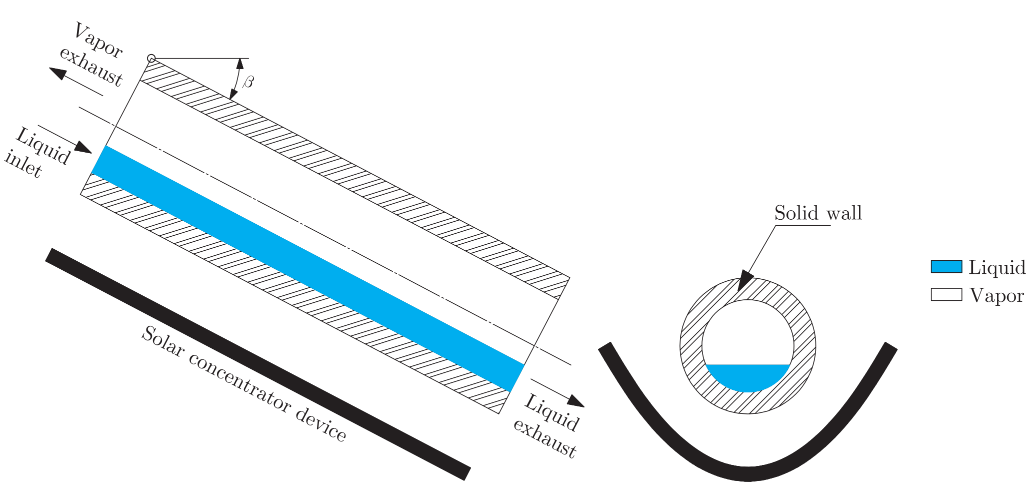

Fig. 1. Schematic representation of the counter-current gravity stratified flow layout.

excludes vertical and quasi-vertical pipes. It happens in horizontal and inclined pipes, making the gravity force responsible for its stratification so that the heaviest phase occupies the bottom side, Rohsenow, Hammet, and Cho [3], Wallis [4] and Taitel and Duckler [6]. As in our case, for low enough velocities, a smooth interphase is maintained separating two continuous phases, not even reaching the wavy regime. The moderate vapor production and the large void fraction makes that this regime does not switch to another one. The flow can be co-current or counter-current depending upon the relative motion of both phases, here each fluid stream defines a phase. If both phases flow in the same direction, it is called co-current, otherwise is counter-current, Kandlikar [7], which is the layout of interest in this paper.

With this layout, the vapor is produced directly without intervening any intermediate heat carrying fluid, for that using pressurized water, steam or thermal oil, as customary. Cost, weight, and bulk are reduced with direct steam production as well as system complexity. For many industrial processes, the temperatures involved are in the order of 120–250 °C (medium temperature solar collection, Coccia et al. [8]), depending upon the pressure levels. In any case, these temperatures are lower than those required by steam generation for power production, around 400–500 °C, thus the pipe thermoelastic bending problem is of a much lesser importance, e. g. [9,10]. With this layout, the flow is established when a pure substance liquid (or multicomponent mixture for absorption cycle applications), slides continuously, under the effect of