Walks of bubbles on a hot wire in a liquid bath

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Abstract – When a horizontal resistive wire is heated up to the boiling point in a subcooled liquid bath, some vapor bubbles nucleate on its surface. The traditional nucleate boiling theory predicts that bubbles generated from active nucleate sites grow up and depart from the heating surface due to buoyancy and inertia. However, we observed here a different behavior: the bubbles slide along the heated wire. In this situation, unexpected regimes are observed; from the simple sliding motion to bubble clustering. We noticed that bubbles could rapidly change their moving direction and may also interact. Finally, we propose an interpretation for both the attraction between the bubbles and the wire and for the motion of the bubbles on the wire in terms of Marangoni effects.

The self-propulsion of a droplet has attracted a growing interest. It has been shown that it is possible to move a droplet in a controlled way using magnetic [1] or electrical [2] fields, vibrating bath [3], circular hydraulic jump [4] but also by changing the wetting condition [5,6] or even the geometry [7]. Another propulsion mechanism is the Marangoni effect: it could be thermal [8–10] or chemical [8,11–13]. Surprisingly only few papers considered self-propulsion mechanisms for bubbles (this question is, for instance, marginally presented in [14]).

In the present letter, we will address the question of self-propelled bubbles on a horizontal heated wire immersed in a liquid bath. The bubbles considered here are generated by nucleate boiling on the wire but, as shown, our results are more generally applicable.

When such a metallic wire is heated up to the boiling point in a subcooled liquid bath some vapor bubbles nucleate on its surface. In the literature, it is admitted that these bubbles, generated from active nucleate sites, grow up and depart from the heating surface, experiencing buoyancy, inertia and wetting forces (e.g., [15]).

What we observed is that, for a silicone oil bath, beyond a threshold in injected power \( P \) (corresponding to the silicone oil boiling temperature) bubbles effectively nucleate on the wire surface but instead of what is commonly expected, they immediately begin to move along the wire. Typical images of this bubble motion are depicted in fig. 1 and can be seen in the video Free_d.m4v supplied as supplementary material. One can see on these pictures a thermal plume attached to each bubble. These plumes are the signature of the liquid refractive index variation due to heating. One can also notice that bubbles are interacting: when two bubbles come into contact they can bounce (see fig. 1 between 0.04 s and 0.07 s) or fuse (see fig. 1 between 0.00 s and 0.02 s).

![Succession of images of bubbles moving on the wire](http://example.com/video.png)
A. Duchesne and H. Caps

Such phenomena (bubble motions, bouncing and fusion) were already observed by Peng et al. [16] in an experimental setup approaching the one described here. They used horizontal heated platinum sub-millimeter wires immersed in water or alcohol subcooled baths. They were so in partial wetting condition.

In the present letter, we completely renew the description of the phenomenon and its comprehension. In particular we bring two major improvements to the setup proposed by Peng et al.: the use of silicone oil for the liquid bath and the choice of constantan for the metallic wire. Choosing silicone oil for the liquid bath ensured a complete wetting state and so increased deeply the reproducibility of the observed phenomena since wetting hysteresis and contact forces are now avoided. The use of constantan, a metallic alloy with a temperature-independent electrical resistivity, allows us to use the injected power as a well-defined controlled parameter and so to present the first phase diagram for sliding bubbles on a heated wire. This methodical analysis led us to the discovery of a rich collection of behaviors for bubbles on a thin wire.

The present paper is divided in two parts: a first part focusing on the mechanism of attraction between a bubble and a heated wire and a second part describing the different regimes observed in the experiment and the associate propulsion mechanism.

**Experimental setup.** – A sketch of the experimental setup is depicted in fig. 2. A horizontal 5 cm long resistive wire of diameter $\phi \in [0.1; 1]\ mm$ immersed in a liquid bath is fed by an electric generator through two large aluminum electrodes with a negligible resistivity. The wire is thus heated up through Joule’s effect with current setting up to 64 A so that the injected power $P$ may reach 200 W. The surrounding liquid bath is constituted by 1.5 L of low viscosity silicone oil (with a kinematic viscosity $\nu \approx 1.5\ cS$ and a density $\rho \approx 950\ kg\ m^{-3}$) and maintained at a constant temperature $T_{\text{bath}} \in [5^\circ C; 95^\circ C]$. In order to keep a constant temperature for this liquid bath, it is thermalized using a water-bath.

The setup is completed by a fast camera acquiring at a rate of 1000 fps placed in front of the wire in a horizontal plane.

**Bubble-wire interaction.** – The first question we would like to address is: why do the bubbles not simply leave the wire after a rapid growth? In a complete wetting situation, it is admitted that when a bubble nucleates at a surface, its maximal size is fixed by a balance between buoyancy, inertia and viscous friction (see for instance [17]). At the time and length scales considered here, inertia and viscous forces appear to be totally negligible compared to buoyancy. The absence of contact force is also ensured by the use of silicone oil.

To explain this intriguing phenomenon, we suggest that the bubbles visible in fig. 1 are no more in contact with the wire surface and that a layer of liquid separates the bubble from the solid. This hypothesis is in agreement with observations made by Lu and Peng [18] in a partial wetting situation. Thus, a possible scenario is that microscopic bubbles (up to few tens of microns) nucleate on the wire surface and then depart from the wire surface but keep attracted by it. Following this scenario we must now understand why bubbles remain attracted by the wire even if they are not in direct contact with it.

Taking into account the temperature differences relative to the bubble appearance, we interpret this attraction as resulting from Marangoni stresses: the bottom of the bubble being close to the wire, the temperature at the bubble bottom should be close to the boiling temperature of the liquid, $T_{\text{boil}}$, whereas the top of the bubble is further from the thermal boundary layer and so closer to the bath temperature $T_{\text{bath}}$. As described in the literature [19], such a temperature difference leads to a surface tension difference. The latter may lead to an overpressure which might compensate buoyancy and the convective flow caused by the heated wire (see fig. 3(a)).

However, one should recall that a bubble internal temperature difference cannot be achieved if the bubbles are only constituted by a pure vapor of silicone oil at the equilibrium state. Two hypotheses can then be proposed to overcome this apparent difficulty: bubbles are constituted either by dissolved gases (e.g., air) or by gases resulting from the degradation of the silicone oil due to the heating. To conclude on the validity of our hypotheses, we injected air bubbles close to the wire using a syringe and we observed exactly the same behaviors below and above the silicone oil boiling point (see the supplementary video Air-Liq.mp4). This complementary experiment increases significantly the strength of our arguments on Marangoni’s force as driving mechanism. It also reveals the large scope of the present study: the free-motion regime (described further) appears to be the general behavior of all bubbles composed by a mixture of gases in a similar setup.
correspond to
φ
black triangles to
=0
φ
is the value predicted by eq. (3). Insert: R
bath temperature is T
Marangoni flows. (b) R
traction between the bubble and the wire: the temperature dif-
Fig. 3: (Colour online) (a) Sketch showing the mechanism of at-
ments considered here. Assuming the case of a bub-
thermal plume) is typically 25 mm
3
πρgR
4
. For millimetric bubbles, F
boil
−
Ma
= 200 °C, T
bath
= 25 °C and γ′ = 5.5 · 10−5 N m−1 K−1 [21] we get R
max
≈ 1 mm. This prediction is experimentally tested by measuring the radius of departure of the bubbles while neglecting the sudden departures resulting from fusions. The comparison il-
illustrated in fig. 3(b) shows a rather good agreement in
terms of order of magnitude and all the measurements
are below the theoretical limit. Moreover, all points col-
clude line is the value predicted by eq. (3). Insert: R
max
vs. T
bath
with
= 0.4 mm and P = 55 W. The continuous black curve is a
fit of the experimental data with a law in √ΔT.

In order to propose an order of magnitude approach, we
assume a 2D constant thermal gradient around the bubble
reading G = (T
boil
− T
bath
)/ΔT, where R is the bubble radius.
Marangoni’s force reads

\begin{equation}
F_{Ma} = \int_S \gamma \frac{d\gamma}{dS} dS = \int_S \gamma \frac{d\gamma}{d\tau} dS,
\end{equation}

with γ the surface tension and γ′ = \frac{d\gamma}{d\tau}. In the vertical
direction, we obtain:

\begin{equation}
F_{Ma_z} = \frac{4}{3} \pi R \gamma' \Delta T,
\end{equation}

with ΔT = T
boil
− T
bath
.

We balance this force with the buoyancy force F_A = \frac{4}{3} \pi \rho g R^3 (with ρ the liquid density and g the acceleration
due to gravity) and the friction due to the convective flow v_{liq}
caused by the heated wire, F_D = \frac{1}{2} \rho v^2_{liq} \pi R^2 C_D (with C_D the drag coefficient acting on the bubble). Direct measurements using injected particles show that the flow velocity due to the heated wire (i.e., outside the bubble thermal plume) is typically 25 mm/s for all the experiments considered here. Assuming the case of a bub-
ble in a constant velocity flow, one can estimate C_D =
16/Re + 2 [20]. For millimetric bubbles, F_A/F_D \sim 10
meaning that the force exerted by the wire convective flow
(surely overestimated in the previous approximation) is
negligible, to a first order, compared to buoyancy.

Balancing F_{Ma_z} with the buoyancy F_A leads us to the
maximal radius before the bubble departure:

\begin{equation}
R_{max} = \sqrt{\frac{\gamma' \Delta T}{\rho g}}.
\end{equation}

Taking T
boil
= 200 °C, T
bath
= 25 °C and γ′ = 5.5 · 10−5 N m−1 K−1 [21] we get R
max
≈ 0.75 mm at large P values. The expected square
root dependency of R_{max} with ∆T is tested in the inset of
fig. 3(b) and the agreement validates our approach.

Considering that the origin of the attraction between
the wire and the bubbles is answered, we will look closer
at the motion of the bubbles on the wire. We will evidence
and describe two different regimes: the “free motion” and
the cluster.

**Free-motion regime.** – Beyond the boiling threshold,
the first regime we observe is named “free-motion” regime
and corresponds to bubbles freely circulating on the wire.
It is illustrated in fig. 1 and in fig. 4(a) and (b). This
regime differs from what can be observed with partially
wetting liquids where bubbles may remain motionless up
to their departure [16]. On the contrary, in the present
situation, the bubbles are observed to move soon after their
appearance. For a horizontal wire, there is no preferential
direction for the bubble displacement. Direct observations
also reveal that bubbles may appear and move above or
beneath the wire, even if the top position is more stable
due to buoyancy.

We have observed a range of bubble diameter D from
the resolution size of the camera (∼10 μm) up to millime-
ter length. The bubble size always increases with time, ei-
ther by evaporation or by fusion with another bubble. As
described previously, beyond a critical radius R_{max} bub-
bles leave the wire due to buoyancy.

As P is increased, the bubble density d (i.e., the number
of bubbles per unit of length) increases as well. This ef-
efect is evidenced by the comparison between fig. 4(a) (low
density) and fig. 4(b) (high density), where the density is
increased by more than one order of magnitude.

The bubble velocity V can reach 100 mm/s, which is
typically one hundred times a bubble diameters per sec-
ond. Figure 4(a) is a spatio-temporal diagram taken 50 μm
above the wire surface. One sees that the maximal veloc-
ity is almost the same for all the bubble diameters. This
result is particularly surprising, given that the Reynolds
number \( Re = \frac{VD}{\nu} \) (where \( \nu \) is the kinematic viscosity assumed to be homogeneous around the bubble) typically ranges between 5 and 200, suggesting that inertia should play a role. When the bubble density becomes too important, the large bubbles never reach their maximal velocity due to the too frequent interactions with smaller bubbles (see fig. 4(b)). Nevertheless, even at high bubble density, the small bubbles reach a maximal velocity very close to the one observed before. In that sense one can conclude that the maximal velocity \( V_{\text{max}} \) on the wire depends only very slightly on the injected power \( P \). This is visible in fig. 5, where \( V_{\text{max}} \) is plotted vs. \( P \) for \( \phi = 0.4 \text{ mm} \) and \( T_{\text{bath}} = 25^\circ\text{C} \). \( V_{\text{max}} \) increases very slightly with the injected power.

**Thermal boundary layer.** The existence of a thermal boundary layer plays a crucial role in the proposed propulsion mechanisms of bubbles along the wire. We will therefore address this question more in depth. The boundary layer thickness, \( \delta \), is given by the typical length where the convection overcomes the conduction and so by a critical Rayleigh number. Thanks to the seminal work of Boetcher [28], the critical Rayleigh number around a horizontal cylinder can be estimated between 1 and 10. Therefore the order of magnitude for the boundary layer thickness is one hundreds of microns.

This estimated thickness stands for the thermal boundary layer of one-phase liquid around the wire. In the presence of bubbles, this thickness could be modified. Indeed, bubbles moving along the wire will remove the boundary layer. If we assume that a bubble mixes entirely the boundary layer on its path, we can estimate the growth of \( \delta \) as

\[
\delta(t) \sim \sqrt{kt},
\]

As far as we know, Peng et al. have never compared their model with direct measurements (although numerical simulations provided a good agreement [25,26]). We verified that, in our situation, these arguments were credible. We balanced the component of \( F_{\text{Ma}} \) in the wire direction with the drag friction and the creation of a dynamic meniscus (with the coefficients extracted from [27]) and obtained that a temperature difference \( \Delta T_{\text{prop}} \) of only a few degrees (typically 5 K) is enough to obtain the observed velocities.
where $\kappa$ is the thermal diffusivity ($\sim 10^{-7} \text{m}^2/\text{s}$ for silicone oil). The typical time $\tau_d$ to fully develop the thermal boundary layer is 0.1 s. This estimated $\tau_d$ is much larger than the typical time between two bubble passages at a considered position and, therefore, the time average boundary layer thickness will be significantly smaller than the expected one in the non-evaporating (or static bubble) case. This latency time can be estimated as $\tau = 1/(dV)$ where $d$ is the bubble density (number of bubbles per unit of length) and $V$ is the average speed value for all the bubbles present on the wire. For a low density regime as in fig. 4(a), bubbles have almost the same velocity (independent of their radius) $V \approx V_{\text{max}}$ and we can estimate $\tau \approx 10^{-2} \text{s}$ and so $\delta \sim 30 \mu\text{m}$.

For a very dense regime, as in fig. 4(b), most of the bubbles are nearly motionless and so we can assume that the thermal boundary layer thickness is significantly larger than in the previous case and reach its maximal value.

This thermal boundary layer thickness has also an influence on $R_{\text{max}}$ and may explain the tendency observed in fig. 3(b). Even if we assumed a constant gradient in temperature along the entire height of the bubble, this gradient is in fact mainly concentrated in the thermal boundary layer. So, the Marangoni stress, obtained by the integration of the temperature gradient, will be smaller for a small value of $\delta$ and larger for a fully developed thermal boundary layer. This explains why when the bubble density is important we observe a plateau for $R_{\text{max}}$ at a value larger than the one observed for the low injected power (i.e., low density). For large $P$ values, the larger bubbles are almost motionless and the thermal boundary layer is thicker.

Clusters regime. – In the middle of the “free-motion” regime, we discovered an unexpected phenomenon: the appearance of clusters of a few (typically 5) motionless bubbles. These bubbles have a quite important size ($\sim 0.5 \text{mm}$) while smaller bubbles keep circulating between these clusters. This situation is visible in fig. 7(a) (see also the supplementary video Clusters_lq.m4v). If we further increase the heating power $P$, clusters expand over the whole wire up to cover it as a single motionless cluster (see fig. 7(b)). To be more precise, it is an almost motionless cluster: due to the heat transfer, bubbles grow up, may fuse and then leave the wire, leading to a reorganization of the bubbles on the wire. However, this process is very slow in comparison to our acquisition time (see the supplementary video Clusters_lq.m4v). If we further increase the injected heat ($\phi$ unchanged), we observe that this unique cluster dislocates into smaller clusters until this regime ends and the system comes back to the situation previously described where isolated bubbles move freely, the “free-motion” regime.

It is worth noticing that even if the organization and the dynamic of the bubbles totally differ from the “free-motion” regime, the density is similar to the one previously observed. This is also true for $R_{\text{max}}$, as reported in fig. 3(b), and for the wire temperature (observed using an iron steel wire in a complementary experiment). These observations indicate that these bubble clusters may be only the result of a statistical organization as, for instance, the one reported in [29].

One can also mention that such clusters are also observed in a system very similar to the one considered in the present article. Suematsu et al. reported that self-propelled camphor boats in a 1D system can form aggregates of different size [30]. One can notice that these boats are self-propelled using chemical Marangoni flows and so that they can “see” each other through the local chemical concentration. This is reminiscent of our experiment where bubbles can see each other through the thermal boundary size.

Phase diagram. – A phase diagram built with our two control parameters ($\phi, P$) is presented in fig. 8 and summarized all the different presented regimes. Red squares correspond to heating power values insufficient for bubbles nucleation on the wire surface (see fig. 8(a)).

Beyond the boiling threshold, the first regime we observed is the “free-motion” regime, where bubbles freely circulate on the wire. It is represented on the phase diagram by green diamonds. When $P$ is increased, the bubble density (i.e., the number of bubbles per unit of length) increases as well. This change of density is symbolized by an intensity gradient on the phase diagram (fig. 8).

For very high densities, when the wire is almost completely covered by bubbles, a small increasing of $P$ could dramatically change the system: one can see the
A. Duchesne and H. Caps

Fig. 8: (Colour online) Phase diagram at $T_{\text{bath}} = 25^\circ C$ built with our two control parameters: the wire diameter $\phi$ and the injected power $P$. Red squares correspond to a situation without bubbles (insufficient heating powers). Green diamonds stand for the “free-motion” regime and blue disks for the “clusters” regime. The dashed line represents the limit beyond which film boiling was observed. (a) $\phi = 0.2\text{ mm}$, $P < 10\text{ W}$. (b) $\phi = 0.2\text{ mm}$, $P = 17.5\text{ W}$. (c) $\phi = 0.2\text{ mm}$, $P = 10\text{ W}$. (d) $\phi = 0.2\text{ mm}$, $P = 30\text{ W}$.

appearance of a vapor film which will totally isolates the wire from the liquid bath. This phenomenon is called film boiling. Because of Rayleigh-Taylor instability, this vapor film is destabilized following a well-defined wavelength [31,32]. The dashed line in fig. 8 represents the limit beyond which film boiling was observed. (a) $\phi = 0.2\text{ mm}$, $P < 10\text{ W}$. (b) $\phi = 0.2\text{ mm}$, $P = 17.5\text{ W}$. (c) $\phi = 0.2\text{ mm}$, $P = 10\text{ W}$. (d) $\phi = 0.2\text{ mm}$, $P = 30\text{ W}$.

In the middle of this “free-motion” regime, the clusters regime is represented by blue disks. One can notice that for the largest wire, we do not observe the clusters regime. This could be explained by the fact that, for a larger wire radius, the bubbles diameters are of the same order or below the wire diameter and so motions in depth could be observed.

The presented measurements have been repeated in two different aquariums with different sizes. We verified that transitions between regimes do not change with the aquarium dimensions. We also checked that these transitions are not hysteretic. These pieces of information confirmed that the physical mechanisms implied in this experiment are located at the wire scale. Nevertheless, this is not the case for the film boiling regime. We observed dependences on the wire dimensions, on the wire fixation system and hysteretic transitions. We did not investigate further this regime, clearly beyond the scope of this study.

**Conclusion.** – In this letter, we evidenced different regimes for the behaviors of bubbles nucleated on the surface of a heated resistive wire immersed in a subcooled bath of silicone oil: bubbles can move along the wire and aggregate in clusters. We showed that the results obtained in the “free-motion” regime could be extended to the analogous system constituted by air bubbles on a hot thin wire in a subcooled bath. We proposed simple interpretations to the phenomena of attraction between the bubble and the wire or to the motion along the wire. The common point is thermal Marangoni flows. The comparison between these models and experimental evidences furnished convincing agreement, given the simplifying hypothesis we took.

This letter opens the door to a lot of different questions touching many fields in physics: for instance, we believe that the clusters regime can be seen as a statistical phenomenon, a simplified experiment with air bubble of controlled size could be of interest. The fact that the maximal velocity appears to be independent of the bubble radius is a very puzzling result from an hydrodynamical point of view and, once again, new experiments conducted with air bubbles could be of great interest. The interactions between bubbles, bouncing or fusion, remain also an open question. Moreover, preliminary experiments showed that the bubbles interact with the thermal boundary layer, does it constitute a new system with memory effects? To conclude, the thermal aspect of this experiment is also full of questions, among others: how is the thermal transfer influenced by this mechanism?

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Walks of bubbles on a hot wire in a liquid bath

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