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Influence of boiler size and location on one-dimensional two-phase vertical pipe flow

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A B S T R A C T

We study the evolution of flow and temperature of a fluid moving upstream in a long, thin vertical pipe when a boiler element is involved. The main goal of this work is to understand how the size and position of the boiler will affect the flow and temperature in the pipe over time, as current literature considers cases where the heater or boiler covers the whole length of the pipe, or when already boiling fluid enters a pipe without a boiler. Therefore, we shall allow for a boiling element which covers only a fraction of the pipe when devising out mathematical model. The boiling process results in a transition to different multiphase flow regimes, and we therefore consider a two-phase flow model. From this model, we obtained a simplified one-dimensional model, since we are concerned with a long, thin pipe, under reasonable assumptions and reductions which still preserve the desired physics. We performed a stability analysis for the boiling boundary denoting the phase change in this model. We then obtained numerical simulations for the steady and transient solutions. The numerical results suggest that both the size and position of the boiler strongly affect the flow regime. In particular, depending on the size of the boiler, transition to other phases might not always occur, and depending on its position along the pipe, the fluid coming out at the top of the pipe might not have the desired thermal profile. As such, one may tailor the position and size of the boiler element in order to obtain a useful thermal profile for particular applications. Such results are of possible relevance in industrial applications where heating or boiling of fluid is required.

1. Introduction

Multiphase flow is defined as any fluid flow consisting of more than one phase or component [1]. There are different stages that the multiphase flow takes when moving upwards along a pipe with some boiling action, called *flow regimes.* When evaporation begins, small gas bubbles begin to form near the walls of the pipe, which then detach and move along the liquid continuum. Such flow regimes are called *bubbly flows* [2]. When the spacing between the bubbles is large enough so that no collisions occur, we have the so called *dispersed bubbly flow*, while if collisions are frequent we have *dense bubbly flow* [3]. As the gas flow increases, the size of the bubbles increases and the flow regime is called *slug flow* [2]. The gas has the form of large Taylor bubbles, which have a bullet shape [3], and they are separated by liquid slugs. Smaller gas bubbles may also be present in the liquid slug [2]. As the gas flow rate increases further, the liquid slugs are penetrated by the gas [3], and as a result the slugs lose their structure [2], they fragment, and their contents fall [3]. The liquid is then lifted by the gas and the whole procedure repeats. This is the *churn flow* regime and is known to be chaotic [3]. For very high gas flows, the *annular flow* regime is observed. In this case, the gas and liquid flow as separate continuous phases [3] with the liquid forming a film at the pipe wall, surrounding the gas flow [2]. As evaporation continues, the liquid film eventually evaporates and a gas *disperse flow* is observed with small liquid droplets [2]. Disperse flows are defined as flows which consist of finite particles, drops or bubbles (the disperse phase) distributed in a volume of the continuous phase [1]. In general vertical two-phase flow regimes tend to be axisymmetric as the effect of gravity is parallel to the motion [4]. If any other forces exist that are not perpendicular to the flow direction then they might affect the axisymmetry of the flow [4]. The description of these flow regimes is not exhaustive, in fact there are eighty four different flow regimes suggested in literature [4], but not all apply to vertical upwards flow.

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Nomenclature

Roman symbols

α	gas volume fraction
β	liquid volume fraction
Γ	Rate of change of phase due to boiling
ρ_g	density of the gas phase
ρ_l	density of the liquid phase
A	cross-sectional area of the tube
a	Height at which the boiler starts
b	Height at which the boiler ends
C_{pg}	Specific Heat of the gas
C_{pl}	Specific heat of the liquid
E_g	Energy transport to the gas phase
E_l	Interfacial Energy transport to the liquid phase
F_{gi}	Interfacial stress on the gas phase
F_{gw}	Wall stress on the gas phase
F_{li}	Interfacial stress on the liquid phase
F_{lw}	Wall Stress on the liquid phase
f_{lw}	Friction factor from the wall
F_{meter}	force from the meter
h_g	enthalpy of the gas phase
h_l	enthalpy of the liquid
H_{gi}	Heat transfer coefficient of the gas phase
h_{gi}	Average interfacial enthalpy of the gas phase
H_{li}	Heat transfer coefficient of the liquid phase
h_{li}	Average interfacial enthalpy of the liquid phase
L	Length of the pipe
p	pressure
p_{out}	pressure at the top of the pipe
R	Ideal gas constant
$r(t)$	Boiling boundary
$s(t)$	Superheat boundary
T_g	Temperature of the gas phase
T_l	Temperature of the liquid phase
T_{gi}	Interfacial temperature of the gas phase
T_{li}	Interfacial temperature of the liquid phase
T_{sat}	Saturation temperature
u	velocity of the liquid phase
u_0	initial velocity of the liquid phase
v	velocity of the gas phase

Depending on parameter values, some regimes might not be possible. An important parameter is the size of the diameter of the pipe [3–5] which affects the existence or non-existence of some flow regimes. For example, Taitel *et al.* [5] suggested that bubbly flow can exist in small pipes only at high liquid rates. A detailed description of the conditions for transition to a different regime in upward gas-liquid flow in vertical pipes is given by Taitel et al. [5] and Rouhani et al. [4]. Boundaries and external conditions, such as the wall roughness, wall heat flux and flow acceleration, might also affect the flow regimes [4]. One of the most important effects of wall heat flux is dryout, where the liquid loses contact with the wall and as a result the local frictional pressure falls dramatically [4]. A reversed annular flow (a two-phase core is surrounded by a layer of steam in contact with the wall) is observed in this case [4].

There are three ways that multiphase flows can be studied: experimentally, theoretically through mathematical models, and through numerical simulations [1]. There are limitations however to how much experimental studies can resemble reality, and therefore proper mathematical models have to be derived that can be studied either theoretically or computationally [1]. There are different types of models that can be used to study two-phase flows, such as homogeneous, drift-flux, two-fluid [2], and slip flow models, each with its own limitations [6]. The drift-flux model is suitable in cases where gravity has a great effect such as flooding and flow reversal [6]. The slip flow model is suitable for high speed uni-directional flow [6]. The most important characteristics of two-phase flow is the presence of interfaces between each phase and the existence of moving boundaries between the different regimes which requires constitutive relations [6]. Each phase can be modelled separately, but having a multi-boundary problem makes it mathematically difficult or impossible to obtain analytical results [6]. The best approach to model a two-phase flow is through averaging, which essentially eliminates unwanted parameters [6]. There are three main types of averaging: Eulerian, Lagrangian, and Boltzmann statistical averages [6].

One goal for studying multiphase flows is to understand under what conditions instabilities might occur. There are different kinds of instabilities, depending on the system studied [2]. For example, a dryout, as mentioned earlier, might lead to failure (burnout or corrosion) of the system especially when this happens in a periodic manner [2]. Different types of instabilities exist such as quasi-static instabilities, concentration waves and dynamic instabilities although one can argue whether concentration waves can be characterised as instabilities [1]. In static-instabilities one considers phenomena that happen on a small time scale, such as transition to annular flow [7] under specific assumptions. Examples of quasi-static instabilities include the turbomachine surge [8,9] observed in compressors, fans, or pumps [1], Ledinegg instability [10] which usually occurs in coffee percolators [1], and Geyser instability [1].

Multiphase flow and boiling processes in pipes continues to be an active area of work in the literature [11–14]. There have also been studies on how one might best orient or design pipes for boiling flows [15,16], and also studies on how applied heating at the walls of pipe or other enclosures will modify the properties of such flows [17]. Generally, studies on boiling flow within a pipe fall either into the category of already boiling flows or the category of flows within a pipe with a single large boiler along the entire length of the pipe which generates the multiphase flow through applied heating at the surface of the pipe. Another option is to modify the region of the pipe on which there is a boiler. In many practical applications, particularly for long and thin pipes, one will find it excessive or inconvenient to have a boiler along the entire pipe length. However, to the best of our knowledge, there has been no systematic study of what will happen when only a fractional boiler is applied along a partial boundary around a long, thin pipe.

In the present paper, we are interested in developing a model for a cylindrical pipe that is heated with a boiler on the boundary in some region (not, in general, the entire pipe length), in order to better understand the thermal processes at play. Applications might include coffee makers [18,19], nuclear reactors, refrigerator systems [3], and thermosyphons [20]. Despite the potential applications, we did not find a study of two-phase vertical pipe flow due to a boiler over a segment of the pipe in the literature. As such, we are motivated to consider this problem. In Section 2, we obtain a one-dimensional model for the two-phase pile flow, under the assumption that the primary change in flow and thermal variables occurs with height. In order to better understand the influence of the various parameters used in this model, in Section 3 we