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Output-based modal control of three-dimensional pool-boiling systems

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ABSTRACT

Topic is feedback stabilisation of a nonlinear pool-boiling system in three spatial dimensions (3D). Regulation of its unstable (non-uniform) equilibria has great potential for application in micro-electronics cooling and thermal-management systems as well as for fundamental boiling experiments. Here, as a first step, stabilisation of such 3D equilibria is considered. A control law is designed that regulates the heat supply to the heater as a function of the Fourier-Chebyshev modes of its internal temperature distribution. This admits a controller that is tailored to the system dynamics, as these modes intimately relate to the physical eigenmodes. The internal temperature distribution is, similar to practical situations, estimated from a finite number of measurement positions on the heater surface by an observer. Performance of this output-based modal controller is demonstrated and analysed by simulations of the nonlinear closed-loop system. This provides first proof of principle of the proposed control strategy for the regulation of 3D boiling states.

1. Introduction

Ever smaller device sizes and higher power consumption permanently challenge thermal-management schemes for systems ranging from consumer and high-end micro-electronics [1–4] to batteries and high power-switching devices as e.g. insulated gate bipolar transistors (IGBTs) in electric vehicles (EVs) [5,6]. Key objective is maintaining device temperatures within operating limits under highly-dynamic conditions. Boiling heat transfer has the potential to tackle the growing thermal-management demands, as it affords heat-transfer capacities as well as thermal homogeneity substantially beyond that of conventional methods leaning on single-phase convective heat transfer by air or liquids [7,8]. However, full exploitation of boiling heat transfer is severely limited by the risk of "burn-out", the sudden formation of a vapour blanket on the device that leads to an abrupt collapse of the cooling capacity [9]. Insight into the dynamics underlying "burn-out" and ways to actively control it is imperative to overcome this hazard. Better control of boiling systems is furthermore of great relevance to fundamental experimental studies, which in general assume homogeneous conditions on the fluid–heater interface [10–12]. However, existing control loops in laboratory set-ups cannot always establish homogeneity; (momentary) heterogeneous conditions (e.g. dry spots) may occur. This may potentially compromise experimental studies. These issues motivate the present study, which aims at deepening insight into the dynamics of boiling systems and laying the groundwork for robust control strategies.

Pool-boiling may serve as physical representation for thermal management based on boiling heat transfer. Such systems in essence consist of a heater which is submerged in a pool of saturated liquid (Fig. 1). Pool-boiling is characterised by three boiling regimes, i.e. nucleate, transition and film boiling, through which the system evolves with increasing temperature [13]. The safe and efficient nucleate boiling regime is the desired state for thermal management. If the heat supply exceeds the so-called critical heat flux (CHF), the system switches to the film-boiling regime via the intermediate state of transition boiling. This transition is highly unstable and causes a sharp increase in temperature and decrease in heat flux due to the sudden formation of a thermally-insulating vapour film on the fluid–heater interface [9].

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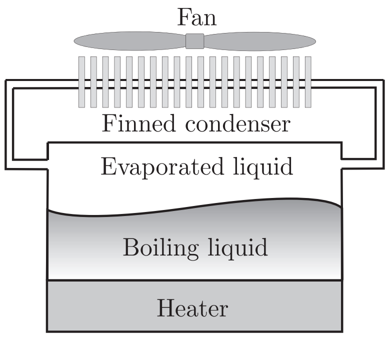

Fig. 1. Schematic representation of a pool-boiling system.

Utilising boiling heat transfer for thermal management (and in particular cooling) entails a trade-off between efficiency (close proximity to CHF) and safe operation (certain distance from CHF) (refer e.g. to Ref. [14]). Robust control strategies that safely facilitate boiling heat transfer close to CHF under dynamic operating conditions offer a promising solution, yet their realisation poses a formidable challenge. (Studies by Refs. [10–12] offer experimental proof that control in all boiling regimes is – in principle – possible.) The present study expands on [14], where transitional states in a two-dimensional (2D) pool-boiling model are stabilised, and takes a further step towards realisation of these control strategies by aiming at stabilisation of unstable transition-boiling states in a three-dimensional (3D) pool-boiling model. Moreover, in favour of the practical relevance of the analysis, only the temperature in a finite number of points – rather than the its full internal distribution – is considered available, similar to an actual controller based on temperature sensors. (Refer e.g. to Ref. [12] for temperature sensing in boiling systems.) The internal temperature field, required by the control law, is estimated from these measurements by an observer.

In this study pool-boiling systems are modelled by the 3D nonlinear heater-only model proposed in Ref. [15]. This model leans on the phenomenological connection between the local boiling mode and the interface temperature and describes the system dynamics entirely in terms of the internal temperature distribution within the heater. Successful stabilisation of the one-dimensional (1D) simplification of this model has been achieved in Ref. [16] by regulation of the heat supply via a linear state feedback based on the internal temperature profile. Stabilisation of a similar 1D system via P-control is discussed in Ref. [17]. (The 1D approach in essence models the beforementioned homogeneous boiling conditions assumed in experiments.) A 2D counterpart of the 1D control strategy from Ref. [16] is designed in Ref. [14]. Here this control strategy is further expanded to the 3D case and made more realistic by implementation of an observer to the control strategy.

Key to the proposed control strategy is the expression of the temperature profile within the heater by a Fourier-Chebyshev expansion, which are intimately related to the physical eigenmodes of the system. This modal-control strategy enables robust regulation of unstable states in the 1D and 2D system and significantly outperforms standard (PID) controllers [16,18].

The control strategy for the 3D system expands on that developed for the corresponding 2D simplification in Ref. [14]. An essential new element is the incorporation of an observer for estimation of the system state from the output in a finite number of positions. The output-based modal approach is demonstrated for the stabilisation of equilibria of the 3D nonlinear system. These equilibria have heterogeneous interfacial temperature distributions and are representative of transition boiling [19]. It must be stressed that stabilisation of such heterogeneous states is to be accomplished by uniform adjustment of the heat supply. This is a further element in favour of practical relevance.

This paper is organised as follows. In Section 2 the 3D nonlinear model is introduced and its equilibria are recapitulated. Furthermore, the stability behaviour of these equilibria is investigated. The controller-observer combination for stabilisation of the transition states is introduced in Section 4, including the methodology for efficient pole analysis. Performance of the linear controllers in the closed-loop nonlinear model is investigated in Section 5 by way of numerical simulations. Convergence of the discrete model to the original continuous system is examined in Section 6. Conclusions are drawn in Section 7.

2. Definition and open-loop analysis of the pool-boiling model

2.1. Three-dimensional model definition

The 3D pool-boiling system is modelled by the non-dimensional 3D heater-only model introduced in Ref. [15]. The heater consists of the 3D cuboid $\mathcal{H} = [0,1]\times[0,D]\times[0,H]$ (Fig. 2(a)), with $\mathbf{x} = (x,y,z)\in\mathcal{H}$ and boundary $\Gamma = \partial\mathcal{H} = \Gamma_H\cup\Gamma_A\cup\Gamma_F$. Scaling and orientation of the heater are such that the longest horizontal side coincides with the x-axis, meaning the relative heater width is restricted to $D \leq 1$. The boundaries are given by $\Gamma_A = \{\mathbf{x}\in\mathcal{H}|x = 0\vee x = 1\vee y = 0\vee y = D\}$ (adiabatic sidewalls), $\Gamma_H = \{\mathbf{x}\in\mathcal{H}|z = 0\}$ (uniform heat supply) and $\Gamma_F = \{\mathbf{x}\in\mathcal{H}|z = H\}$ (fluid–heater interface). Heat transfer inside the heater is described by the superheat $T(\mathbf{x}, t)$, i.e. the temperature excess beyond the boiling point of the fluid in which the heater is submerged, which is governed by

$$\frac{\partial T}{\partial t} = \kappa\nabla^2 T, \quad T(\mathbf{x},0) = T_0(\mathbf{x}), \tag{1}$$

with the corresponding boundary conditions

$$\left.\frac{\partial T}{\partial \nu}\right|_{\Gamma_A} = 0, \quad \left.\frac{\partial T}{\partial z}\right|_{\Gamma_H} = -\frac{1+u(t)}{\Lambda}, \quad \left.\frac{\partial T}{\partial z}\right|_{\Gamma_F} = -\frac{\Pi_2}{\Lambda}q_F(T_F), \tag{2}$$

with ν the outward normal on Γ_A, $T_0(\mathbf{x})$ the initial condition of the temperature excess and $q_F(T_F)$ the boiling heat transfer as a function of the interface temperature $T_F(x, y, t) := T(x, y, H, t)$. Variable $u(t)$ is the spatially uniform variation of the uniform heat supply at the heater bottom Γ_H by which temperature regulation is to be accomplished. The output $\mathbf{w}$ of the system (used for the state estimation) is measured on an equidistant grid of $(R+1)\times(S+1)$ points on the fluid–heater interface:

$$\mathbf{w} = [w_{00} \ \cdots \ w_{rs} \ \cdots \ w_{RS}]^T, \quad w_{rs} = T_F(\tilde{x}_r,\tilde{y}_s), \ (\tilde{x}_r,\tilde{y}_s) = \left(\frac{r}{R},\frac{sD}{S}\right) \tag{3}$$

The system is parameterized by the non-dimensional quantities Λ (non-dimensional thermal conductivity), κ (non-dimensional thermal diffusivity), D (relative heater width), H (relative heater thickness) and Π_2 (ratio critical heat flux to typical heat supply). Physical considerations imply $\Lambda H/\kappa = |1-\Pi_2|$, meaning the five parameters have only four degrees of freedom. Refer to Ref. [15] for a detailed discussion. Here (Λ, H, D, Π_2) is chosen as independent set and fixed at $(\Lambda, H, D, \Pi_2) = (0.2, 0.2, 1,2)$ unless explicitly stated otherwise. Parameters for heat-flux function q_F are fixed according to Ref. [14].

The nonlinear heat-flux function $q_F(T_F)$ describes the local heat exchange between heater and boiling fluid and, on physical