

# A Dynamic Film Model of the Pulsating Heat Pipe

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*This article deals with the numerical modeling of the pulsating heat pipe (PHP) and is based on the film evaporation/condensation model recently applied to the single-bubble PHP (Das et al., 2010, "Thermally Induced Two-Phase Oscillating Flow Inside a Capillary Tube," Int. J. Heat Mass Transfer, 53(19–20), pp. 3905–3913). The described numerical code can treat the PHP of an arbitrary number of bubbles and branches. Several phenomena that occur inside the PHP are taken into account: coalescence of liquid plugs, film junction or rupture, etc. The model reproduces some of the experimentally observed regimes of functioning of the PHP such as chaotic or intermittent oscillations of large amplitudes. Some results on the PHP heat transfer are discussed.*  
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**Keywords:** oscillating, pulsating, heat pipe, simulation

## 1 Introduction

The pulsating (or oscillating) heat pipe (PHP) is a long capillary tube bent into many branches and partially filled with a two-phase, usually single component, working fluid [1]. The tube is simple, and a wick structure is not required. The fluid spontaneously forms multiple vapor bubbles separated by liquid plugs inside the tube. Evaporation of liquid in the hot (evaporator) sections and subsequent condensation in the cold (condenser) sections create oscillations of the bubble-plug structure. These oscillations are very important because they lead to a substantial increase in heat transfer rate in comparison with other types of heat pipes [2]. In addition to the latent heat transfer characteristic for them, the sensible heat transfer is important in PHP. While sweeping a section belonging to an evaporator, a liquid plug accumulates the heat, which is then transferred to the condenser section when the plug penetrates there.

Because of their simplicity and high performance, PHPs are often considered as highly promising. Their industrial application is, however, limited because their functioning is nonstationary and thus difficult to be controlled. During the past decade, researchers have extensively studied PHPs [3]. Tong et al. [4], Miyazaki and Arikawa [5], Khandekar et al. [6], Xu et al. [7], Gi et al. [8], and Inoue et al. [9] carried out flow visualization studies with several working fluids. These experiments confirmed the existence of self-sustained thermally driven oscillations in PHPs. Several experimental groups [10–14] performed experiments with different tube diameters, configurations, orientations, and filling ratios and studied the thermal performance of PHPs in different conditions. However, the functioning of PHPs is not completely understood. A complicated interplay of different hydrodynamic and phase-exchange phenomena needs to be accounted for. The experimental studies of the background physical phenomena that cause the instability or are responsible for the PHP behavior are only few [14,15].

There are several modeling approaches available in the literature. Shafii et al. [16] initiated the modeling approaches for multi-branch PHPs. The evaporation-condensation mass exchange was accounted for with the temperature difference terms  $\propto(T_{\text{wall}} - T_i)$ , where  $T_{\text{wall}}$  was either  $T_e$  or  $T_c$  depending on the bubble location. The problem was solved numerically with the explicit Euler scheme. Periodical (nearly sinusoidal) oscillations appeared after

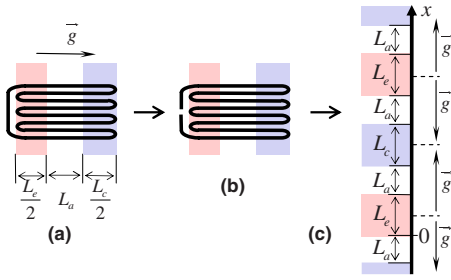
a transient. Their amplitude was small: The displacement amplitude did not exceed the evaporator size. It was concluded that the heat is transferred mainly via the sensible heat transfer; the latent heat transfer was an order of value smaller. The same model has been used later by another team [17].

It is well known from the analysis of the conventional heat pipes that in reality, most of the evaporation in the evaporator occurs through the liquid films that might cover only a part of the heated surface. Dobson [18,19] introduced a lumped meniscus model where the films are considered to be of constant thickness  $\delta_f$  but of varying length. Apart from the film introduction, the model was similar to that in Ref. [16]. Single-bubble PHP with an open end was considered. The oscillations were unstable and consisted of a nearly periodical pattern that began with a strong displacement during which the meniscus penetrated into the evaporator. This initiated high frequency declining to zero oscillations around an average position situated in the condenser. Das et al. [15] attempted to reproduce the results of Dobson with his model for the same parameters. They obtained only small amplitude periodical oscillations during which the meniscus never penetrated into the evaporator. They attributed the disagreement to the poor stability of the numerical algorithm (explicit Euler) used by Dobson. The fourth order Runge–Kutta method, well known to be stable, was used in Ref. [15]. A rigorous analytic analysis of a simplified version of the model, where the evaporation-condensation dynamics is modeled with the  $(T_{\text{wall}} - T_i)$  term, was also carried out by Das et al. An analytic expression giving the condition, under which the self-sustained oscillations appear, was obtained. It was shown that such a model leads necessarily to small amplitude oscillations.

A 2D model of the single-bubble PHP was considered by Zhang and Faghri [20]. A conceptual difference with the previous approaches concerned the vapor equation of state. Instead of the ideal gas model, the vapor was considered to be at saturation temperature  $T_{\text{sat}}$  corresponding to its pressure  $P$ . Small amplitude periodic nearly harmonic oscillations were obtained. Holley and Faghri [21] applied the same assumption to the PHP with spatially varying diameters.

Das et al. introduced the film evaporation-condensation model. The film is introduced similarly to Refs. [18,19]. The vapor mass exchange is assumed to be limited by the heat conduction in the film like in Ref. [20]. This leads to the mass exchange rate  $\lambda_l [T_{\text{wall}} - T_{\text{sat}}(P)] / (\delta_f h_{lv})$ , where  $T_{\text{sat}}(P)$  is the gas-liquid interface temperature. This approach is different from all previous approaches because a strong temperature gradient is assumed to exist in the vapor so that the temperature  $T$  of its bulk is allowed to

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**Fig. 1** (a) Sketch of the closed loop PHP with the default gravity direction. Evaporator is to the left. Topological transformations of the tube. (b) Unlooping. (c) Unbending and projection to the  $x$  axis. The splitting of the  $x$  axis to branches is shown.

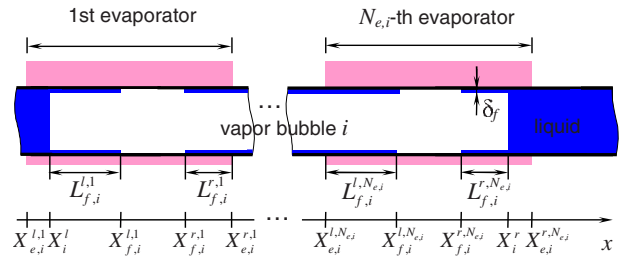
be different from  $T_{\text{sat}}(P)$ . The validity of this assumption is checked in Ref. [15] a posteriori. The simulations have shown that most of the time  $T > T_{\text{sat}}(P)$ . The same form of the mass exchange term has been used recently by Senjaya et al. [22]. They, however, did not use the variable films. The film evaporation-condensation model was validated against the single branch experiment [15]. It reproduces oscillations the amplitude of which might be larger than the size of the evaporator. The purpose of the present article is to apply it to the multibubble PHP. The closed loop PHP will be considered. The model, however, can be applied also to the unlooped PHP.

## 2 Problem Statement

Like in Refs. [16,17], the PHP meandering tube is projected to a straight axis  $x$  so that it consists of a periodic sequence of different domains corresponding to the PHP sections (Fig. 1). One PHP spatial “period” of length  $L_p = 2L_a + L_c + L_e$  is assumed to contain the sections in the following order: evaporator, adiabatic, condenser, and adiabatic. The point  $x=0$  is assumed to coincide with the beginning of an evaporator. The PHP branch is half of a period ( $L_b = 0.5L_p$ ) beginning in the middle of a condenser or an evaporator.  $L_t = N_p L_p$  is the total PHP length. Each bubble is identified by the index  $i$ . The neighbor from the right side liquid plug is denoted by the same index. The total number  $M$  of bubbles may change in time.

Unlike Ref. [16], the axis and the periodical pattern of sections on it are continued to infinity in both directions. At  $t=0$ , the bubbles are positioned at the axis and may move at  $t>0$  along the infinite axis  $x$  as far as needed. This means that the  $x$  value itself does not have any significance; only the relative positions are meaningful; they are determined with the remainder operator defined as  $y \bmod z = y - z \text{int}(y/z) \geq 0$ , where  $\text{int}(z)$  means the integer part of  $z$ , i.e., the largest integer smaller than  $z$ . For example,  $x$  belongs to the evaporator if  $x \bmod L_p \leq L_e$ . Since the PHP loop is closed, each point  $x$  is equivalent to the point  $L_t + x$ . Such an approach is convenient because it simplifies the management of any kind of bubble motion, particularly their unidirectional circulation. Within such a description, the coordinate  $X_i^l$  of the left meniscus of the bubble  $i$  is always smaller than that of its right meniscus  $X_i^r$ , and the bubble order does not change during their motion. Note that the coordinate  $X_M^r$  of the left end of the last liquid plug is larger than that of its right end  $X_1^l$ . The constant temperatures  $T_e$  and  $T_c$  are imposed at the inner walls of the evaporator and condenser.

**2.1 Film Dynamics in Evaporators.** According to the film evaporation/condensation model [15], the film length may vary because of two reasons: (i) evaporation or condensation and (ii) film deposition (Landau–Levich phenomenon) or film “eating up” during receding or advancing of the liquid meniscus, respectively. We generalize this model here to the case of multiple branches. The liquid film is assumed to always cover the inner walls of the



**Fig. 2** Vapor bubble  $i$  that extends over  $N_{e,i}$  evaporators and the liquid films inside it

tube (i.e., to be continuous) in the condenser and adiabatic sections when the whole bubbles or their parts are located inside them. The film may be partially or completely evaporated in the evaporator. The films are assumed to have a homogeneous thickness  $\delta_f$  in all the sections.

Let us consider the  $i$ th bubble that may extend over several PHP bends or, equivalently, evaporators (Fig. 2). The number  $N_{e,i}$  of pairs of films per bubble (left and right each) coincides with the number  $\text{int}(X_i^r/L_p) - \text{int}[(X_i^l - L_e)/L_p]$  of evaporators to which at least a part of the bubble belongs if the latter quantity is nonzero. In the opposite case,  $N_{e,i}=1$  to describe the continuous film in the adiabatic and condenser sections. The evaporators are counted left to right by the index  $k=1, \dots, N_{e,i}$ . The (non-negative) lengths of the left and right films of the bubble in the  $k$ th evaporator are denoted as  $L_{f,i}^{l,k}$  and  $L_{f,i}^{r,k}$ , respectively. When the film in the evaporator is not continuous, their dynamics is described by the equations (see Eq. (26) of Ref. [15])

$$\dot{L}_{f,i}^{l,k} = \begin{cases} 0 & \text{if } L_{f,i}^{l,k} = 0, \dot{X}_i^l > 0, \text{ and} \\ & X_i^l \in k\text{th evaporator} \\ -\dot{m}_{fe,i}^{l,k}/(\rho_l \pi d \delta_f) & \text{if } X_i^l \notin k\text{th evaporator} \\ -\dot{m}_{fe,i}^{l,k}/(\rho_l \pi d \delta_f) - \dot{X}_i^l & \text{otherwise} \end{cases} \quad (1)$$

$$\dot{L}_{f,i}^{r,k} = \begin{cases} 0 & \text{if } L_{f,i}^{r,k} = 0, \dot{X}_i^r > 0, \text{ and} \\ & X_i^r \in k\text{th evaporator} \\ -\dot{m}_{fe,i}^{r,k}/(\rho_l \pi d \delta_f) & \text{if } X_i^r \notin k\text{th evaporator} \\ -\dot{m}_{fe,i}^{r,k}/(\rho_l \pi d \delta_f) + \dot{X}_i^r & \text{otherwise} \end{cases} \quad (2)$$

where the dot means the time derivative. Evidently, the condition “ $X_i^s \in k$ th evaporator” may be satisfied only for  $k=1$  if  $s=l$  and for  $k=N_{e,i}$  if  $s=r$ . The mass evaporation rate at the  $k$ th evaporator  $\dot{m}_{fe,i}^{s,k}$  from the film  $s \in \{r, l\}$  is defined by the interfacial heat balance equation

$$h_{lv} \dot{m}_{fe,i}^{s,k} = U \pi d L_{f,i}^{s,k} [T_e - T_{\text{sat}}(P_i)] \quad (3)$$

As discussed in Sec. 1, the heat transfer coefficient is defined by the expression

$$U = \gamma \lambda_l / \delta_f \quad (4)$$

where  $\gamma \leq 1$  is a coefficient accounting for the spatial variation in the film thickness that exists in reality. The meaning of Eqs. (1) and (2) is simple: The film length may decrease due to evaporation or due to the meniscus advancing in the direction of the film edge (eating up of the liquid film). The film length increases when the film is left during the receding motion of the meniscus (Landau–Levich film deposition). It is assumed that the triple contact line (i.e., film edge) is pinned and does not recede in the absence of evaporation.

The coordinates of the left and right film edges in each of  $N_{e,i}$  evaporators ( $X_{f,i}^{l,k}$  and  $X_{f,i}^{r,k}$ , respectively) may coincide with one of the ends of the evaporator or with a position of a meniscus if the

corresponding film length is zero. Provided that  $X_i^l$ ,  $X_i^r$ ,  $L_{f,i}^{l,k}$ , and  $L_{f,i}^{r,k}$  are known,  $X_{f,i}^{l,k}$  and  $X_{f,i}^{r,k}$  can be determined from the following reasoning.

When no part of the bubble situates in evaporators,  $N_{e,i}=1$  and the film is continuous as mentioned above. This is equivalent to a junction of the left and right films at a point (denoted as  $X_j^l$ ) that needs to be chosen. This choice is of importance because in the simulation it defines the point of the film rupture that may occur. Therefore,  $X_j^l = X_{f,i}^{l,1} = X_{f,i}^{r,1}$  is assumed to coincide with the left or right meniscus (i.e., with  $X_i^l$  or  $X_i^r$ ), correspondingly to the direction of the bubble motion so that the evolution of the film edges exhibits no discontinuity when the Landau-Levich film begins to be deposited according to Eqs. (1) and (2).

When at least a part of the bubble situates in evaporators, one applies the following expressions to each of them ( $k = 1, \dots, N_{e,i}$ ):

$$X_{f,i}^{l,k} = \begin{cases} X_i^l & \text{if } X_i^l \in \text{kth evaporator} \\ X_{e,i}^{l,k} & \text{otherwise} \end{cases} + L_{f,i}^{l,k} \quad (5)$$

$$X_{f,i}^{r,k} = \begin{cases} X_i^r & \text{if } X_i^r \in \text{kth evaporator} \\ X_{e,i}^{r,k} & \text{otherwise} \end{cases} - L_{f,i}^{r,k} \quad (6)$$

Here,

$$X_{e,i}^{l,k} = L_p \left[ \text{int} \left( \frac{X_i^l - L_e}{L_p} \right) + k \right] \quad (7)$$

is the left edge of the kth evaporator and  $X_{e,i}^{r,k} = X_{e,i}^{l,k} + L_e$  is its right edge.

At some occasion, Eqs. (5) and (6) may result in  $X_{f,i}^{l,k} \geq X_{f,i}^{r,k}$  (i.e., in a small film overlap allowed in the numerical calculation where the time steps are discrete). This signifies an appearance of a continuous liquid film. The point  $X_j^k$  (where the film will disrupt should the film rupture occur) needs to be defined. It is assumed to coincide with the point of film junction where the film is thinner there and likely to be evaporated quicker than elsewhere. Once  $X_j^k$  is defined,  $X_{f,i}^{l,k}$  and  $X_{f,i}^{r,k}$  are reassigned to  $X_j^k$ . Next,  $L_{f,i}^{l,k}$  and  $L_{f,i}^{r,k}$  are recalculated with Eqs. (5) and (6).

**2.2 Remaining Vapor Bubble Governing Equations.** Condensation occurs to the film that surrounds a bubble portion  $L_{c,i}$  located in the condenser. Similar to the evaporation description, the film condensation rate  $\dot{m}_{fc,i}$  is defined by the expression

$$h_{lv} \dot{m}_{fc,i} = U \pi d L_{c,i} [T_{\text{sat}}(P_i) - T_c] \quad (8)$$

Although much weaker than at the film interface, the mass exchange occurs at the remaining meniscus part (its portion of the size  $L_m \ll d$  adjacent to the tube wall) and exists even if the film is evaporated completely. The heat balance on the meniscus depends on whether the meniscus  $s \in \{r, l\}$  situates inside the evaporator or the condenser,

$$h_{lv} \dot{m}_{me,i}^s = U_m \pi d L_{me,i}^s [T_e - T_{\text{sat}}(P_i)] \quad (9)$$

$$h_{lv} \dot{m}_{mc,i}^s = U_m \pi d L_{mc,i}^s [T_{\text{sat}}(P_i) - T_c] \quad (10)$$

where  $U_m < U$  and

$$L_{me,i}^s = \begin{cases} L_m & \text{if } X_i^s \in \text{evaporator} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

$$L_{mc,i}^s = \begin{cases} L_m & \text{if } X_i^s \in \text{condenser} \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

The total bubble mass change rate  $\dot{m}_i$  can be expressed as

$$\dot{m}_i = \sum_{s=r,l} \left[ \sum_{k=1}^{N_{e,i}} \dot{m}_{f,i}^{s,k} + \dot{m}_{me,i}^s - \dot{m}_{mc,i}^s \right] - \dot{m}_{fc,i} \quad (13)$$

The energy equation of the  $i$ th bubble is [16,23]

$$m_i c_{vv} \dot{T}_i = \dot{m}_i R_v T_i + Q_i^{\text{sens}} - P_i S (\dot{X}_i^r - \dot{X}_i^l) \quad (14)$$

where the sensible heat exchange with the dry evaporator walls is described by the expression

$$Q_i^{\text{sens}} = U_v \pi d L_i^{\text{sens}} (T_e - T_i) \quad (15)$$

where  $U_v = 2\lambda_v/d$  (it is assumed that the boundary layer in the vapor is the tube radius) and

$$L_i^{\text{sens}} = \sum_{k=1}^{N_{e,i}} (X_{f,i}^{r,k} - X_{f,i}^{l,k}) \quad (16)$$

The vapor equation of state is approximated with the ideal gas equation

$$P_i = \frac{m_i R_v T_i}{S(X_i^r - X_i^l)} \quad (17)$$

Note that the ideal gas assumption is used [16,23] while deriving Eq. (14).

**2.3 Liquid Plug Governing Equations.** The  $i$ th liquid plug, i.e., that to the right of the  $i$ th bubble, has the mass

$$m_{l,i} = \rho_l S (X_{i+1}^l - X_i^r) \quad (18)$$

where the index  $i+1$  denotes the bubble to the right of the  $i$ th bubble. The velocity  $V_i$  of the plug's center of mass is

$$V_i = 0.5 (\dot{X}_{i+1}^l + \dot{X}_i^r) \quad (19)$$

It obeys the momentum equation

$$\frac{d(V_i m_{l,i})}{dt} = (P_i - P_{i+1})S - F_i \text{sgn}(V_i) + G_i \quad (20)$$

where  $G_i$  is the gravity term discussed below. The viscous friction force  $F_i$  is defined by the expression corresponding to the single phase friction [18]

$$F_i = \frac{1}{2} K d \rho_l \pi (X_{i+1}^l - X_i^r) V_i^2 \quad (21)$$

$$K = \begin{cases} 16 & \text{Re} < 1 \\ 16/\text{Re} & 1 \leq \text{Re} < 1180 \\ 0.078 \text{Re}^{-0.25} & \text{Re} \geq 1180 \end{cases}$$

$$\text{Re} = |V_i| d / \nu \quad (22)$$

As in the previous modeling approaches, an additional contribution of the bends to  $F_i$  is neglected.

The liquid is assumed to be incompressible. This implies that the liquid plug volume may vary because of only two reasons: (i) phase change at its menisci and (ii) liquid film deposition or, on the contrary, eating up. The velocity of the plug ends relative to its center of mass and is thus nonzero and is defined by the change in the plug volume. This condition leads to the following condition of liquid mass balance in the plug:

$$\dot{m}_{l,i} = \dot{m}_{me,i+1}^l - \dot{m}_{mc,i+1}^l + \dot{m}_{me,i}^r - \dot{m}_{mc,i}^r + \pi d \delta f_l$$

$$\left\{ \begin{aligned} & \dot{X}_{i+1}^l \text{ if } X_{i+1}^l \in \text{evaporator and } \dot{X}_{i+1}^l < 0 \\ & \dot{X}_{i+1}^l \text{ if } X_{i+1}^l \in \text{evaporator, } \dot{X}_{i+1}^l > 0, \text{ and } L_{f,i+1}^{l,1} \neq 0 \\ & 0 \text{ otherwise} \end{aligned} \right\} - \left\{ \begin{aligned} & \dot{X}_i^r \text{ if } X_i^r \in \text{evaporator and } \dot{X}_i^r > 0 \\ & \dot{X}_i^r \text{ if } X_i^r \in \text{evaporator, } \dot{X}_i^r < 0, \text{ and } L_{f,i}^{r,N_{e,i}} \neq 0 \\ & 0 \text{ otherwise} \end{aligned} \right\} \quad (23)$$

The first of the three options in both braces corresponds to the film deposition, and the second corresponds to the film eating up. The

equations for  $\dot{X}_i^l, \dot{X}_i^r$  need to be obtained from Eqs. (18), (19), and (23). It is evident that  $\dot{X}_{i+1}^l \approx \dot{X}_i^r \approx V_i$  within quite small terms of the order  $\delta_f/d$  and  $\rho_v/\rho_l$  that describe the liquid volume variation. For this reason,  $V_i$  can be used in the conditional clauses of Eq. (23) instead of  $\dot{X}_{i+1}^l, \dot{X}_i^r$ . The set of Eqs. (18), (19), and (23) becomes linear and can be solved straightforwardly for  $\dot{X}_i^l, \dot{X}_i^r$ . We do not, however, write their explicit expressions here because they are cumbersome.

The liquid volume variation was neglected in previous works. It is introduced here to provide the conservation of the total fluid mass in the PHP. A small error that arises when the conservation is violated accumulates and may become important at large simulation times.

**2.3.1 Gravity Term.** The gravity sign is constant along each PHP branch but alters between branches (see Fig. 1(c)). The default gravity direction coincides with the  $x$  axis direction within the branch number  $n=0$  that starts at  $x=0.5L_e$ . The gravity sign corresponding to the branch number  $n$  is thus  $(-1)^n$ . The branch number at a given  $x$  is

$$n_b(x) = \text{int}\left(\frac{x - 0.5L_e}{L_b}\right) \quad (24)$$

The branch numbers of the liquid plug left and right ends are therefore  $n_i^l = n_b(X_i^l)$  and  $n_i^r = n_b(X_{i+1}^l)$ , respectively. The gravity force reads

$$G_i = \rho_l S g \left\{ (-1)^{n_i^l} \left[ (X_{i+1}^l - \frac{1}{2}L_e) \bmod L_b - \frac{1}{2}L_b \right] - (-1)^{n_i^r} \left[ (X_i^r - \frac{1}{2}L_e) \bmod L_b - \frac{1}{2}L_b \right] \right\} \quad (25)$$

It is evident that for  $n_i^l = n_i^r$  (i.e., when the entire plug belongs to one branch),

$$G_i = m_{l,i} g (-1)^{n_i^l} \quad (26)$$

The inclination angle  $\theta$  of the PHP with respect to the vertical direction can be simulated by replacing  $g$  by  $g \sin \theta$ .  $\theta = \pi$  can be used to describe the opposite (condenser on the top) PHP position.

**2.3.2 Heat Diffusion in Liquid.** The temperature distribution in the liquid plug  $T_{l,i} = T_{l,i}(x, t)$ , where  $x \in (X_i^r, X_{i+1}^l)$ , is governed by the heat diffusion equation [16],

$$\frac{\partial T_{l,i}}{\partial t} = D \frac{\partial^2 T_{l,i}}{\partial x^2} + D \frac{4\text{Nu}}{d^2} (T_{\text{wall}} - T_{l,i}) \quad (27)$$

The last term accounts for the heat transfer with the tube wall [16]. The Nusselt number depends on the plug velocity and length. The expressions for Nu for different ranges of Re are taken from Ref. [24].  $T_{\text{wall}}$  is  $T_e$  or  $T_c$  depending on where  $x$  situates. The last term is absent at all if  $x$  belongs to the adiabatic section.

The boundary conditions for Eq. (27) are given at the menisci,

$$T_{l,i}(X_i^r) = T_{\text{sat}}(P_i) \quad (28)$$

$$T_{l,i}(X_{i+1}^l) = T_{\text{sat}}(P_{i+1}) \quad (29)$$

Note that all previous equations of the model are independent of  $T_l$  because  $T_e$  and  $T_c$  are imposed and independent of the heat load. Equation (27) can thus be solved *after* the calculation of the PHP dynamics. In our numerical code, it is, however, solved together with all other equations so that the boundary conditions where  $T_e$  and  $T_c$  depend on the heat load could be easily implemented in the future.

**2.4 Heat Exchange Rates.** The instantaneous sensible heat power taken by the  $i$ th bubble-plug pair from the evaporator is calculated with the following expression:

$$Q_{e,i}^{\text{sens}} = 2\pi\lambda_l \int \text{Nu}(T_e - T_{l,i}) dx + Q_i^{\text{sens}} \quad (30)$$

where the integration is performed over the portion of the liquid plug located in the evaporator. The heat power given to the condenser is calculated accordingly,

$$Q_{c,i}^{\text{sens}} = 2\pi\lambda_l \int \text{Nu}(T_{l,i} - T_c) dx \quad (31)$$

where the integration is performed over the portion of the liquid plug located in the condenser. The instantaneous latent heat power taken by the  $i$ th bubble-plug pair from the evaporator is

$$Q_{e,i}^{\text{lat}} = h_{lv} \sum_{s=r,l} \sum_{k=1}^{N_{e,i}} m_{f_{e,i}}^{s,k} \quad (32)$$

That given to the condenser is

$$Q_{c,i}^{\text{lat}} = h_{lv} m_{f_{c,i}} \quad (33)$$

The instantaneous heat power is the sum of the corresponding terms over all bubbles of the PHP,

$$Q_s^k = \sum_i Q_{s,i}^k \quad (34)$$

where  $k \in \{\text{sens}, \text{lat}\}$  and  $s \in \{e, c\}$ . The total heat power reads

$$Q_s = Q_s^{\text{lat}} + Q_s^{\text{sens}} \quad (35)$$

In the stationary regime, the condition

$$\langle Q_c \rangle = \langle Q_e \rangle \quad (36)$$

where the angle brackets mean that time average should be valid for long enough averaging times: The amount of heat taken from the evaporator should be equal to that given to the condenser.

**2.5 Bubble-Plug Events.** There are several kinds of events that can change the bubble-plug morphology. They cause a change in the equations to be solved on the next time step. One of such events, the film junction, was described in Sec. 2.1. It changed equations but conserved their number. In this section, we rather discuss the events that change the number of both differential equations and unknowns.

First, it is the vapor bubble recondensation. It occurs when a moving liquid plug overtakes another plug. The vapor pressure grows and fast condensation occurs. A bubble located between two plugs completely disappears, and a new long plug forms. Its mass is a sum of the masses of the parent plugs, and its velocity is determined from the momentum conservation. On the next time step, the number of bubble-plug pairs drops by 1, and the number of equations reduces accordingly.

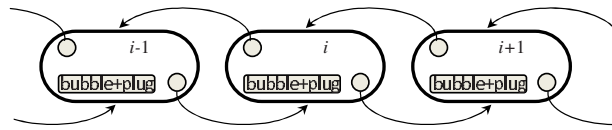
Another event met very often is a change in the number of liquid films. Such an event occurs when a bubble penetrates into an extra evaporator or, on the contrary, withdraws from it. The  $N_{e,i}$  number then changes, which means that the number of differential equations (1) and (2) changes, too. Other yet nonimplemented events include the vapor bubble creation by boiling or the complete liquid plug evaporation.

### 3 Numerical Implementation

The spatial integration of Eq. (27) is performed at each time step and needs to be discussed first.

**3.1 Spatial Integration of the Heat Diffusion Equation.** The  $i$ th plug is divided into  $N_{l,i} + 2$  finite elements  $\Delta x_i^k$ . All (except two ending) elements are of the same length; two ending elements are half-length. The element length varies slightly from plug to plug to keep the total number of elements integer. The node points  $X_i^k$  are in the centers of the internal  $N_{l,i}$  elements. The node temperatures are denoted as  $T_{l,i}^k$ . The temperature values at  $X_i^0 = X_i^r$  and





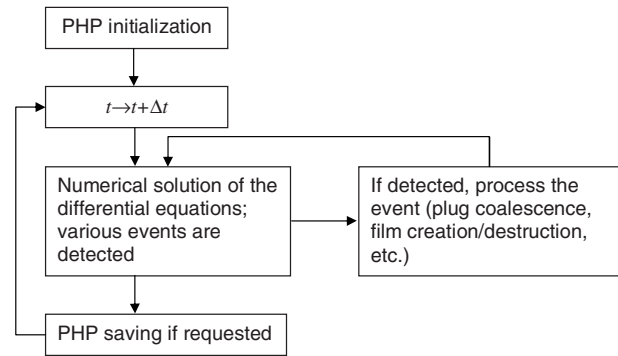
**Fig. 3 Computer representation of the instantaneous state of the PHP as a doubly connected list. Each of its node (an oval) contains the state of a bubble-plug pair and two pointers (circles) to the previous and to the next nodes.**

$X_{i,i+1}^{N_{l,i}+1} = X_{i+1}^l$  are given by the boundary conditions (Eq. (28)), so that there are  $N_{l,i}$  unknown temperatures per plug. The finite volume method [25] is used, and Eq. (27) is integrated over each element. This results in the following discrete analog of Eq. (27) written for  $k=1, \dots, N_{l,i}$ :

$$\frac{\partial T_{l,i}}{\partial t} \Big|_k = \frac{2D}{\Delta x_i^k} \left( \frac{T_{l,i}^{k+1} - T_{l,i}^k}{\Delta x_i^{k+1} + \Delta x_i^k} + \frac{T_{l,i}^k - T_{l,i}^{k-1}}{\Delta x_i^k + \Delta x_i^{k-1}} \right) + D \frac{4Nu}{d^2} (T_{\text{wall}} - T_{l,i}^k) \quad (37)$$

**3.2 Data Structure.** The code is object oriented and is written with C++. All variables are dynamically allocated. The code can thus deal with a PHP with arbitrary PHP geometry and time-varying number of plugs, bubbles, and liquid films. The code makes use of the Microsoft Foundation Class (MFC) library to take advantage of the serialization (saving and restoring to/from data files) of the objects of the unknown in advance size. Each vapor bubble or liquid plug is implemented as a C++ object and encapsulates a number of scalar and vector “member” variables proper to each of them. The  $i$ th bubble scalar members include  $T_i, m_i, P_i, X_i^l, X_i^r, N_{e,i}, Q_{c,i}^{\text{lat}}, Q_{e,i}^{\text{lat}}$ , a unique bubble identification number, and a pointer to the neighboring (from the right) liquid plug. The pointer is simply a computer memory address where the target object is located. The pointer may have a null value to indicate the plug absence, which is useful to simulate the last bubble in the unlooped PHP. In the present article, only the closed loop PHP is considered so that each bubble has a plug. The vector member variables of the bubble include the liquid film lengths and edge coordinates. They are allocated dynamically so that their length  $N_{e,i}$  may vary. The scalar plug variables include  $V_i, m_{l,i}, N_{l,i}, Q_{c,i}^{\text{sens}}, Q_{e,i}^{\text{sens}}$ , and a pointer to its (left neighbor) bubble. The vector members of a plug are  $\Delta x_i, X_i^r$ , and  $T_{l,i}$ .

In the remaining part of this section, the term PHP is used to denote the instantaneous state of all its bubbles and plugs. PHP is implemented as a doubly connected list (Fig. 3). The doubly connected list is an array, the  $i$ th node of which contains the data (of a bubble and its plug) and the pointers to both previous and next nodes. Note that in this case,  $i$  is an identifier of the node rather than its sequential number. The previous and the next nodes are denoted as  $i-1$  and  $i+1$ , respectively, just for the sake of illustration. The double connectivity allows fast access to these variables. Unlike the conventional (e.g., FORTRAN) arrays, such data structures can contain objects of different and variable lengths. This is convenient for several reasons. One of them is that the objects corresponding to plugs may contain the vectors of different and time-variable sizes  $N_{l,i}$ . The lists are convenient for another reason. Unlike the standard arrays, the list nodes are not necessarily written continuously into the computer memory. Therefore, it is very easy to suppress or, on the contrary, add a node somewhere in the middle of the PHP (which corresponds to the bubble recondensation or nucleation, respectively) without modifying the whole PHP in the computer memory. It is easy to understand from Fig. 3. Consider the suppression of the  $i$ th node. It consists in the redirection of the upper pointer of the node  $i+1$  to the node  $i-1$  and of the lower pointer of the node  $i-1$  to the node  $i+1$  (Fig. 3). The variables of the plug  $i-1$  are changed to account for the plug coalescence, as described in Sec. 2.5, and their numerical meshes



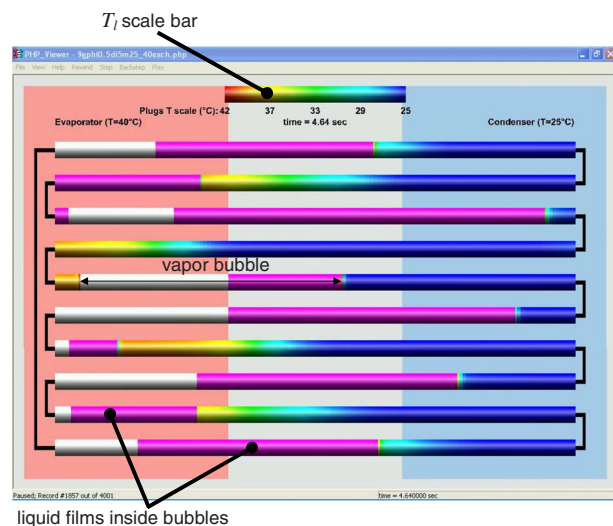
**Fig. 4 General scheme of the C++ program**

used for liquid temperature calculation are merged. The  $i$ th node can then be de-allocated (i.e., the memory occupied by it is liberated). These changes do not concern other nodes, so they are not modified at all. The standard array implementation would require the change in indices and a complete rewriting of the whole PHP into the computer memory, which would slow down the execution because the corresponding amount of information is quite large. For the closed loop PHP, the list is looped, i.e., a pointer belonging to the last node points to the first node and vice versa.

The PHP states at different time moments are recorded as another list. As previously, the standard array cannot be used because the memory amount required for each PHP state may be different and is unknown in advance. This “PHP list” needs to be only simply connected, which means that each node contains the PHP and a (single) pointer to the next node. This pointer allows the sequential access to the PHP states, e.g., for plotting. The PHP list may also be saved to a data file of a specific .php format that can then be read by the post-processing utility described below.

**3.3 General Algorithm.** The set of ordinary differential equations consists of Eqs. (1), (2), (13), (14), (20), (23), (19), and (37), which total to  $\sum_i^M (2N_{e,i} + N_{l,i} + 5)$  equations. Unlike previous works [16,17,22], they are written in the conventional differential form so that their numerical integration can be performed with any numerical method (and not only with the explicit Euler method used in Refs. [16,17,22]). The fourth order Runge–Kutta method (Fig. 4) is used here. It is renowned for its numerical stability and is thus better than the explicit method that can cause oscillations of numerical origin. The evaluation of the right-hand sides of the equations may lead to a detection of an event that changes the number of equations (see Sec. 2.5). If detected, the event is processed as discussed in Sec. 3.2. The number of equations and the equations themselves are updated, and the time step is recalculated.

**3.4 Data Post-Processing.** The number of PHP variables is large and changes in time. The data analysis is impossible without a clear understanding of the position of each meniscus and film edge with respect to the PHP sections at each time moment. In the absence of a suitable commercial software, a specific data post-processing “PHP\_VIEWER” utility had to be developed. PHP\_VIEWER possesses a conventional Microsoft Windows graphic user interface (Fig. 5). The name of the .php file is displayed close to the application name at the top of the screen above the menu. Some auxiliary information (the sequential number of the PHP record and the corresponding time) is shown in the status bar at the bottom of the screen. The evaporator (left) and condenser (right) locations are represented with rectangles, the width of which is to scale with respect to the PHP (see Fig. 1). The condenser and evaporator temperatures are displayed above them. The time of the current record is shown in between. The topology of the PHP bends is shown schematically with black connectors. The tube diameter is not to scale. The liquid temperature in the plugs is



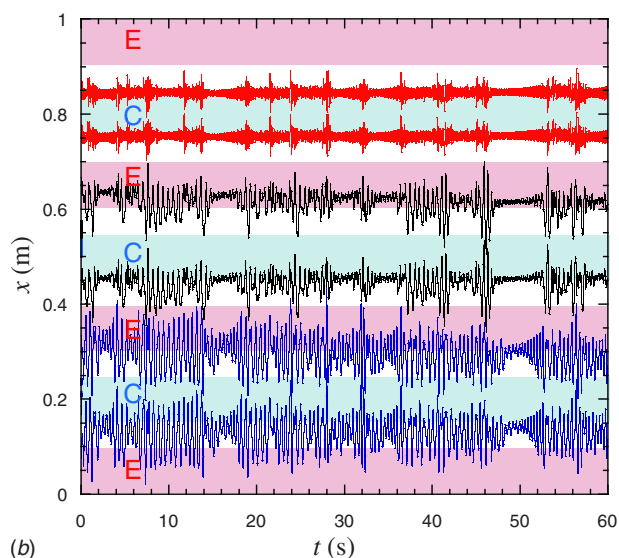
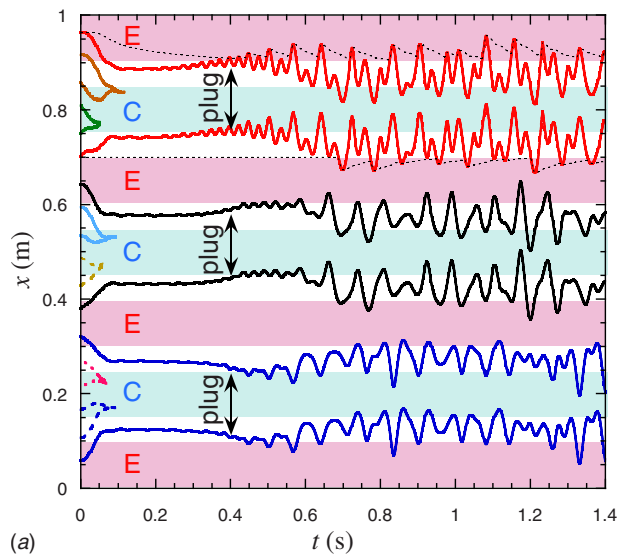
**Fig. 5** The screen of the PHP\_VIEWER version 1.6 in the liquid temperature visualization mode. The liquid films partially cover the internal tube walls inside the vapor bubbles. The temperature is indicated with coloring of the liquid plugs.

represented with a color. There are menu items usual for any video player. They allow controlling the animation speed and the navigation inside the data file (stepping record by record, jumping to a record with a given number, etc.).

#### 4 Results and Discussion

The simulation runs were performed for the numerical parameters shown in Table 1. The initial temperature of the fluid was chosen to be homogeneous and equal to  $0.5(T_e + T_c)$ . The equidistant bubbles are distributed along the PHP. The menisci are initially at rest.

It is well known [6] that there are many different regimes of PHP functioning. The present modeling shows some of them, particularly the regime of chaotic oscillations (Fig. 6). Its early stage is illustrated in Fig. 6(a). Since the number of bubbles can only be reduced during the PHP evolution, their large number (usually 9) is chosen initially. Figure 6(a) shows that the positions of some menisci join each other at  $t < 0.2$  s. This corresponds to the bubble recondensation that occurs inside the condenser. The bubbles keep disappearing until only one per evaporator remains. The liquid gathers in the condenser under the action of gravity (see Fig. 1(a)). The film that remains in the evaporator does not, however, evaporate instantly (see the upper dotted line in Fig. 6(a)). This may cause an instability of the system, i.e., the devel-



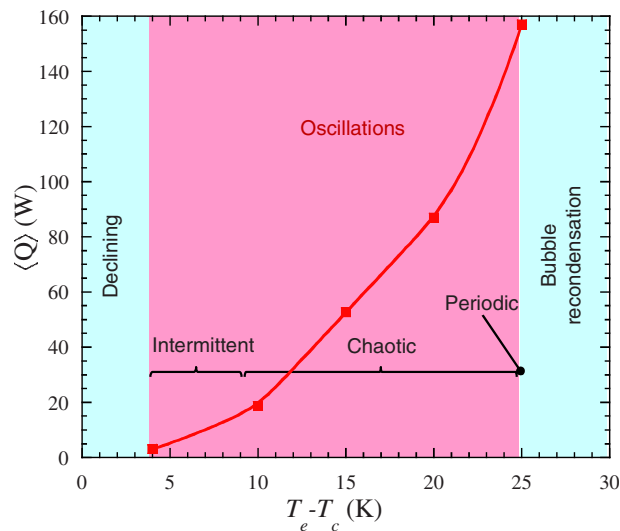
**Fig. 6** Examples of the chaotic oscillation regime within the linear PHP representation schematized in Fig. 1(c). Evaporator (E) and condenser (C) sections are shown with the background bars; adiabatic sections are in between. PHP is shown partially with evolution of only several menisci. (a) Short-time evolution. The bubble recondensation occurs at an early stage. The evolution of only two film edges is shown by dotted lines. (b) Long-time evolution for  $T_e = 45^\circ\text{C}$ ,  $T_c = 25^\circ\text{C}$ ,  $\phi = 0.55$ , and  $\delta_f = 40 \mu\text{m}$ .

**Table 1** Parameters used for the numerical simulation

PHP parameters	
Fluid	Water
$N_p$	5
$d$	5 mm
$L_e$	10 cm
$L_c$	10 cm
$L_a$	5 cm
Constants	
$\gamma$	0.47
$L_m$	0.2 mm
$U_m/U$	0.3
$\Delta t$	$10^{-4}$ s

opment of oscillations. Their amplitude grows during a short transient before attaining the developed oscillation regime. The amplitude in this regime depends on the parameters (see below) and may be large. During large oscillations, the menisci penetrate both into the condenser and the evaporator. The films persist in the evaporator; the film length oscillates (see the dotted lines). The liquid volume change is almost invisible so that both ends of each liquid plug oscillate synchronously. A portion of the  $x$  axis corresponding to three plugs is shown in Fig. 6. They seem to oscillate quite independently. Even the amplitude of their oscillations may be different: Compare the lower and upper plugs in Fig. 6(b). The long-time PHP evolution (Fig. 6(b)) shows that the oscillations are indeed chaotic: No periodic repetition can be mentioned. This is a dynamic chaos well known to occur in the complex systems.

The regimes of oscillations are convenient to be presented at the heat transfer curve (Fig. 7). The oscillation exists when the temperature difference  $\Delta T = T_e - T_c$  falls within a certain interval.



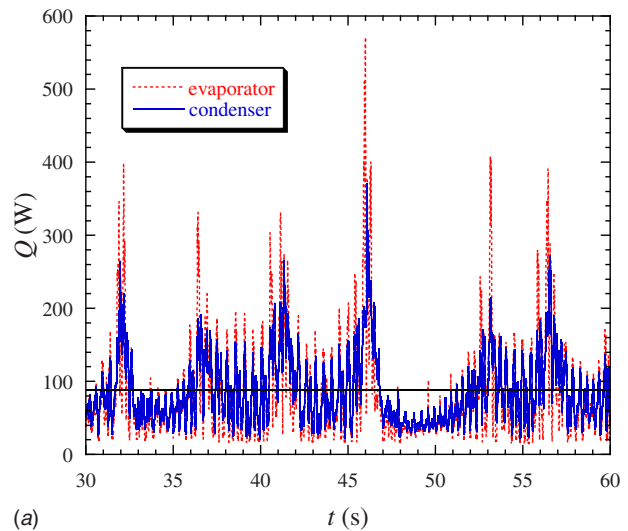
**Fig. 7 Heat transfer curve and PHP regimes for  $T_c=25^\circ\text{C}$ ,  $\phi=0.55$ , and  $\delta_f=40\text{ }\mu\text{m}$**

Within this interval, one may distinguish the chaotic regime discussed above and the intermittent regime. The latter is characterized by a sequence of intervals during which the system oscillates strongly and the periods of weak motion. Generally, the amplitude is very small near the lower oscillation threshold. Below the threshold, the oscillations decline to an equilibrium state where the vapor exists only in the evaporator and adiabatic sections, and the condenser sections are completely filled by the liquid. The pressure inside the bubbles becomes equal to the saturation pressure corresponding to  $T_e$ , i.e.,  $T_e=T_{\text{sat}}(P_i)$  for every  $i$ . This state is attained via condensation/evaporation, during which the mass of the vapor in each bubble relaxes to that required by the vapor equation of state. The films in the evaporator may exist, but their lengths do not vary any more (see Eq. (3), the right-hand side of which vanishes). At lower volume fractions, the liquid plugs do not fill completely the condenser sections so that the above equilibrium state cannot be attained: The heat exchange always exists. The stability of such a configuration is yet to be studied.

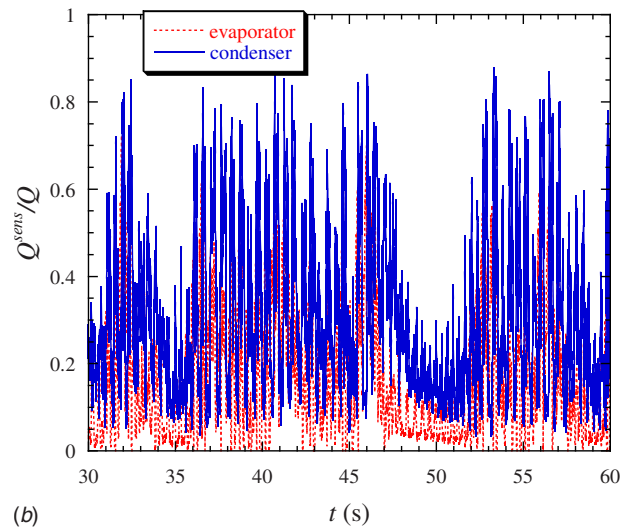
When  $\Delta T$  is larger than the upper oscillation threshold, the initial perturbation eventually declines. However, the scenario is different from the low  $\Delta T$  case. During the initial transient, the oscillations develop. Their amplitude becomes large like in the chaotic regime; the bubbles are compressed strongly between the plugs, which have different inertia and thus move with different velocities. At some point, one of the bubbles is compressed so strongly that it recondenses. This leads to a creation of a liquid plug with yet larger inertia, which causes the bubble recondensation in the chain that in most cases ends up in a creation of a single plug and a single bubble and the motion stops.

It is likely that the introduction of boiling will cause an instability of the final equilibrium state of the bubble recondensation regime. Indeed, in the final single-bubble state, the liquid situates necessarily in the evaporator, and the boiling should occur and cause a restart of the oscillations.

The oscillation regime depends strongly on the chosen value of the film thickness  $\delta_f$ . The influence of  $\delta_f$  was studied for the following set of the fixed parameters:  $T_e=35^\circ\text{C}$ ,  $T_c=25^\circ\text{C}$ , and  $\phi=0.55$ . It turns out that the  $\delta_f$  decrease leads to the same sequence of regimes as the  $\Delta T$  growth. At  $\delta_f>90\text{ }\mu\text{m}$ , the self-sustained oscillations are nonexistent. The  $\delta_f$  decrease leads to an appearance of the intermittent oscillations. Their amplitude grows as  $\delta_f$  decreases until the bubble recondensation appears and causes the oscillation disruption at  $\delta_f\approx 5\text{ }\mu\text{m}$ . This shows the importance of the  $\delta_f$  choice.



(a)

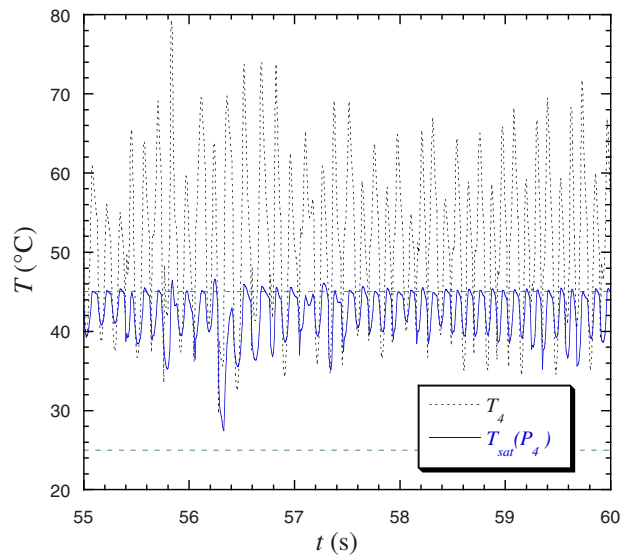


(b)

**Fig. 8 Examples of the PHP heat exchange rate evolution in condenser and evaporator for the same parameters as Fig. 6(b). (a) Total heat exchange. The time average  $\langle Q \rangle$  is shown with a horizontal line. (b) Part of the sensible heat exchange. The average values are 0.18 for evaporator and 0.29 for condenser.**

The heat transfer rate varies chaotically (Fig. 8(a)) during the oscillations according to the dynamics of the menisci. During the developed oscillations, equality (37) is satisfied within a few percent. The sensible heat exchange part may, however, be different in the condenser and in the evaporator (Fig. 8(b)). It is comprehensible since the condenser is occupied by the liquid most of the time. Accordingly, a part of the sensible heat exchange in the condenser is larger than that in the evaporator. The part of the sensible heat exchange increases with the amplitude of the oscillations because the liquid sweeps more often hot and cold walls. The average in time  $Q$  value is shown in Fig. 7 as a function of  $\Delta T$ . One can see that a quite efficient heat exchange can be achieved even without boiling, which is likely to lead to the continuation of the curve into the “bubble recondensation” region, as discussed above.

The temperature inside the liquid is inhomogeneous (see Fig. 5). One can see the thermal boundary layers that form near the menisci inside the liquid plugs. They appear because the pressure (and thus the gas-liquid interface temperature  $T_{\text{sat}}$ ) changes quickly during the oscillations;  $T_{\text{sat}}$  is sometimes 40–50 K larger



**Fig. 9 Typical evolution of temperatures obtained for a bubble from Fig. 6(b). The evolutions of the left and right ends of this bubble correspond to the third and second curves from the top of Fig. 6(b), respectively. The horizontal dashed lines correspond to  $T_c$  and  $T_e$ .**

than  $T_e$ . The analysis shows that the vapor pressures can also attain high values. The vapor temperature rises strongly due to this compression and can be essentially higher than  $T_e$  (Fig. 9). This has been already observed in the single-bubble modeling [15]. During the developed oscillations, the vapor is overheated: Its temperature exceeds  $T_{sat}$  by 10–20 K on average. This shows that the hypothesis [20,21] about the vapor at saturation temperature is hardly consistent.

The thickness of the boundary layers is different in different liquid plugs. It is defined by the value  $\sqrt{D\tau}$ , where  $\tau$  is an average period of the oscillations of a plug that grows with its mass.

## 5 Conclusions

A new model for PHP with an arbitrary number of branches and arbitrary time-varying number of bubbles has been presented above. It is more complex than the previous models and is capable of describing the chaotic self-sustained oscillations of large amplitude. It is shown to correctly reproduce some features of experimental models such as the intermittent oscillation regime. Some analysis of the flow in the PHP and the heat transfer has been performed. An oscillation threshold occurs at a small temperature difference. Another threshold, which occurs at a large temperature difference, would probably be yet larger if the boiling were taken into consideration. The boiling thus needs to be implemented.

More studies need to be performed even for the present formulation of the model. In particular, the influence of the initial conditions (initial values of  $M$ ,  $T_i$ ,  $X_i^s$ , etc.) might be of importance because the system is chaotic.

To perform more realistic modeling, more information is required on the phenomena that occur during the PHP functioning. In particular, it is a priori evident that a strong viscous dissipation occurs in the liquid films and near the contact lines (i.e., film edges). This effect leads to an additional pressure drop across each meniscus. The available literature information on this phenomenon is scarce. The effect of the PHP bends on the pressure drop should be accounted for. The film thickness is an important parameter, which is imposed here to be constant and is taken to be micrometric like in previous works [18,19]. However, it depends on the plug velocity and possibly on the evaporation/condensation rate and should thus vary with time. Third, the vapor compression

has not yet been assessed experimentally. It is not clear if the liquid plug return force is caused entirely by the evaporation/condensation effect (assumed in the models where the vapor was always at a saturation temperature) or also by the vapor compression like in the present approach.

## Acknowledgment

Two of my students, B. Pottier and A. Tanniou, participated in the development of the simulation code during their four month internship in our laboratory. Their contribution is gratefully acknowledged as well as the corresponding CEA/SBT grants.

## Nomenclature

$c_{vv}$	= vapor specific heat at constant volume (J/(kg K))
$D$	= liquid heat diffusivity (m <sup>2</sup> /s)
$d$	= tube diameter (m)
$F$	= viscous friction force (N)
$G$	= gravity force (N)
$g$	= gravity acceleration (m <sup>2</sup> /s)
$h_{lv}$	= latent heat (J/kg)
$K$	= friction coefficient
$L$	= length (m)
$M$	= total number of bubbles or plugs
$m$	= mass (of vapor by default) (kg)
$N$	= total number
$n$	= sequential branch number
$Nu$	= liquid Nusselt number
$P$	= vapor pressure (Pa)
$Q$	= heat exchange rate (W)
$R_v$	= vapor gas constant (J/(kg K))
$Re$	= liquid Reynolds number
$S$	= tube section area (m <sup>2</sup> )
$T$	= temperature ( $T_i$ of the vapor) (K)
$t$	= time (s)
$U$	= heat transfer coefficient (of film transfer if no indices) (W/(K m <sup>2</sup> ))
$V$	= velocity ( $V_i$ of the liquid plug) (m/s)
$X$	= absolute position at the $x$ axis (m)

## Greek Symbols

$\Delta$	= difference
$\delta_f$	= liquid film thickness (m)
$\gamma$	= coefficient in Eq. (4)
$\lambda$	= heat conductivity (W/(m K))
$\nu$	= liquid kinematic viscosity (m <sup>2</sup> /s)
$\phi$	= volume fraction of liquid in PHP
$\rho$	= density (kg/m <sup>3</sup> )

## Superscripts

$k$	= index
$l$	= left
$lat$	= latent
$r$	= right
$s$	= $r$ or $l$
$sens$	= sensible

## Subscripts

$a$	= adiabatic
$b$	= branch
$c$	= condenser
$e$	= evaporator
$f$	= liquid film
$i$	= bubble or plug identifier
$j$	= film junction
$l$	= liquid
$m$	= meniscus
$p$	= PHP spatial period



$s$  =  $e$  or  $c$   
 sat = at saturation  
 $t$  = total  
 $v$  = vapor  
 wall = internal tube wall

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