Thermocapillary and shear driven flows in gas/liquid system in annular duct

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Abstract. We report the results of numerical study of two-phase flows in annulus for different aspect ratios obtained in the frame of the JEREMI experiment preparation. The geometry of the physical problem is a cylindrical and non-deformable liquid bridge concentrically surrounded by an annular gas channel under conditions of zero gravity. Thermocapillary (Marangoni) convection in liquid bridge of Pr = 68 is analyzed in the case when the interface is subjected to an axial gas stream. The gas flow is counter-directed with respect to the Marangoni flow. The inlet gas velocity $U_g$, temperature difference $\Delta T$ between end rods of the liquid bridge and aspect ratio are the control parameters of the system. In the case when the gas stream comes from the cold side, it cools down the interface to a temperature lower than that of the liquid beneath, and in a certain region of the parameter space that cooling causes instability due to a temperature difference in the direction, perpendicular to the interface. The present study is focused on the influence of the aspect ratio on the existence and characteristic features of the oscillatory regime.

1. Introduction

The dynamics of fluid systems with interfaces remains a challenging problem in fluid physics. In such systems, the variation of surface tension due to thermal or compositional gradient along the interface can cause convective flows in the bulk fluid [1],[2]. This effect is especially important in microgravity environment, where buoyancy convection is absent and thermocapillary forces often constitute the sole cause of motion. The investigation of instabilities induced by the thermocapillary effect has been initiated by [3] who has shown that the temperature dependence of the free surface tension by itself is capable of producing an instability in a fluid layer heated from below. Interfacial flows play an important role in many natural and technological processes, such as propagation of liquid jets, motion of thin liquid films, evolution of ocean waves, etc. A wide range of important applications promoted the development of different techniques for interfacial flow control.

Thermocapillary (or Marangoni) effect essentially affects the process of crystal growth by floating zone method [4]. During this process, the feed material is slowly moved through a ring heater, so a small zone of the material near the heater is melted. The melt recrystalizes at the melt-crystal interface to form a single crystal. The liquid zone between the feed material and crystal is kept by surface tension. To study the heat and fluid flows in the melt zone, a
liquid bridge (or half-zone) model is often used. In this model, the liquid is placed between two cylindrical rods (hot and cold) with a common axis. The surface tension gradient due to temperature variation along the free surface drives thermocapillary flow from hot to cold rod near the free surface and in the opposite direction at the axis. This flow is stationary for small temperature differences $\Delta T$ between the rods. When $\Delta T$ reaches some critical value, the flow becomes unstable, oscillatory in the case of high Prandtl liquids. The latter are represented by standing or axially running hydrothermal waves characterized by the azimuthal wave number $m$. Stability of thermocapillary flows generated by a temperature gradient directed along the liquid surface has been extensively studied in different geometries. The new flow states were recently reported [5].

The use of forced coaxial gas flow has been proposed as a way to stabilize the Marangoni convection in liquid bridges, which might have important technological applications in the floating zone technique. The planned experiment JEREMI (Japanese and European Research Experiment on Marangoni Instabilities) in Japanese KIBO module at the ISS aims at studying the influence of an external coaxial gas flow on the Marangoni convection in liquid bridges filled with silicone oil under zero gravity conditions. In the context of this experiment, some preparatory experimental and numerical studies are underway. The present study is one of the first steps on the way of the experiment preparation.

2. Problem formulation

We consider the system consisting of two co-axial cylinders, see geometry and notations in Fig. 1. The outer cylinder is a solid tube of radius $R_{out}$. The inner cylinder consists of two solid rods of radius $R_0$ and a liquid bridge between them, which is kept in its position by the surface tension force. Gas of a constant flow rate $Q_{in}$ enters from the right or left and flows through the annular duct of a size $(R_{out} - R_0)$. The solid rods are rather long; the distance from the tube inlet is $H$ while $H/(R_{out} - R_0) = 10$. It provides a fully developed flow in the gas, i.e. a velocity profile unchanging in the flow direction, before reaching the liquid zone. The flow structure at the entrance zone was analyzed earlier by [6], [7].

Upon reaching the liquid zone, a forced gas flow interplays with a liquid thermocapillary flow, which is present when the temperature difference is imposed between the rods. After passing the liquid zone of the length $d$, the gas continues to move through the annular duct over the distance $H$ up to the tube outlet. The total length of the tube is $L = 2H + d$. The geometrical dimensions are given in Table 1.

In this study the gravity is not taken into account and the liquid bridge is placed horizontally in Fig. 1. Numerical study is performed in a geometry as close as possible to the laboratory set-up and with exact physical properties of the fluids. Thus the small grooves are captured by the numerical code. The physical properties of the fluids are given in Table 2. The gas is assumed to be incompressible in consistency with the low pressure drop between the tube ends.

| $R_{out}$ | $R_0$ | $D_h$ | $H$ | $d$ | $L$ |
|----------|-------|-------|-----|-----|-----|
| $10^{-3}m$ | $10^{-3}m$ | $10^{-3}m$ | $10^{-3}m$ | $10^{-3}m$ | $10^{-3}m$ |
| 5 | 3 | 4 | 20 | 3 – 6 | 43 |

Table 1. Geometrical scales used in calculations, unless otherwise stated.
Figure 1. Geometry and scales used in numerical simulations. Gas may enter into the duct from the left or right side.

The dynamics of the system in the geometry of Fig. 1 is described by the momentum, continuity and heat transfer equations for an incompressible Newtonian fluid which are written for gas ($g$) and liquid ($l$) in cylindrical coordinates $(r, z)$:

\[
\begin{align*}
\frac{\partial}{\partial t} \mathbf{V}^g + (\mathbf{V}^g \cdot \nabla) \mathbf{V}^g &= -\frac{1}{\rho^g} \nabla P^g + \frac{\mu^g}{\rho^g} \nabla^2 \mathbf{V}^g, & \nabla \cdot \mathbf{V}^g &= 0, \\
\frac{\partial}{\partial t} T^g + \mathbf{V}^g \cdot \nabla T^g &= \chi^g \nabla^2 T^g, \\
\frac{\partial}{\partial t} \mathbf{V}^l + (\mathbf{V}^l \cdot \nabla) \mathbf{V}^l &= -\frac{1}{\rho^l} \nabla P^l + \frac{\mu^l}{\rho^l} \nabla^2 \mathbf{V}^l, & \nabla \cdot \mathbf{V}^l &= 0, \\
\frac{\partial}{\partial t} T^l + \mathbf{V}^l \cdot \nabla T^l &= \chi^l \nabla^2 T^l,
\end{align*}
\] (1)

where the velocity $\mathbf{V} = [V, U]$ includes the radial $V$ and axial $U$ components; $T$ is the temperature; $\mu$ is the dynamic viscosity; $\chi$ is the thermal diffusivity and $\rho$ is the density. The boundary conditions on the liquid–gas interface $r = R_0$ are:

a) a balance of viscous and thermocapillary stresses

\[\mu^l \partial_r U^l + \sigma_T \partial_z T^l = \mu^g \partial_r U^g,\] (2)

where the surface tension $\sigma$ is a linear function of temperature

\[\sigma(T) = \sigma(T_0) - \sigma_T (T - T_0), \quad \sigma_T \equiv -\partial_T \sigma = \text{const},\]

and $T_0$ is the reference temperature equal to the mean temperature of the system $T_0 = (T_{\text{cold}} + T_{\text{hot}})/2$;

b) axial velocities of liquid and gas are equal; radial velocities vanish (interface deformation is neglected)

\[U^l = U^g, \quad V^l = V^g = 0;\] (3)

c) heat fluxes in the liquid and gas and temperatures of liquid and gas are equal; here $k$ is the thermal conductivity

\[k^l \partial_r T^l = k^g \partial_r T^g, \quad T^l = T^g.\] (4)
On the liquid bridge axis $r = 0$ the symmetry conditions are imposed:

$$\partial_r U^l = 0, \quad V^l = 0, \quad \partial_r T^l = 0.$$  \hspace{1cm} (5)

No-slip conditions are imposed on the wall of the external tube $r = R_{\text{out}}$:

$$U^g = 0, \quad V^g = 0.$$  \hspace{1cm} (6)

The temperature of the external wall can be considered as a control parameter, but it is taken equal to the mean temperature of the system if it is not stated otherwise:

$$T^g(r = R_{\text{out}}) = T_0.$$  \hspace{1cm} (7)

No-slip conditions and constant temperatures are also imposed on the supporting rods:

- on the left rod $0 \leq z \leq H$: $U^l = V^l = 0, \quad T^l = T_{\text{cold}}$;
- on the right rod $H + d \leq z \leq L$: $U^l = V^l = 0, \quad T^l = T_{\text{hot}}$.  \hspace{1cm} (8)

The inlet conditions at $z = 0$ or $z = L$ (depending on which side gas enters into the duct), $R_0 < r < R_{\text{out}}$ are:

$$U^g = U_0 = \text{const}, \quad V^g = 0, \quad T^g = T_{\text{in}},$$  \hspace{1cm} (9)

alternatively, a constant flow rate, calculated as $Q_{\text{in}} = U_0 \pi (R_{\text{out}}^2 - R_0^2)$, can be fixed.

Let us discuss the outlet conditions imposed at $z = 0$ (in the case where gas enters from the right), $R_0 < r < R_{\text{out}}$. The flow velocity and pressure at the outlet are not known prior to the solution of the flow problem. The ”soft” conditions applied at outflow boundaries when the velocity profiles are physically appropriate for fully-developed flows are:

$$\partial_z U^g = 0, \quad \partial_z V^g = 0, \quad \partial_z T^g = 0.$$  \hspace{1cm} (10)

The question whether these conditions allow perturbations to penetrate back inside the tube have been previously investigated by [6]. The simulations were performed with an extended outlet part to analyze artificial boundary effects. The results for the length $0 < z < L$, and an extended length $0 < z < L + H/2$ appeared to be rather similar.

The system is multi-parametric and the major control parameters are: Marangoni number $Ma$, Prandtl number $Pr$, Reynolds number of gas $Re^g$ and aspect ratio $\Gamma$

$$Pr = \frac{\mu}{\rho \chi}, \quad Re^g = \frac{\rho^g U_0^g R_h}{\mu^g}, \quad Ma = \frac{\sigma T \Delta T d}{\mu^l \chi^l}, \quad \Gamma = \frac{d}{R_0}.$$  \hspace{1cm} (11)

here $\nu = \mu/\rho$ is the kinematic viscosity and $R_h = 2 (R_{\text{out}} - R_0)$ is the hydraulic radius which is a typical length scale in a pipe. For the geometry and fluid properties listed in Tables 1–2 the dimensionless parameters can be written in a way convenient for comparison

$$Pr^l = 68, \quad Pr^g = 0.75, \quad \Gamma = 2, \quad Re^g = 280 U_0^g [m/s], \quad Ma = 1.91 \cdot 10^5 \Delta T d [m].$$

The local heat flux through the interface is defined as $\tilde{q}(z) = -k^l \partial_r T^l (r = R_0)$. In the discussion of the results the non-dimensional heat flux $q$ and the average heat gain/loss through the unit of the free surface $q_{av}$ will be used

$$q(z) = \frac{\tilde{q} R_0}{k^l \Delta T} = -\frac{R_0 \partial T^l}{\Delta T \partial r}; \quad q_{av} = \frac{1}{d} \int_0^d q dz$$  \hspace{1cm} (12)
Table 2. Physical properties of silicone oil 5 cSt and air.

| fluid       | μ     | χ     | k     | ρ     | σT = dσ/dT | Pr |
|-------------|-------|-------|-------|-------|------------|----|
| Silicone oil| 4.56 \cdot 10^{-3} | 7.31 \cdot 10^{-8} | 0.11  | 912   | −6.37 \cdot 10^{-5} | 68 |
| air         | 17.9 \cdot 10^{-6}  | 1.9 \cdot 10^{-5}  | 0.025 | 1.225 | 0.713       |

The heat flux \( q \) is positive when the liquid locally loses heat and negative when heat gain. Correspondingly, \( q_{av} \) is positive (negative) when the liquid integrally loses (gains) heat. Similarly to [8] the averaged heat flux can be considered as modified average Biot number \( Bi_{av} = -q_{av} \).

Commercial solver FLUENT v.6.3 (laminar steady) was used for solving governing Eqs. (1)–(10). The problem was solved using dimensional variables in two domains for each phase separately with taking into account the boundary conditions at the interface Eqs. (2)–(4). With a user defined function, a special procedure of flows coupling was created where values for shear stresses balance on the gas-liquid interface were taken from the previous iteration time step.

3. Results and discussion

3.1. Stationary flows

In the absence of a gas stream the flow is induced by thermocapillary stresses due to the temperature gradient along the interface. The thermocapillary flow arises in the liquid for arbitrary small temperature difference \( \Delta T \) between the supporting rods. The liquid moves from the hot to the cold side along the interface and the flow pattern consists of one vortex with a center shifted to the hot side. In this paragraph we compare two kinds of flows: (i) the flows in a single phase liquid bridge and (ii) two-phase flows in a system which consists of a liquid bridge and a passive gas, \( U_g^0 = 0 \). The flow in the gas is driven by the liquid shear. The flow structure in gas consists of two small recirculation regions with the same direction of circulation (cat’s eyes) embedded in a globally circulating flow over the whole duct region (see Fig. 2b). These recirculation regions correlate with two peaks on the interface velocity profile shown in Fig. 3b.

Figure 2. Temperature field and isolines of stream functions in two phases without forced gas motion, \( \Delta T = 5K, U_g^0 = 0 \cdot m/s, T_g = T_0 \) and \( \Gamma = 2 \).

\[ 5 \]
The local heat flux (a) and the velocity (b) along the free surface when $\Delta T = 5K$ and $\Gamma = 2$. Curves 1, 2, 3 correspond to the passive gas with temperature $T_{\text{cold}}$, $T_{\text{mean}}$, $T_{\text{hot}}$, respectively. Temperature of the external tube is equal to the temperature of gas. The dashed curve in graph (b) corresponds to the case when ambient gas is not considered.

Here we would like to draw the attention to the following point: the presence of ambient gas at mean temperature, which is natural for any experiment, diminishes the interface temperature, see Fig. 2a. To analyze the effect of a heat gain/loss we performed simulations for the cases when the temperature of ambient gas is equal to the mean temperature of the system and either cold or hot rod. The wall of an external tube is kept at the temperature of the gas. In the present study, the buoyancy is absent but the conductive heat transfer between liquid and gas plays an important role. For the cases mentioned above the local heat flux $q$ is shown in Fig. 3a and velocity profiles in Fig. 3b where curves 1, 2 and 3 correspond to the ambient gas at the temperatures $T_{\text{cold}}$, $T_{\text{mean}}$, $T_{\text{hot}}$, respectively. It is seen without calculating an integral of $q(z)$ that the mean (as well as total) heat flux in cases 1 and 2 is positive (heat loss) while in case 3 it is negative (heat gain).

Correspondingly, the presence of ambient gas changes the temperature gradients along the interface which is crucial for the driving force. Two peaks on the velocity profile are induced by large local temperature gradients near hot and cold rods that accelerate/decelerate the liquid flow due to thermocapillary stresses, see the dashed line in Fig. 3b. The modification of the temperature profile by gas leads to the adjustment of the velocity on the interface with more pronounced changes near the hot side. The peak velocity on the cold side is too large for being shown in the graph scale, it ranges from $-5.0 \, \text{mm/s}$ to $-5.9 \, \text{mm/s}$ for curves 1-3. Only in the case of hot gas the flow on the free surface slows down with respect to the adiabatic case. Surrounding gas at mean or colder temperature accelerates the flow. We may conclude that the heat loss, $q_{av} > 0$, enhances the flow on the interface (curve 1 and 2 in Fig. 3b) while the heat gain slows down the flow (curve 3).

3.2. Development of the oscillatory instability under the action of a cold gas

3.2.1. Oscillatory regimes

Hereafter we consider the flow patterns when gas enters from the cold side. For majority of liquids $\partial \sigma / \partial T < 0$ and the thermocapillary flow is directed from the hot to the cold side at the interface. A gas at the mean temperature is moving against the Marangoni flow and causes a competition between the action of shear and thermocapillary stresses. When a gas stream approaches the liquid zone near the cold corner, it faces the typical sharp maximum of Marangoni velocity (see Fig. 3b), which strongly resists the incoming gas flow. For small gas velocities the shear stress is too weak to blow away this peak. Because gas is entering from
the cold side and moves along the cold rod, its temperature approaches $T_{\text{cold}}$ on the side of the liquid. Thus, the gas affects the liquid flow not only via shear stress but also by cooling the nearby interface and reducing the temperature gradient, driving the velocity peak. The flow topology depends on the gas speed.

The shear and thermocapillary stresses act to pull the interface apart and, as a result, oscillatory instability sets in at a certain set of control parameters: $U_0$, $\Delta T$ and $\Gamma$. Here our attention is focused on the development of oscillatory regimes and their features for different aspect ratios while the instability mechanism will be described elsewhere. At the threshold of instability a strong Marangoni force acts near the hot side and significantly suppresses the oscillations in that region. The oscillations of the velocity and temperature start in the central part of the free surface. The instability occurs in a limited region of the parameter space. For each analyzed aspect ratio two different regimes of instability are identified as function ($\Delta T$ vs $U_0$).

In the first oscillatory regime two vortices, attached to the cold and hot ends, keep the flow direction controlled by the Marangoni force. The snapshots of temperature and flow field for this regime are shown in Figs. 4-5 for aspect ratio $\Gamma = 1.5$. At that time instant the flow pattern consists of three independent vortices. Two of them adjacent to the hot and cold walls rotate counterclockwise and the middle vortex rotates clockwise. The size and shape of the convection cells in this oscillatory regime are correlated with the changes in the gas speed. The disturbances oscillate in time, spread in the region between the vortices, and decay before attaining either the cold or the hot end.

In the second oscillatory regime observed at higher gas velocities. One typical vortex exists at the hot side, which is controlled by Marangoni force, and another permanent vortex sets on the cold side, being controlled by the gas stream. The snapshots of temperature and flow field for this regime are shown in Figs. 6-7 for aspect ratio $\Gamma = 1.5$. The smaller vortices attached to the central part of the interface are actively moving between the strong vortices with opposite directions of the circulation. There exists a time instant when a flow pattern consists of a sequence of four counter rotating vortices. The vortices near the solid walls tend to destroy their weaker counter-rotating neighbours and push the pair of central vortices against each other. After destroying them the basic vortices stretch from one of the walls to the center of the liquid zone, particularly this instant is shown in Figs. 6-7. Later on, the four-vortex flow state appears again. With a further increase in the gas speed the stable core of the vortex near the cold side expands drastically compressing the area where oscillations occur. After invading the major part of the interface, where the Marangoni force could be active, the instability decays.
3.2.2. Influence of the aspect ratio on the stability of the flow

The described above instability occurs inside the limited range of the control parameters $U_g^0$, $\Delta T$ and $\Gamma$. The threshold of the instability for different $\Delta T$ only weakly depends on the gas speed. Figure 8 demonstrates that for the aspect ratio $\Gamma = 1$ the critical gas speed (or $Re_g^\text{cr}$) practically does not change when the temperature difference increases by 40%, i.e. $\Delta T$ varies from 14 K to 20 K. Perhaps, calculations with smaller sampling in $U_g^0$ could reveal the effect of $U_g^0$ but it would be weak. For example, our analysis showed that for $\Gamma = 2$ the critical gas speed changes by about 20% when the temperature difference is increased by 2.5 times (not shown by plots), i.e. $\Delta T$ varies from 8 K to 20 K. This gives a hint that the shear stress provided by gas is not a major contributor in the mechanism of instability.

But in the same time the range of gas velocities, where oscillatory regime is present, considerably depends on the length of a liquid bridge. The shorter is the liquid bridge the smaller is region of parameters where instability occurs. For short liquid bridge, when temperature gradient along the interface is larger for the same $\Delta T$, more intensive gas flow is necessary.

Figure 6. Snapshot of temperature field in the second oscillatory regime when $\Gamma = 1.5$, $\Delta T = 20 K$, $U_g^0 = 4 m/s$.

Figure 7. Snapshot of flow field in the second oscillatory regime when $\Gamma = 1.5$, $\Delta T = 20 K$, $U_g^0 = 4 m/s$.

Figure 8. Dependence of the oscillations frequency on gas velocity $U_g^0$ for different $\Delta T$ when $\Gamma = 1$.

Figure 9. Dependence of the oscillations frequency on gas velocity $U_g^0$ for different $\Gamma$ when $\Delta T = 20 K$. 

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Figure 10. Amplitude of axial velocity oscillations versus $U_0^g$ for different aspect ratios (a) $\Gamma = 1.5$, (b) $\Gamma = 2.0$ at different points of the interface: 1 - near cold rod; 2 - in the middle of liquid bridge; 3 - near hot rod;

for appearance of oscillatory regime. In addition, the solid walls impose strong constraints on the spreading of perturbations. Figure 9 shows dependence of the oscillations frequency on gas velocity $U_0^g$ for different $\Gamma$ when $\Delta T = 20 K$. Indeed, for $\Gamma = 1$ (red curve) oscillations start at much higher $U_0^g$ than for $\Gamma = 2$. Note that the critical temperature difference at the threshold of instability for $\Gamma = 1$ is $\Delta T_{cr} = 14 K$ while for $\Gamma = 2$ is much smaller, $\Delta T_{cr} = 8 K$.

As common tendency, increasing of gas velocity $U_0^g$ leads to growing of the oscillation frequency for all considered $\Gamma$. Nevertheless the development of flow pattern depends on the length of the liquid zone. For the relatively long liquid zones, i.e. $\Gamma \geq 2$ the oscillation frequency continuously grows indicating a smooth transition between regimes described above, see Fig. 9. However in case of short liquid zones (for $\Gamma \leq 1.5$) a strong jump of the frequency occurs when gas velocity $U_0^g = 4.1 m/s$ for $\Gamma = 1$ and $U_0^g = 3.5 m/s$ for $\Gamma = 1.5$. This frequency jump is associated to the change of the oscillatory flow regimes. One more notable conclusion follows from comparative analysis of curves behaviour in Fig. 8. It follows that for short liquid bridges the second regime, at which a permanent vortex is created by the gas flow near the cold wall, occurs only for relative large thermal stresses, i.e. $\Delta T \sim 20 K$ when $\Gamma = 1$.

All the transitions are clearly seen in Fig. 10 where oscillation amplitudes of axial velocity are presented for different aspect ratios and gas velocities. As a general trend the oscillations amplitude is largest in the middle of the free surface (red curves) and smallest near the hot wall, where the flow is controlled by Marangoni force (dark blue curve).

Figure 11. Flow pattern for the same case as in Fig.10b when gas velocity $U_0^g = 4 m/s$
The variation of the amplitude in the middle of the liquid zone reflects the flow pattern transitions in the best way. For $U_{g0}$ just above the threshold of instability a little vortex moves at the central part of the interface and never penetrates deep inside the liquid. With the increase of $U_{g0}$ the vortex in the middle of the interface grows, and at a certain time moment it reaches the symmetry axis in a long liquid zones. The first small decrease of the amplitude on green (a) or red (b) curves in Fig. 10 is attributed to this transition.

Position of the maximum amplitude with respect to the gas velocity depends on the aspect ratio. For shorter liquid bridges where transition between regimes occurs via jump of frequency and amplitude (Fig. 10a), the maximum of the amplitude is achieved shortly before transitions. For long liquid bridge with continuous and smooth development of the flow the maximum of the amplitude is achieved in the second regime when vortices near the solid walls with opposite circulation attain approximately the same strength. With further increase of $U_{g0}$ the vortex on cold side becomes more active and powerful than that on the hot side. Note that with the increasing liquid bridge length the temperature gradient along the interface becomes smaller and it results in comparable magnitude of the amplitudes for different $\Gamma$.

Figure 11 shows the flow pattern for long liquid zone $\Gamma = 2$ just before decaying instability, when the gas flow is strong, $U_{g0} = 4.0 \text{ m/s}$. The vortex created by the gas shear stress on cold side dominates and forces to oscillate the vortex, created by Marangoni force, which was usually steady. Correspondingly the oscillation amplitude at this point, see Fig. 10b, is the same in the middle or near the hot side.

4. Conclusions

We have performed an extensive computational study on the effects of the ambient air flow on a thermocapillary convection in a high Prandtl number liquid silicone oil 5cSt, $\text{Pr} = 68$. The mathematical model assumed incompressibility of the liquid and gas, linear dependence of the surface tension on temperature, with all other thermophysical properties of the fluids being taken as constant. The geometry of the physical problem is a cylindrical and non-deformable liquid bridge concentrically surrounded by an annular gas channel under conditions of zero gravity. The inlet velocity, temperature difference between end rods of the liquid bridge and aspect ratio are the control parameters of the system. We report on oscillatory instability, which occurs in the liquid when gas enters from cold side. The flow patterns, frequency and amplitude of oscillations are thoroughly analyzed for different aspect ratios.

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