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Simulation of Taylor flow evaporation for bubble-pump applications

Alexander S. Rattner [a], Srinivas Garimella [b,*]

[a] Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802, United States
[b] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30318, United States

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ABSTRACT

Single-pressure absorption systems incorporate bubble-pump generators (BPGs) for refrigerant separation and passive fluid circulation. In conventional spot-heated BPGs, heat is transferred over a small area, requiring high source temperatures. Distributed-heated BPGs receive thermal input over most of the component surface, enabling low temperature operation. In this investigation, a Volume-of-Fluid phase-change simulation formulation is developed and validated. This approach is applied to the evaporating Taylor flow pattern in distributed-heated BPGs. A 2-D axisymmetric simulation is performed, which yields detailed information about the developing heat transfer and two-phase flow phenomena. Results are used to assess predicted trends and sub-models from a 1-D segmented BPG model. Close agreement is obtained between segmented model and simulation results for bubble rise velocity (5–7% deviation), bubble and slug lengths, void fraction (3%), and hydrodynamic pressure drop (18%). Specifying average Taylor bubble lengths from the simulation as an input to the segmented model reduces hydrodynamic pressure drop deviation to 6%. Simulated flow-evaporation heat transfer coefficients are significantly higher than those predicted using analytic models from the literature. A new flow evaporation heat transfer correlation that accounts for developing slug flow effects is proposed, and yields close agreement with simulation results for heat transfer coefficient (AAD = 11%) and overall heat transfer rate (2%). Overall, this investigation provides validation for a distributed-heated BPG modeling approach, which can enable passive refrigeration for diverse applications.

1. Introduction

1.1. Background

Bubble-pump generators (BPGs) are key components of single-pressure absorption refrigeration technologies, such as the diffusion absorption refrigeration (DAR) cycle. BPGs are usually configured as externally heated vertical tubes that receive liquid refrigerant-absorbent solution from a lower reservoir. External heat is supplied to desorb vapor refrigerant from the solution, and the buoyancy of rising bubbles pumps liquid through the BPG tube (Fig. 1). Thus, the BPG component separates the refrigerant stream and provides the hydrostatic head to drive solution flow through other components, enabling fully passive system operation. The liquid–vapor mixture usually flows through the BPG in the Taylor or slug flow regime [1].

Conventional BPGs are *spot heated* [2,3], with all heat transfer occurring over a small area near the base of the component (indicated in Fig. 1). This mode of operation enables high solution pumping rates and simple analysis, as flow rates are uniform along the major portion of the component. However, these designs require high input temperatures (150–200 °C [4,5]), usually delivered with electrical resistance heaters or chemical fuel (*e.g.*, propane). If the heat transfer area can be increased, then lower temperature thermal sources such as solar heat or engine waste heat can be employed. Recently, a number of investigations of *distributed-heated* BPGs in which heat transfer occurs over most of the component surface [4,6] have been performed. Rattner and Garimella [1] demonstrated stable distributed-heated operation of a steam-water BPG with thermal input only ∼10 K above the fluid saturation temperature.

Few experimental or modeling studies have been conducted for distributed-heated BPGs. Experimental validation of models has primarily been global in nature, focusing on outlet flow rates and overall heat transfer. This approach does not provide local details of axially varying quantities (*e.g.*, void fraction, pressure gradient, wall heat flux), and does not permit independent evaluation of sub-models. It is difficult to perform more detailed experimental investigations because the two-phase flow pattern develops continuously, and the need for external heat input and insulation may preclude optical access. However, by directly simulating these

* Corresponding author.
E-mail address: sgarimella@gatech.edu (S. Garimella).

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Nomenclature

A	area (m^2)
A_D	diagonal entry in discretized momentum matrix equation ($kg\ m^{-3}\ s^{-1}$)
Bo	Bond number ($(\rho_L - \rho_V)gD^2/\sigma$)
C_0	distribution parameter in bubble velocity model
Ca	capillary number ($\mu_L j/\sigma$)
c_p	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
D	diameter (m)
D_H	hydraulic diameter (m)
f_i	body force vector ($kg\ m^{-2}\ s^{-2}$)
f	Darcy friction factor, or blending factor
G	mass flux ($kg\ m^{-2}\ s^{-1}$)
Gz	Graetz number ($D\ Re_j\ Pr_L/L_s$)
g	gravitational acceleration (9.81 $m\ s^{-2}$)
h	convection heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
H	height (m)
i	enthalpy ($kJ\ kg^{-1}$)
ID	inner diameter (m)
j	superficial velocity ($m\ s^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L	length (of liquid slug or Taylor bubble)
L_b^*	dimensionless bubble length ($L_b/(Re_b\ D_b)$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
n	number of mesh cells in a direction
$\hat{n}$	cell-face normal
N_f	viscous force parameter ($\sqrt{\rho_L(\rho_L - \rho_V)gD^3/\mu_L^2}$)
Nu	Nusselt number (Nu = h D/k)
OD	outer diameter (m)
p	pressure (Pa)
$p_{\rho gh}$	dynamic pressure (hydrostatic contribution removed) (Pa)
Pr	Prandtl number ($\mu c_p/k$)
Q	heat transfer rate (W)
q	heat flux ($W\ m^{-2}$)
$\dot{q}_{pc}$	Volumetric phase-change heat source ($kW\ kg^{-1}$)
r	radius (m)
R'	thermal resistance × unit length ($m\ K\ W^{-1}$)
R''	thermal resistance × unit area ($m^2\ K\ W^{-1}$)
Re_b	Taylor bubble Reynolds number ($\rho_V(U_B - U_{LF})D_B/\mu_V$)
Re_{CF}	coupling-fluid Reynolds number ($\rho_{CF}U_{CF}D_{H,CF}/\mu_{CF}$)
Re_j	superficial Reynolds number ($\rho_L jD/\mu_L$)
s	under-relaxation factor
t	time (s)
T	temperature (°C)
T_0	reference temperature (°C)
u	velocity vector ($m\ s^{-1}$)
u^*	velocity field, corrected to prevent interface smearing ($m\ s^{-1}$)
U	phasic velocity ($m\ s^{-1}$)
V	volumetric flow rate ($m^3\ s^{-1}$)
$\dot{v}_{pc}$	volumetric dilatation rate due to phase change (s^{-1})
x	mass flow quality
x_i	position vector (m)
z	axial position from bubble pump inlet (m)

Greek characters

α	void fraction
α_1	liquid-phase-fraction in a mesh cell
$\dot{\alpha}_{1,pc}$	phase-fraction volumetric source due to phase change (s^{-1})
β	length fraction of Taylor-flow unit cell occupied by Taylor bubble
δ_f	liquid film thickness (m)
Γ	drift flux parameter in bubble velocity model
Δ	difference
θ	generic material property
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	fluid density ($kg\ m^{-3}$)
σ	surface tension ($kg\ s^{-2}$)
τ	shear stress ($kg\ m^{-1}\ s^{-2}$)
φ	volumetric flow rate through mesh cell faces ($m^3\ s^{-1}$)

Subscripts

0	non-limited value
avg	average value
b	Taylor bubble (in Taylor-flow model)
BPG	bubble pump generator
Ca	capillary scale
CF	coupling fluid
d	dynamic component of pressure drop
DevSlug	model assuming developing flow in liquid slug
evap	evaporation
f	cell-face value
hs	hydrostatic forces
i	initial value, inner tube, cell or node index in discretized model
in	inlet value
int	interface threshold value (in phase-change model), or interface position
L	liquid phase
L0	value for all channel flow being liquid
LS	large diameter tube scale
LV	phase change (liquid-to-vapor)
LW	value from Liu and Winterton boiling model [47]
mod	model value
o	outer tube
out	outlet value
r	radial component
s	liquid slug (in Taylor-flow model)
sat	saturated thermodynamic state
seg	segment value in discretized model
sim	simulation value
trans	flow-transition pressure drop
V	vapor phase
wall	domain wall or inside wall of steam tube
WF	working fluid
WK	value from model of Wadekar and Kenning [48]
z	axial component

flows, it is possible to evaluate spatially varying quantities and individually assess BPG sub-models.

A number of mature approaches have been developed to simulate adiabatic two-phase flows, including Volume-of-Fluid (VOF) [7], level set [8], direct interface tracking [9], and two-fluid Eulerian-Eulerian formulations. However, techniques for simulating two-phase flows with phase-change heat transfer are still in their infancy. Phase-change formulations generally incorporate a thermal-energy transport equation in addition to the governing flow equations, and apply appropriate phase-change source terms in the vicinity of liquid–vapor interfaces [10,11]. Such techniques can be applied to investigate developing two-phase flow phenomena in BPGs, enabling high fidelity assessment of incorporated sub-models. In the next section, reviews of prior work on *distributed-heated* BPGs and the most relevant phase-change flow simulation studies are presented.