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On the interfacial deformations and thermal characteristics exhibiting self-similar behavior under the action of a line heat source

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Abstract

Interfacial dynamics resulting from a heating source located near the interface play a crucial role in dictating the heat and momentum transport in the near-interface region. This paper aims towards simultaneous characterization of interfacial deformation and thermal behavior under the action of a line heating source placed below the interface. Experiments have been conducted on aqueous glycerol with a heating wire at different power inputs and depths from the interface. The interfacial deformations are mapped and quantified by employing moon glade background oriented schlieren, which offers real-time, non-intrusive whole field measurements based on the deflection of light rays from liquid interface. Infrared thermography is used to measure transient interfacial temperature variations. Results show that the interface exhibits a convex-shaped deformation under the influence of the heating wire for all cases of heating power and depth. The maximum interface temperature coincides with the peak interfacial deformation. However, the region of thermal influence is smaller compared to the deformed region. Non-dimensionalization of transient interface deformation and temperature profiles establishes the underlying similarity of the phenomenon as non-dimensional interface perturbation profiles overlap for all cases of height and heating power. These characteristics are also observed for normalized temperature profiles at different wire depths.

Keywords: Interface; Near-interface flow; Self-similar behavior; Moon glade background oriented schlieren; Infrared thermography

1. Introduction

Interface deformation under the influence of heating inside a liquid domain has been a subject of immense interest for a long time. This is due to its implications in circulations near the interface and near-surface convection, which affect the heat and mass transfer in the region (Kurosaki et al. 1989; Hughes and Griffiths 2008; Chiu-Webster et al. 2008; Wählin et al. 2010)
as well as its pertinence to the manufacturing industry, where interface deformation may lead to poor surface finish, non-uniformity in paint and coating thickness (Anand 1969; Lavielle et al. 1998). The interface deformation results from the induced natural convection set about due to the temperature gradients prevailing between the interface and the liquid bulk. In this direction, as part of efforts made to develop a fundamental understanding of the phenomenon, different configurations of the process have been studied wherein the liquid is heated from the bottom through a plate or a wire (Wang and Huang 2005; Hughes and Griffiths 2008; Rudenko et al. 2022). Some studies have included heating or cooling of the interface to study the interface dynamics (Castillo and Velarde 1982; Burelbach et al. 1996). Different competing forces and mechanisms are at work, which bring about the deviation of the interface from its equilibrium position. As such, it is important to characterize these deformations to understand the interaction, and thus, the scales of various competing forces.

The driving force for the interface deformation is the vertical temperature gradient introduced between the liquid bulk (by a heating element) and the interface. This temperature gradient results in a convective flow rising from the heated region toward the interface. As the heat is transported to the interface (through the bulk fluid), surface tension gradients are established and Marangoni convection over the interface follows. The interface behavior is determined by these two competing phenomena; the convective flow driven by the vertical temperature gradient tends to deform the interface in a convex configuration by the action of rising convection currents/plumes from the locally heated region. On the other hand, Marangoni convection pulls the liquid away from the heated regions towards the colder region, thus resulting in concave-shaped interface deformation directly over the heating element. The behavior of the interface is thus dependent on the fluid transport properties as well as the position of the heating element and the heat flux supplied.

Following the experiments on free surface deformations by Bénard (Bénard 1901) and the instability analysis carried out by Pearson and Scriven & Sterling (Pearson 1958; Scriven and Sterling 1964) for a heated bottom surface, Kayser & Berg (Kayser and Berg 1973) studied the interface deflections induced in a shallow pool by a heating wire placed inside the liquid bulk. They identified different mechanisms of interface deformation for liquids (glycerol and silicone oil) based on varying surface tension. Fernandez & Sanz (Jiménez-Fernández and García-Sanz 1989) proposed an analytical formulation for the interface deformation in thin layers as a function of the thickness of the liquid layer. Roze & Gouesbet studied the behavior of wave propagation over the interface due to line heating based on a heated wire below the free surface (Rozé and Gouesbet 1997). They reported that under high heating rates and close
proximity of wire to the interface, unstable wave structures were observed leading to complex spatio-temporal behavior. The oscillations of the interface, referred to as ‘optical heartbeats’, originating from a wire maintained at a constant temperature were investigated by Weill et al. (Weill et al. 1985). The free surface deformations were determined by schlieren and shadowgraphy, and the critical temperature for the occurrence of these oscillations exhibiting laminar-to-turbulent transition was determined. Marchuk and Fedorets et al. performed numerical simulations for the deformations in thin liquid layers heated from above and below (Marchuk 2009; Fedorets et al. 2014). It was observed that the convective flow in the liquid layer enhanced the local deformations caused by the thermocapillary flow over the surface. Convective plumes rising from the heated wire and impacting the interface were captured by Vinnichenko et al. using IR thermography and background oriented schlieren (Vinnichenko et al. 2014a). Different surface layer characteristics were observed for water and ethanol which determined the heat transfer characteristics over the free surface. They identified that liquids having high surface tension exhibit a stationary free surface layer with the formation of large thermal cells. In another study, Vinnichenko et al. measured the surface deformations due to convection currents produced in Rayleigh-Bernard convection through bulk heating and by a heating wire under the interface (Vinnichenko et al. 2020). Recently, Rudenko et al. carried out a detailed study of near-interface horizontal convection caused by a heating wire along the interface (Rudenko et al. 2022). The study was carried out for water which features a stationary surface film, impeding Marangoni convection caused by thermal gradients over the interface. The variations of velocity profile and boundary layer thickness with heating power were established and a relation between the Nusselt number and Rayleigh number was arrived at.

It can be concluded from the above discussion that significant efforts have been made by a range of researchers toward quantifying the interface deformation resulting from the heating of the bulk liquid. These deformations have been attributed to the mutually competing buoyancy and thermocapillary forces, which gives an insight into the near-interface transport mechanisms. Thermocapillary forces, a prominent feature of the phenomenon, are directly associated with the interface temperature profile. Even though numerous studies have been carried out to understand the interface deformation phenomena associated with bulk heating, the combined (simultaneous) experimental measurements of interface temperature and deformations are scarce in the open literature. To the best of our knowledge, a relation between the interface deformation and the driving temperature gradient developed between the interface and the bulk fluid has not been explicitly reported. This would give an insight into the effectiveness of convection and thermocapillary forces which could be used to estimate the
flow patterns in the near-interface region. In an effort to bridge this research gap, the present work reports simultaneous measurements of interface deformation and the temperature field developed over the interface from a heating wire under the interface of an aqueous solution of glycerol (80% wt. glycerol). Infrared thermography has been employed to determine the spatio-temporal distribution of interface temperature. A non-intrusive reflective synthetic schlieren technique, commonly referred to as Moon-glade background oriented schlieren, is used to determine the free surface deformations. These techniques are used in tandem to understand the extent of thermal and hydrodynamic effects and behavior of the interface throughout the phenomenon. Experiments reported have been carried out by varying the heating rates and distance of the heating wire from the interface. The transient evolution of the interface and the driving temperature gradient have been presented to quantify the scales of different mechanisms associated with the phenomenon. The variation of the interface deformation and temperature for different heat fluxes and wire depths has been presented. It was observed that the interface was subjected to a convex-shaped deformation as soon as the heating was applied to the wire, while there was a definite lag between the heating and the change in interface temperature as the depth of the wire was increased. Subsequently, non-dimensionalizing the results obtained from moon-glade background oriented schlieren reveal that there is an underlying similarity for different cases of experiments that have been carried out in this study.

2. Experimental setup and methodology

The experimental setup was arranged to generate free surface deformations, visualize the time-varying whole field interface topography and quantify temperatures resulting from a heated horizontal wire placed under the interface. The schematic diagram of the experimental setup is shown in Fig. 1. The set-up consists of a PMMA (polymethyl methacrylate) cuboidal test cell (120×130×60 mm³), which contains the pool of the aqueous glycerol solution (80% wt. glycerol) of 25 mm depth. Due to the highly hygroscopic nature of glycerol, a diluted aqueous solution of glycerol was used for the present set of experiments to decrease the affinity of the liquid to absorb moisture from the atmosphere, which could lead to the possible change of the thermophysical properties over the course of the experimental runs. A nichrome wire (numbered as “2” in Fig. 1) of diameter \( D \) 0.3±0.02 mm was stretched under tension and maintained in a horizontal configuration by two wire holders, which were also used to adjust the distance of the wire from the interface. The distance between the interface and the wire was measured using a micrometer. The nichrome wire was connected to a DC power supply to heat the wire by passing a current through it. A k-type thermocouple was attached to the nichrome
wire to measure the temperature of the wire throughout the experiment. The liquid pool was open to ambient and the experiments were carried out at the ambient temperatures of 24-25°C with the relative humidity maintained at about 40%. Fig. 2 shows the cross-section view of the experimental configuration of the wire in the aqueous glycerol pool and the different flows present during the heating process. As indicated in Fig. 2 (b), the convex deformation of the interface is primarily due to the convective plume rising from the heated wire which impacts the interface. As heat is transported to the interface, temperature gradients and hence surface tension gradients are established over the interface (as surface tension is a function of temperature). These surface tension gradients give rise to thermocapillary flows over the interface from heated regions (lower surface tension $\gamma$) to regions at lower temperatures (higher surface tension $\gamma$).

The moon-glade BOS technique, employed in this study to characterize the interface deformation, is a reflection based schlieren technique. The configuration for this technique consists of a high-power LED light source (Phlox, 40 W, color 5700 K) adjusted over the top of the interface at an angle (~ 7°) with the horizontal. The light source is illuminated through a random dotted background pattern having an average dot size of 100 $\mu$m. The reflection of the
dotted pattern from the interface is captured by a digital camera (Basler acA2040) with a 7×zoom lens (Navitar) mounted opposite to the light source, as shown in Fig. 1. The images of the interface are captured at 1 frame per second (fps) with a resolution of 1500×1500 pixels.

For infrared (IR) thermography, an IR camera (FLIR X6540sc) was integrated with the setup to quantify the interfacial temperatures, as shown in Fig. 1. The IR camera was inclined at an angle of ~50° and recorded the phenomenon at 1 fps at a spatial resolution of 348×640 pixels. The IR camera was calibrated for the given configuration in order to determine the air-liquid interface emissivity. The calibration was carried out using a k – type thermocouple placed in the liquid bulk. The system was allowed to attain steady-state condition at different temperatures (24°C to 41°C) and the temperature was measured by the thermocouple immersed in the liquid. Simultaneously, interface temperature measurements were carried out using the IR camera. As glycerol has very low evaporation rates, the temperature of the interface and the bulk liquid can be considered to be the same at steady state. The two measurements showed similar temperatures for the interface emissivity of \( \varepsilon = 0.88 \) (see section S4 of supplementary information). Due to the inclination of the camera, keystone correction of the IR thermographs was carried out based on the pixel size obtained using a reference image of a rectangular object aligned with the interface. The uncertainties associated with the temperatures measured with the thermocouple and the IR camera were ±1° C. Both the digital camera and the IR camera were synchronized and triggered simultaneously and the setup was placed on a vibration-isolating optical table. The experiments were carried out for four different wire depths \( L \) ranging from 1 mm to 7 mm, while the pool depth was kept constant. At each wire position,
the thermal and hydrodynamic variations of the interface are studied at three different power inputs \( Q \) of 15, 20 and 30 W/m.

3. Data reduction methodology

Moon glade background oriented schlieren (MGBOS) is a reflective variant of BOS, a synthetic schlieren technique (Vinnichenko et al. 2020; Kochkin et al. 2022; Srivastava et al. 2022). BOS, in transmission mode, is employed for systems that have reasonable optical access through the bulk and is used to quantify the physical quantities by determining the displacement of the background pattern due to the changes in the optical path traversed by the light (Moisy et al. 2009; Raffel 2015; Shahdhaar et al. 2022; Shimazaki et al. 2022). Unlike the transmission mode, MGBOS can also be used for systems with limited optical access as the light need not pass through the entire medium but is reflected from the air-liquid interface. MGBOS is a technique to characterize the whole-field deformations in the interface non-intrusively based on the deflection of reflected light rays from the interface. The optical setup and the schematic ray diagram of MGBOS are shown in Fig. 3. The technique has a relatively simple setup compared to traditional schlieren techniques (Srivastava et al. 2022). A background pattern is
attached to a white light source and the reflection of the pattern from the free surface of the liquid is captured using a camera and lens system. When the interface undergoes deformation, there is a change in the angles of incidence of the light ray onto the interface and, thus, the reflected light rays are shifted by an angle twice that of the interface deformation. This results in an apparent displacement or distortion of the background pattern and these distortions can be related to the slope of the interface. In practice, a randomized dot pattern is used for the background as it provides better accuracy, lower bias and uncertainties in comparison to the symmetric patterns (Hargather and Settles 2012; Thielicke and Sonntag 2021).

Under paraxial approximation, the slope of the interface can be related to the displacement of the reflected pattern as (Vinnichenko et al. 2020):

\[
\frac{\partial h}{\partial x} = \frac{1}{2H} r_x
\]  
(1)

\[
\frac{\partial h}{\partial y} = \frac{1}{2H} r_y
\]  
(2)

where \( h \) is the height of interface perturbation from the undisturbed position, \( H \) is the distance between the illuminated pattern and the air-liquid interface, \( r_x \) and \( r_y \) are the \( x \) and \( y \) components of the displacement vector \( \mathbf{r} \), respectively. The displacement vectors are quantified by employing cross-correlation based particle tracking using Fast Fourier Transform (FFT) window deformation algorithm, which was implemented in MATLAB PIVlab toolbox (Thielicke and Sonntag 2021). The images of the reflected pattern captured using the digital camera (at different time instants after heating the wire) were compared against a reference image, with no perturbations, captured before heating [Fig. 4(a) and Fig. 4(b)]. Prior to tracking the displacements of the dots, the images were processed using CLAHE with a 64-pixel kernel for contrast enhancement and noise removal. In order to resolve the large as well as small displacement vectors, the images were analyzed by four interrogation passes with the interrogation window size 64 × 64 and 32 × 32 pixels for the first two passes followed by two passes with a size of 24 × 24 pixels with 50% overlap. Fig. 4(c) shows the displacement vectors obtained after tracking the displacement of the dotted pattern due to the interface deformation by cross-correlation of the deformed image with the reference image. The displacement fields in the \( x \) and \( y \) directions are shown in Fig. 4(d) and Fig. 4(e), respectively. The uniformly heated wire is placed along the \( x \)-direction and it can be observed that the displacement of the dots is primarily in the \( y \)-direction, which is perpendicular to the wire. The derived displacement vectors can be related to the slope of the interface by combining Equations (1) and (2) and rewriting as:
\[ \nabla h = \frac{p_{x\text{ratio}}}{2H} \hat{p} \]

where \( \hat{p} (= r_x \hat{i} + r_y \hat{j}) \) is the displacement vector field and \( p_{x\text{ratio}} \) is the ratio of pixel size (mm/pixel) of the illuminated dot pattern plane to the pixel size (mm/pixel) at the plane of the liquid free surface. The interface topology is reconstructed through the gradient field obtained from Equation (3) by numerical integration based on least square approximation with zero offset, as shown in Fig. 4(f) (see supplementary multimedia file for the transient background pattern deflection and evolution of the interface deformation and temperature.).

As mentioned earlier, consecutive images were captured at 1 fps and, thus, the correlation time interval for the analysis is \( \Delta t = 1s \). In order to determine the uncertainty in cross-correlation based particle tracking, the particle disparity method is used (Sciacchitano et al. 2013). The uncertainty thus obtained for an interrogation window of size 24 × 24 pixel was found to be 0.5 pixel. Based on this value, synthetic tests were performed during the data processing of the present data to determine the maximum uncertainty associated with the measurement of the interfacial perturbations. The uncertainty associated with the digital image correlation algorithm was introduced to the displacement fields \((r_x \text{ and } r_y)\), which were
numerically integrated to estimate the uncertainty propagation during the data processing in order to obtain the interface deformation. Gaussian noise with a mean corresponding to the displacement of 1 pixel and variance of 0.01 was introduced in the displacement fields, which were then integrated to obtain the interface profile. In these tests, the maximum uncertainty was calculated to be 1.6 $\mu$m. A series of images were also captured for the stationary or undisturbed interface to detect stochastic noise and errors, which turned out to be less than 0.2 $\mu$m.

3.1 Validation of methodology

In order to validate the experimental technique and the data reduction methodology, tests were conducted to quantify the interface deformation caused due to the presence of a heating wire placed under glycerol-air interface using a similar configuration as employed by Vinnichenko et al. (Vinnichenko et al. 2020). Fig. 5 depicts the comparison of the interface profiles obtained from the present set of experiments with the results reported by Vinnichenko et al. at different time instants. The convective plume rising over the heated wire impacts and deforms the air-glycerol interface with time. The spatial map of these transient interface deformations was captured and quantified using the Moon glade BOS technique. The interface has a prominent convex-shaped deformation, the extent of which amplifies with time. It is observed that the interface profiles obtained using the methodology discussed above (Moon glade BOS) is in close correspondence with the data from the open literature. The maximum difference between the peak deformations, as captured in the present work and that reported by Vinnichenko et al. (Vinnichenko et al. 2020), was seen to be 18.6% at time $t = 20$ s. This

![Graph showing comparison of interface profiles](image)

Fig. 5. Comparison of the surface profiles at different time instants for the present experimental configuration and Vinnichenko et al. (2020)
difference between the two results decreased with time reaching 6.9% at \( t = 80 \) s. However, the deformations observed in the present experiments were symmetric, while the data presented by Vinnichenko et al. exhibited asymmetry at higher time instants.

4. Results and discussion

In the present study, experiments were conducted by submerging a heating wire under the interface of an aqueous glycerol solution (80% glycerol by wt.). The properties of water, pure glycerol and aqueous glycerol solution used in the present study are given in Table I (Cheng 2008; Takamura et al. 2012).

**Table I.** Thermophysical properties of water, pure glycerol and aq. glycerol (80% glycerol by wt.) at 25°C

<table>
<thead>
<tr>
<th>Properties</th>
<th>Water</th>
<th>Glycerol</th>
<th>Aq. Glycerol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ( \rho ) (kg/m(^3))</td>
<td>997.05</td>
<td>1257.7</td>
<td>1204.8</td>
</tr>
<tr>
<td>Viscosity, ( \mu ) (N-s/m(^2))</td>
<td>8.9×10(^{-4})</td>
<td>0.9057</td>
<td>4.535×10(^{-2})</td>
</tr>
<tr>
<td>Specific Heat, ( c_p ) (kJ/kg-K)</td>
<td>4.182</td>
<td>2.386</td>
<td>2.6841</td>
</tr>
<tr>
<td>Thermal Conductivity, ( k ) (W/m-K)</td>
<td>0.607</td>
<td>0.286</td>
<td>0.3326</td>
</tr>
<tr>
<td>Coefficient of expansion, ( \beta ) (K(^{-1}))</td>
<td>2.1×10(^{-4})</td>
<td>5×10(^{-4})</td>
<td>4.822×10(^{-4})</td>
</tr>
<tr>
<td>Surface tension, ( \gamma ) (N/m)</td>
<td>0.072</td>
<td>0.0632</td>
<td>0.067</td>
</tr>
</tbody>
</table>

Fig. 6 shows the concurrent whole-field transient evolution of the interface topology and thermal field caused by the heating wire placed under the interface. At the start of heating, the interface temperature is constant (same as the ambient temperature) and the interface is uniform with no perturbations, as can be seen at \( t = 1 \) s in Fig. 6. As the heat is added to the system over time by the heating wire located along the x-direction, the deformations are seen primarily in the y-direction that is perpendicular to the wire. The interface deformations and temperature rise are most prominent in the region directly above the wire location throughout the experimental run time. The temperature gradients set up between the heated wire and the interface drive the heat and momentum transfer giving rise to natural convection currents leading to the deformation of the interface. In the present experiments, the deformation of the interface is positive, that is, convex in nature, which suggests the main factor responsible for the interface perturbations is the buoyant force. The interfacial temperature also changes during heating leading to the development of thermal gradients over the interface. Surface tension being a function of temperature, thus results in the surface tension gradients over the free surface, which induce thermocapillary flows over the interface (see Fig. 2). It can be observed
from Fig. 6 that the interface deformation and temperature distribution are almost uniform along the center line region, which is directly above the heating wire. It can also be noted that the temperature and the interface deformations are propagated in the direction perpendicular (y-direction) to the wire with time. The region over which the influence of interface deformation is observed can be seen to be larger than that of the thermally affected region. This is due to the very large Prandtl number (Pr) of the fluid used (aqueous glycerol) for the experiments (Pr ≈ 366 at 25°C), due to which momentum transfer is faster than heat transfer. This observation also finds support from the quantitative data presented in Fig. 7 which illustrates the interface profile and temperature at a plane (x =15 mm) for different depths of
wire from the interface at a heating value of \(Q = 30 \text{ W/m}\). It can be seen that the peaks of deformation and the interface temperature coincide in the \(y\)-direction at \(y = 0\).

As discussed earlier, the temperature gradients on the free surface lead to the development of surface tension gradients along the interface. As a result, thermocapillary flows over the interface are induced, which transport the fluid from the heated region with lower surface tension to the colder region where the surface tension is higher. In the present study, the effects of the thermocapillary flows are not prominent as this flow has an affinity to make the interface have a concave shape in the region of maximum temperature, where the surface tension is minimum. On the contrary, it is evident from Fig. 7 that for each wire depth, the interface profile has a convex shape throughout the heating process. This can be attributed to the fact that the change in the surface tension with temperature for the aqueous glycerol solution is quite small \(\left(\frac{dy}{dT} = 1.02 \times 10^{-4} \text{ K}^{-1}\right)\). Thus, the interface can behave as a stationary layer with no noticeable thermocapillary flows. These inferences drawn from the present experiments also find support in some of the earlier reported works, for instance, Vinnichenko et al. (Vinnichenko et al. 2014b).

It can be seen from Fig. 7 that the interface behavior is identical, both thermally as well as hydrodynamically, for the wire at depths of \(L = 1, 2\) and \(3 \text{ mm}\) under the interface at a heat flux of \(Q = 30 \text{ W/m}\). For \(L = 7 \text{ mm}\), the symmetry in the profiles is lost, as shown in Fig. 7(d), which may be due to the inclusion of the velocity in the \(x\) and/or \(y\) direction in the liquid bulk, giving rise to a 3D flow field, as this case (\(L = 7 \text{ mm}\)) is associated with comparably higher Rayleigh numbers than the other cases of wire depth (see section S3 of supplementary material). Based on the competing dominant forces in the liquid bulk viz. buoyancy force and viscous force, the convective velocity \(u_{\text{conv}}\) scales as

\[
u_{\text{conv}} \sim \frac{\rho_0 \beta \Delta T g D^2}{\mu} \tag{4}
\]

where \(\rho_0\) is the density at \(0^\circ \text{ C}\) and \(\Delta T\) is the difference between the temperatures of the heating wire and the interface. Thus, the convective timescale \(\tau_{\text{conv}}\) and the conduction timescale \(\tau_{\text{cond}}\), respectively, can be written as

\[
\tau_{\text{conv}} \sim \frac{L}{u_{\text{conv}}} \quad \& \quad \tau_{\text{cond}} \sim \frac{\rho_0 c_p \mu}{k} \tag{5}
\]

It is worth mentioning that the timescales of conduction and convection are of a similar order for \(L = 1, 2\) and \(3 \text{ mm}\) (see Table II). This implies that the heat transfer from the wire to the interface through the liquid bulk is due to the combined effect of conduction and convection.
and it is responsible for the similar thermal characteristics of the interface at these wire depths. While in the case of $L = 7$ mm, the conduction timescale is two orders higher than the convection timescale and thus, the heat transport is predominantly due to natural convection.

**Table II.** Conduction and convection timescales for different wire depths ($L$) and heating power ($Q$)

<table>
<thead>
<tr>
<th>Wire Depth ($L$)</th>
<th>Conduction timescale, $\tau_{cond}$ (s)</th>
<th>Convection timescale, $\tau_{conv}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$Q = 15$ W/m</td>
</tr>
<tr>
<td>1 mm</td>
<td>9.7</td>
<td>8.3</td>
</tr>
<tr>
<td>2 mm</td>
<td>38.9</td>
<td>12.9</td>
</tr>
<tr>
<td>3 mm</td>
<td>87.5</td>
<td>16.8</td>
</tr>
<tr>
<td>7 mm</td>
<td>476.4</td>
<td>36.9</td>
</tr>
</tbody>
</table>
This difference in the mechanisms of energy transport results in different interfacial characteristics upon heating, as evident from Fig. 7.

Fig. 8 and Fig. 9 depict the transient variations of maximum interface deformation and maximum interface temperature, respectively, for different heat inputs to the wire positioned at various depths from the interface. From Fig. 8, it is observed that the interface perturbations \((h)\) grow in time as the heat is provided to the liquid through the wire. As the heat is transported to the interface, the temperature of the interface also increases with time (Fig. 9). At any given wire depth \(L\), the peak perturbations and the interface temperature rise at a faster rate as the heat input \(Q\) to the wire is increased. However, as the depth of the heating wire is increased, the resistance to the transport of momentum and thermal energy increases as well due to the very high viscosity \(\mu\) and low thermal conductivity \(k\) of the fluid, respectively. This leads to slower transients and lower magnitude perturbations at deeper positions of the wire [Fig. 8(d)].
Similar trends are observed for the interface deformation across all the wire depths employed in the study (Fig. 8), while in the case of interface temperature, similar trends are observed for wire depths of $L = 1$, 2 and 3 mm [Fig. 9(a), (b) and (c)]. However, for a wire depth of $L = 7$ mm, the interface is maintained at the ambient temperature after the start of the heating for the initial 30 seconds followed by a gradual rise in the temperature [Fig. 9(d)].

The non-dimensional perturbations, shown in Fig. 8, are obtained by normalizing the perturbations observed for different heating rates by the corresponding peak perturbation at 120 s. Similarly, the transient variations of non-dimensional interface temperature in Fig. 9 are attained by normalizing the temperature profile by the maximum interface temperature at 120 s for a particular depth and heating power. Interestingly, it is evident from Fig. 8 and Fig. 9 that for each wire depth, the non-dimensional peak perturbations and temperatures corresponding to different heating values, coincide to a great extent. It is imperative to note that irrespective of the wire depth ($L$) and heating power ($Q$), the non-dimensional parameters follow a common

---

![Fig. 8](image1.png)

![Fig. 9](image2.png)

**Fig. 9.** Variations of maximum interface temperature with time for different heating values at wire depths of a) $L = 1$ mm b) $L = 2$ mm c) $L = 3$ mm and d) $L = 7$ mm; insert in each graph depicts the corresponding temporal variation of maximum interface temperature

120 s. Similarly, the transient variations of non-dimensional interface temperature in Fig. 9 are attained by normalizing the temperature profile by the maximum interface temperature at 120 s for a particular depth and heating power. Interestingly, it is evident from Fig. 8 and Fig. 9 that for each wire depth, the non-dimensional peak perturbations and temperatures corresponding to different heating values, coincide to a great extent. It is imperative to note that irrespective of the wire depth ($L$) and heating power ($Q$), the non-dimensional parameters follow a common
profile, which indicates that there is an underlying scale associated with the hydrodynamic and thermal aspects of the phenomenon. This gives the impression that there is a relation between the non-dimensional parameters of interest associated with the phenomenon.

The measurements of the wire temperature using a thermocouple show that the temperature difference ($\Delta T$) set up between the interface and the heated wire that primarily drives the phenomenon, increases abruptly as the heating starts (till $t \approx 10$ s) and then gradually decreases for all the cases of heating. This temperature gradient is the maximum for the case with the highest heating power at each depth $L$. It was observed that the temperature difference between the interface and the wire ($\Delta T$) was similar at heating rates of $Q = 15$ and 20 W/m for wire depths of $L = 2$ and 3 mm (see section S2 of supplementary information). While in the case of $L = 1$ and 7 mm, distinct temperature gradients were observed for different heating values, with the highest gradients being observed at $Q = 30$ W/m and lowest at $Q = 15$ W/m in both cases. In the case of wire depth $L = 7$ mm, the non-dimensional temperature is seen to increase linearly after $t = 30$ s [Fig. 9(d)], while at other values of depth $L$, the slope of the interface temperature decreases with time. This can be attributed to the difference in the mechanisms of heat transfer observed at different wire depths, as discussed previously.

The temporal variations of the interface perturbation and corresponding interface temperature for different heating power inputs ($Q$) to the wire maintained at different heights are presented in Fig. 10. Distinct temperature profiles are seen at different wire depths for any given heating power input ($Q$); however, the interface deformation profiles ($h$) show similar behavior for different wire depths for a particular heating rate. Also, the difference between the behavior of the dimensional interface deformations tends to diminish as the heating power to the wire is increased. It should be emphasized that there is an inherent similarity in the interface profiles for non-dimensional interface perturbations not only for the different heat fluxes ($Q$) but also for different heights ($L$). This trend is also reflected in the non-dimensional temperature profiles across all wire depths. However, the temperature profile at depth $L = 7$ mm remains an outlier due to the high Rayleigh number ($Ra$) associated with the phenomenon at this wire depth (see section S3 of supplementary material).

Based on Fig. 10, it can be seen that the slope of the non-dimensional temperature with time is higher than the corresponding non-dimensional interface perturbations at wire depths of $L = 1, 2$ and 3 mm. It should be pointed out that even though the temperature of the interface has not changed for several seconds ($\sim 40$ s) in the case of wire depth $L = 7$ mm, the interface deformation starts almost instantly as the heating is started. Thus, in the case of $L = 7$ mm, the
deformation is not due to the impact of the rising convective plume rather, it is the result of the combined action of thermal expansion of the fluid under heating and the high momentum diffusivity of the fluid medium ($Pr = 336$) employed in the study.

Fig. 10. Temporal variations of peak non-dimensional interface deformation (left) and maximum non-dimensional temperature (right) at varying wire depths for different heating values of a) $Q = 15$ W/m b) $Q = 20$ W/m and c) $Q = 30$ W/m; inserts in each graph depict the corresponding temporal variation of peak perturbation and maximum interface temperature.
Conclusion

This paper maps the coupled dynamics of interface deformation and thermal characteristics for a line heat source placed under the interface through the simultaneous application of moon glade background oriented schlieren technique and infrared thermography. The experiments were conducted at different wire depths ($L$) from the interface and power inputs ($Q$) to the heating wire. As a result of the heating, the interface exhibited convex-shape deformation in the region directly over the wire for all the cases of heating and depth. A thermal field was also developed over the interface with the spatial location of maximum temperature coinciding with the peak deformation. It was observed that the region of thermal influence was smaller in comparison to the region of deformation. The interface started to deform on the onset of heating for all the cases considered (measured over $\Delta t = 1$ s). However, a delay in the change of interface temperature was observed when the wire was placed at $L = 7$ mm, which later exhibited a linear increase in interface temperature. Different competing mechanisms of heat transfer were discussed based on the timescales of diffusive and convective transport of thermal energy at different wire depths. The temperature difference between the wire and the interface increased at first ($t \approx 10$ s) and then gradually decreased over the duration of the experiment. Non-dimensionalization of the transient interface deformation and temperature profiles gives an insight into the underlying similarity to the problem as the non-dimensional perturbation profiles overlap for all cases of height and heating power. These characteristics are also observed for the normalized temperature profiles at different wire depths.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>BOS</td>
<td>Background oriented schlieren</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat (kJ/kg-K)</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of the heating wire (m)</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity (m/s$^2$)</td>
</tr>
<tr>
<td>$H$</td>
<td>Pattern to Interface distance (m)</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of the deformation (m)</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity (W/m-K)</td>
</tr>
<tr>
<td>$L$</td>
<td>Depth of the wire (m)</td>
</tr>
<tr>
<td>MGBOS</td>
<td>Moon glade background oriented schlieren</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle image velocimetry</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethyl methacrylate</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>pxratio</td>
<td>Pixel size ratio</td>
</tr>
<tr>
<td>Q</td>
<td>Heating power to the wire (W/m)</td>
</tr>
<tr>
<td>( \mathbf{r} )</td>
<td>Displacement vector</td>
</tr>
<tr>
<td>( r_x )</td>
<td>( x )-component of displacement vector</td>
</tr>
<tr>
<td>( r_y )</td>
<td>( y )-component of displacement vector</td>
</tr>
<tr>
<td>Ra</td>
<td>Rayleigh number</td>
</tr>
<tr>
<td>T</td>
<td>Interface Temperature (°C)</td>
</tr>
<tr>
<td>t</td>
<td>Time (s)</td>
</tr>
<tr>
<td>( T_w )</td>
<td>Temperature of wire (°C)</td>
</tr>
<tr>
<td>( u_{\text{conv}} )</td>
<td>Convection velocity (m/s)</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Coefficient of expansion (K(^{-1}))</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Surface Tension (N/m)</td>
</tr>
<tr>
<td>( \Delta h )</td>
<td>Perturbation at a point (m)</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>Temperature difference between wire and interface (°C)</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Interface emmisivity</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Dynamic viscosity (N-s/m(^2))</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density (kg/m(^3))</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>Density at 0°C (kg/m(^3))</td>
</tr>
<tr>
<td>( \tau_{\text{cond}} )</td>
<td>Conduction timescale (s)</td>
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<tr>
<td>( \tau_{\text{conv}} )</td>
<td>Convection timescale (s)</td>
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</table>

**Supplementary Information**

See supplementary material for the following: 1. Multimedia video file for the transient background pattern deflection and evolution of the interface deformation and temperature and 2. Supplementary information regarding variation of wire and interface temperatures, heat transfer mechanisms and determination of interface emmisivity.

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Consent for publication: All the authors of this manuscript agree with its content and have agreed explicitly to submit the work carried out by them.

Authors’ contributions

Mohammad Autif Shahdhaar: Data curation (lead); Formal analysis(lead); Investigation (equal); Methodology (equal); Writing – original draft (equal). Atul Srivastava: Conceptualization (lead); Funding acquisition (lead); Investigation (equal); Methodology (equal); Project administration (lead); Supervision (equal); Writing – review and editing (equal). Suneet Singh: Project administration (supporting); Supervision (equal); Writing – review and editing (supporting).

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Data availability and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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