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Kurian Jory  
Vellore Institute of Technology

Satheesh Anbalagan (satheeesh.a@vit.ac.in)  
Vellore Institute of Technology

Research Article

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Posted Date: July 21st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1822117/v1

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Numerical Analysis of the Effect of Marangoni Convection in a Shallow Cylinder

Kurian Jory, A. Satheesh*
Department of Thermal and Energy Engineering, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamilnadu 632014, INDIA
*Corresponding Author: Email: satheeesh.a@vit.ac.in

ABSTRACT

A numerical study in a two-dimensional, axisymmetric cylindrical geometry is performed to evaluate the effect of Marangoni convection in shallow liquid layers. The test fluid used is silicone oil. The study aims to understand Marangoni convection for a range of temperature gradients (9.0 K, 11.5 K, and 14.0 K), layer depths (4.0 mm, 4.5 mm, and 5.0 mm) under earth gravity (1.0 g), and microgravity (0.5 × 10^{-3} g) conditions. The finite element method is used to solve the present problem and the numerical models were created using COMSOL V5.6 commercial tool. The influence of fluid meniscus on Marangoni convection is analyzed and found out the thermo-capillary force is less significant in driving the fluid. The present investigation in microgravity ensures the Marangoni convection dominates natural convection. For all the test conditions, it is found that Marangoni convection is influenced more by temperature difference than layer depths. It is observed that the velocity magnitude deviates around 45% for the selected temperatures at 4 mm layer depth, whereas, a 3% deviation is only found between the selected ranges of layer depths at a temperature difference of 11.5 K. From the microgravity study, it is clear that for velocity magnitude at z = 2.5 mm the Marangoni convection contributes to almost 90% of the total convection. It was also observed that the presence of Meniscus will reduce the free surface velocity by almost 60%.

Keywords: Marangoni convection, cylindrical geometry, shallow liquid layers, meniscus, microgravity, COMSOL V5.6.
### Nomenclature

| Symbol | Definition | Unit |
|--------|------------|------|
| $c_p$  | Specific heat | (Jkg$^{-1}$K$^{-1}$) |
| $d$    | Layer depth | (m) |
| $g$    | Gravitational acceleration | (ms$^{-2}$) |
| $Gr$   | Grashof number ($= g \beta T d \Delta T L^3/\nu^2$) | - |
| $k$    | Thermal conductivity | (Wm$^{-1}$K$^{-1}$) |
| $l_c$  | Capillary length ($= \sqrt{\frac{\sigma}{\rho g}}$) | m |
| $Ma$   | Marangoni number ($= \frac{\partial \sigma}{\partial T} \frac{d \Delta T}{\alpha \mu}$) | - |
| $Pr$   | Prandtl number ($= \frac{\nu}{\alpha}$) | - |
| $R$    | Characteristic length | (m) |
| $Ra$   | Rayleigh number ($Ra = \frac{g \beta T d^3}{\nu \alpha}$) | - |
| $T$    | Temperature | (K) |
| $u$, $v$ | Velocity components along $r$ and $z$ axes | m/s |
| $r$, $z$ | Co-ordinates | |

### Greek symbols

| Symbol | Definition | Unit |
|--------|------------|------|
| $\alpha$ | Thermal diffusivity | (m$^2$s$^{-1}$) |
| $\beta$ | Thermal expansion coefficient | (K$^{-1}$) |
| $\nu$  | Kinematic viscosity | (m$^2$s$^{-1}$) |
| $\rho$ | Fluid density | (kgm$^{-3}$) |
| $\sigma$ | Surface tension | (N/m$^{-1}$) |
| $\mu$  | Dynamic viscosity | (kgm$^{-1}$s$^{-1}$) |
\[ \Delta T \quad \text{Temperature difference} \quad (K) \]

**Subscripts**

avg \hspace{1cm} \text{average} \\
\( c \) \hspace{1cm} \text{cold} \\
\( h \) \hspace{1cm} \text{hot} \\
max \hspace{1cm} \text{maximum} \\

**1 Introduction**

The phenomenon where the fluid gets driven by shear stress due to surface tension gradient is called the Marangoni effect and the flow-induced is called Marangoni flow. A gradient in surface tension will naturally induce the liquid to flow away from areas of low surface tension towards higher surface tension as the liquid with a high surface tension pulls the surrounding liquid more. Marangoni convection has been the investigator’s one of the most interesting topics since the second half of the 19th century. In 1855, Thomson identified “On certain curious motions observable at the surfaces of wine and other Alcoholic liquors” which gives an insight into how alcohol is spreading on the surface of the water. He realized that surface tension flows are the reason behind it. A decade later, Mensbrugghe inferred that local difference in surface tension is responsible for all varied instances of surface movements. Carlo Marangoni studied the phenomenon thoroughly and provides a more precise idea of this phenomenon. Hence the effect is named after him. The first relevant experimental analysis is done by Benard at the beginning of the 20th century. He visualized the cellular convection pattern induced by surface tension through his experiments. But after the experiments of Bloke and the theoretical analysis of Pearson, it was clear that the surface tension was the reason behind the formation of Benard cells.

The instability of Benard convection is caused by two mechanisms. The first mechanism, known as Rayleigh–Benard convection, is attributed to the variation in density across the liquid's thickness, while the second, known as Benard–Marangoni convection, is induced by a surface tension gradient created by temperature changes at the liquid's upper free surface. A dimensionless number called Marangoni number (Ma) is introduced as given in Eq. (1)
\[
\frac{Ma}{Ra} = \frac{\sigma}{\beta \rho g} \frac{1}{R^2}.
\]

Where \(Ma\) and \(Ra\) stand for the Marangoni and Rayleigh numbers respectively, \(\sigma\) represents surface tension, \(g\) denotes gravitational acceleration, \(R\) denotes the characteristic length, and \(\rho, \beta\) represents liquid density, the volumetric expansion coefficient respectively.

The capillary length \((l_c)\), the length scaling factor that relates to gravity and surface tension is shown in Eq. (2)

\[
l_c = \sqrt{\frac{\sigma}{\rho g}}
\]

Substituting the value of \(l_c\) in Eq. (2) we get;

\[
\frac{Ma}{Ra} = \frac{1}{\beta} \left(\frac{l_c}{R}\right)^2
\]

Eq. (3) shows that \(Ma\) is inversely proportional to the characteristic’s length \((R)\). Benard–Marangoni convection thus predominates for thin liquid films \((R << l_c)\), whilst, Rayleigh–Benard convection dominates for thick liquid films \((R >> l_c)\). Marangoni convection is not limited to just Benard–Marangoni convection but can be classified based on the change in temperature and concentration that induces gradients of surface tension. Flow-induced by surface tension gradients due to temperature distribution is called thermo-capillary convection and due to concentration gradients is known as solute-capillary convection. In the present study, only thermo-capillary convection is considered to investigate the flow characteristics.

Marangoni convection has a huge scope as it has various engineering applications, such as welding, crystal growth, electron beam melting, etc. Developments in the study of surface tension flows helped to understand the convection process that happens in the melt-pool during crystal growth. The earliest studies of Marangoni convection in crystal growth go back to more than 40 years [1]. The studies on the surface tension flows in floating zone melting showed that the radial inhomogeneities were produced due to thermo-capillary forces at smaller driving forces. At large driving forces, the flow is turbulent and oscillatory. The flow driven by surface tension in the floating zone of sodium nitrate \((\text{NaNO}_3)\) is experimentally observed [2]. Temperature oscillations induced by surface tension have been found inside the zone. Surface tension-driven flow induced by temperature gradient can be of high magnitude at a large free surface and higher values of the temperature gradient. Later,
these studies were extended to find the magnitude of thermo-capillary convection in larger melt volumes of 20 mm × 20 mm × 12.5 mm [3]. The numerical analysis of Czochralski (CZ) crystal growth can be validated using the results of [4], who conducted both numerical and experimental investigations with a fluid of Pr = 6.8.

Nakanishi et al. [5] realized that Marangoni flow aids in the growth of crystals with low oxygen concentration. Additionally, they found that a strong surface flow was directed from the crucible wall towards the crystal under the influence of surface tension. The studies on the effect of gradients in surface tension on the flow field and the oxygen content of the melt [6] showed that the Marangoni convection accelerates the flow velocity at the melt surface and, as a result, affects how rapidly oxygen evaporates from the free surface. The time-dependent analysis and calculation of the thermal and flow fields in Czochralski silicon melt [7] confirmed that the concentration of oxygen in crystals is influenced by Marangoni convection. An increase in Marangoni number will strengthen the radial inward flow which shifts the flow pattern from circumferential to spiral in the Czochralski silicon melt [8]. Meanwhile, the surface tension strengthens the buoyancy convection and the isotherms were observed to be curved downwards.

Li et al. [9] have numerically studied the surface patterns of silicon melt in CZ furnaces, by using a three-dimensional unsteady simulation of thermo-capillary flow for two different layer depths of 3 mm and 8 mm. Flow transit from steady 2-D to steady 3-D flow and then becomes oscillatory at a smaller depth. But at a larger depth, the flow transits directly from 2-D steady to oscillatory. Also only in a deep pool, the Prandtl number does have a significant impact on the critical Marangoni number. Further the study was proceeded with a series of experiments with liquid depths chosen between 1.5 mm and 8.0 mm [10]. They confirmed from their numerical and experimental studies the impact of the Prandtl number is only relevant in a larger depth of the liquid. Researchers have studied Marangoni convection in various geometries to understand the characteristics of the fluid flow which are discussed in the following section.

Riley et al. [11] have studied the effect of combined buoyancy-Marangoni convection in a thin rectangular geometry. The emphasis of the study was on the formation of hydrothermal wave instabilities. They have studied the transition from steady, unicellular convection to oscillatory convection and confirmed the presence of oscillatory hydrothermal waves. Pure Marangoni convection without the presence of buoyancy force in a cylindrical geometry was studied using Particle Image Velocimetry (PIV) [12]. Studies were conducted at different layer depths of 3.9, 4.0, and 4.3 mm, and temperatures of 9.6, 9.9, and 11.8 K. By
heating from above and keeping shallow depths, buoyancy effects were diminished. Numerical simulations in a differentially heated rectangular cavity [13], accurately predicted the flow in the double-layer system even for large aspect ratios by developing a single-layer problem with a modified tangential-stress condition at the interface. Convective flows in a two-layered system was observed with a horizontal temperature gradient [14]. The nonlinear simulation of the silicone oil-HT70 system showed that the direction to which the wave propagates depends on the ratio of layer thickness and Marangoni number. Hydrothermal wave instabilities in Marangoni flow were studied using the shadowgraph method [15]. Two types of waves that are dependent on fluid depth were observed. At larger fluid depths, the first hydrothermal wave occurs which propagates from the radial direction, while at smaller fluid depths the other hydrothermal wave propagates radially at the onset. Studies to determine the characteristics of thermo-capillary flow in differentially heated shallow and deep annular pools indicated that three-dimensional stationary flow is observed more in deep pools (d = 5 mm) and in shallow pools, (depth = 1 mm) hydrothermal wave with curved spikes predominates [16].

The analysis on the effect of heat dissipation on thermo-capillary convection indicated that the hydrothermal waves are dominant at weak heat dissipation rates, but at higher dissipation rates longitudinal rolls near the outer wall are dominant [17]. The thermo-capillary convection in ethanol evaporation at two different layer depths of 55 mm and 60 mm was studied [18]. The experimental study of the temperature distributions along the free surface in both shallow and deep vessels showed that the core holds a large cold region that is home to numerous Marangoni convective cell patterns. The surface velocity is estimated to be in the order of 0.7 cm/s. A shallow annular pool with different aspect ratios containing a binary mixture was chosen to conduct a series of numerical and experimental studies on thermo-capillary convection [19, 20]. Results showed the hydrothermal waves and chaos phenomena will orderly appear with an increase in the surface velocity. Also, transition and flow characteristics are dependent on capillary ratio, aspect ratio, and thermal and surface velocity. A shallow annular pool with different evaporation rates was studied experimentally to understand the effect of surface dissipation [21]. The surface evaporation is dependent on the Marangoni number and the average temperature (T_{avg}). When T_{avg} = 40°C and ΔT = 10°C, the average evaporation rate at depth d = 2.5 mm is 0.792 μm/s and at T_{avg} = 45°C and ΔT = 0, average evaporation rate is 0.752 μm/s. Hence it was proven that Marangoni convection can enhance surface evaporation significantly. Schwabe et al. [22] discussed the geometries that are shallow and under microgravity. Results showed that Marangoni convection is the
dominant convection for these conditions, as natural convection gets minimized. Since the microgravity environment suppresses the effect of gravity, multiple studies were conducted to understand the phenomenon.

Kamotani et al. [23] were among the earliest researchers who conducted experiments in microgravity conditions to learn more about pure Marangoni flows. Experiments were conducted in a cylinder containing 10 centistokes silicone oil with different heating conditions and free surface shapes. Values of Ma range up to $3 \times 10^5$ were used for the test. In microgravity experiments, no oscillations were observed even at higher Ma numbers. Experiments were carried out to understand Benard-Marangoni-Instability on surfaces of silicone oil during the microgravity phase of the sounding rocket MAXUS 2 on which 10 centistokes silicone oil was heated from below to observe convection patterns [24]. Benard-Marangoni convection was visualized and the onset of convection as a function of aspect ratio is measured. The importance of the Marangoni effect under microgravity is numerically investigated by Giangi et al. [25]. Results were presented for values of Ma up to 16,120 and Ra of 5. Additionally, they provided typical space gravity levels, which can range from 0.1 to 2,500 microgravity conditions. A two-dimensional, steady thermo-capillary flow in a liquid bridge under microgravity conditions with a wide range of aspect ratios was studied [26]. A liquid bridge is a mass of liquid sustained by the action of the surface tension force between two parallel supporting disks. The stability of a thermo-capillary flow is highly dependent on the normal temperature gradient at the liquid-gas interface. A three-dimensional thermo-capillary flow in a liquid bridge under microgravity showed that an increase in Marangoni number will strengthen and accelerate the instability of thermo-capillary convection [27]. A correlation for estimating Reynolds number (Re) in terms of (Ma) and (Pr) is developed [28] and can be used to predict whether Marangoni convection or buoyancy convection is predominant in the flow.

Recently, the effect of Prandtl number and pool curvature on the stability of thermo-capillary in annular pools is studied using linear stability and energy analysis [29]. Energy analysis provides information about by which kinetic energy and thermal energy are supplied to the system. The Rayleigh-Bénard-Marangoni convection in a thin metallic layer was performed by applying three different boundary conditions on the top surface: (i) pure radiative heat transfer and (ii) radiative heat transfer with plus positive Marangoni effects (iii) radiative heat transfer with negative Marangoni effects [30]. It was observed that for a thin metallic layer the presence of Marangoni effects enhances the focusing effect irrespective of positive and negative values.
From the above literature, it is clear that the investigation of Marangoni convection has a huge scope in various engineering applications, such as controlling oxygen concentration in crystal growth [5-7], material processing under microgravity [23], [26], studies in shallow annular pools [21], [29], etc. Understanding the influence of Marangoni convection on flow behavior is necessary, as it can be the dominant convection in many environments. From the literature, it is clear that there is further scope for research on Marangoni convection as we are still in the primeval stages of working in a gravity dormant environment. Hence, this present numerical analysis is to identify the necessary conditions for Marangoni convection to dominate. So in the present work a range of temperature from 9.0 K, to 14.0 K, layer depths of 4.0 mm to 5.0 mm under earth gravity (1.0 g), and microgravity (0.5 \times 10^{-3} g) conditions are investigated. The influence of Meniscus on flow behavior is also examined.

2 Physical model

A two-dimensional axisymmetric model selected for the present study is shown in Fig.1. The fluid is assumed to be Newtonian and the thermo-physical properties related to the pressure and temperature are assumed to be constant. The Boussinesq approximation is used to calculate the density term in the buoyancy force. The flow is assumed to be steady, laminar, and incompressible. Under the axisymmetric coordinate system \((r, z)\), the velocity vector can be defined as \(\vec{V} = (v_r, v_z)\), where \(v_r\) and \(v_z\) are the radial and axial velocity components respectively. Under normal gravity conditions, the gravity vector is assumed to act in the downward \(z\)-direction and its value is \(g = 9.8 \text{ m/s}^2\). The governing equations provided by [31] for two-dimensional, axisymmetric cylindrical coordinates are given in Eqs. (4) to (7).
Continuity:

\[ \frac{\partial v_z}{\partial z} + \frac{\partial v_r}{\partial r} + \frac{v_r}{r} = 0 \]  

(4)

\text{r- momentum:}

\[ \left( v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z} \right) = -\frac{1}{\rho} \frac{\partial p}{\partial r} + \nu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_r}{\partial r} \right) + \frac{\partial^2 v_r}{\partial z^2} \right] - \frac{v_r}{r^2} \]  

(5)

\text{z- momentum:}

\[ \left( v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z} \right) = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_z}{\partial r} \right) + \frac{\partial^2 v_z}{\partial z^2} \right] - (1 - \beta \Delta T)g \]  

(6)

\text{Energy:}

\[ (\vec{V}, \nabla)T = \alpha \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right). \]  

(7)

Where, \( \rho, p, v, T, \alpha, \) and \( \beta \) are density, pressure, kinematic viscosity, fluid temperature, thermal diffusivity, and coefficient of thermal expansion respectively.
Fig. 2 shows the typical two-dimensional, axisymmetric model with meniscus and temperature boundary conditions. The fluid chosen is silicone oil of kinematic viscosity ($\nu$) 10 centistokes in a container having a radius $R = 28.07 \times 10^{-3}$ m and the liquid layer depth is ($d$) $4 \times 10^{-3}$ m. The thermophysical properties of the oil are presented in Table 1. Fluid is heated from the top using a copper rod of diameter $5 \times 10^{-3}$ m and height $2 \times 10^{-3}$ m. The free surface can be assumed as undeformable. The temperature at the side and bottom walls ($T_w$) is taken as 298.15 K. The present numerical problem is solved with and without meniscus and the boundary conditions are as follows.

![Fig. 2 Boundary conditions for the model](image)

| Properties                        | Units  | Values         |
|-----------------------------------|--------|----------------|
| Density ($\rho$)                  | kg/m$^3$ | 933.13        |
| Specific heat ($C_p$)              | J/kg-K | 1506.24       |
| Thermal conductivity ($k$)         | W/m-K  | 0.134         |
| Dynamic viscosity ($\mu$)          | kg/m-s | $9.3313 \times 10^{-3}$ |
| Thermal expansion coefficient ($\beta$) | 1/K   | $1.08 \times 10^{-3}$ |
| Surface tension ($\sigma$)         | N/m    | 0.0201        |
When the meniscus is not considered;

At Tip: \( V = 0; \quad z = d; \quad T = T_h \) at \( 0 \leq r \leq 2.5 \text{ mm} \)

At Left and Right walls: \( V = 0; \quad T = T_w \)

At bottom wall: \( V = 0; \quad T = T_b \)

When the meniscus is considered;

At Tip: \( V = 0, \quad T = T_h \) at \((0 \leq r \leq 2.5 \text{ mm}, \quad z = d)\) and \((r = 2.5 \times 10^{-3}, \quad d \leq z \leq d_{\text{tip}})\)

At Left and Right walls: \( V = 0; \quad T = T_w \)

At bottom wall: \( V = 0; \quad T = T_b \)

As the top free surface is assumed to be adiabatic and undeformable (as shown in Fig. 2), denoting \( n \) as the local coordinate normal to the free surface and \( u_n \) as the normal velocity component, boundary conditions can be written as follows

Adiabatic boundary condition:

\[
\frac{\partial T}{\partial n} = 0
\]

Undeformable boundary condition:

\[
u_n = 0
\]

Marangoni convection boundary condition

The Marangoni stress boundary condition gives the relationship between surface tension gradients and local tangential shear stress and is applied at the top free surface. The kinematic boundary condition \([32]\) is expressed as

\[
\tau = \mu \frac{\partial u_t}{\partial n} = \frac{\partial \sigma}{\partial T} \nabla_s T.
\]

Where \( \tau \) is shear stress at the free surface, \( \mu \) denotes dynamic viscosity and \( n \) is local coordinate normal. \( \frac{\partial \sigma}{\partial T} \nabla_s T \) is the surface tension temperature coefficient and tangential surface temperature gradient, respectively.
Axial boundary condition:

The proposed boundary conditions [31] can be written as

\[
\frac{\partial T}{\partial r} = 0; \quad \frac{\partial v_z}{\partial r} = 0; \quad v_r = 0;
\]

3 Methodology

The governing equations are solved by using the finite element method. COMSOL Multiphysics V5.6 is used to solve the two-dimensional steady state, incompressible, laminar flow. In COMSOL “Fluid Heat Transfer” module and “Laminar Flow” module are used to apply the boundary conditions. “Non-isothermal flow” and “Marangoni effect” Multiphysics are used to solve the problem. Non-isothermal flow enables to apply buoyancy effects while “Marangoni effect” apply thermal shear stresses. The single set of algebraic equations for all of the relevant physical models is created using the “Fully coupled technique”. These equations are implemented in a single iteration scheme that is repeated until convergence is achieved. For continuity, the residual criterion of \(1 \times 10^{-9}\) is set in the solution of governing equations. Once the value becomes less than the set tolerance criterion, the solution is assumed to be converged.

4 Results and Discussion

4.1. Grid Independent test

Grid independent test is carried out from course mesh to fine mesh by varying the total number of elements from 29895, 38688, 44640, 53398, and 96013. Fig. 3 shows the surface velocity of silicon oil in the radial direction for the selected range of mesh sizes. From Fig. 3 it is clear that 53398 elements can be taken for study as the variation from the previous mesh size is minimum. Table 2 also confirms it by showing the maximum velocity obtained for different mesh sizes. The maximum velocity is showing a deviation of only about 0.339% as mesh element numbers move from 29895 to 38580. It shows a value of 0.348, 0.173, and 0.275 as it moves from 38580 to 44640 to 53398 to 96013 respectively. Since the least percentage deviation obtained is 0.173, the number of elements can be chosen as 53398.
considering accuracy and the computation time. Hence the present numerical study has been carried out further using 53398 element numbers.

Fig. 3 Variation of free surface velocity magnitude with r coordinate (a) normal view (b) zoomed view for $d = 3.9$ mm, $\Delta T = 9.9$ K
Table 2 Maximum velocity with respect to the number of elements used

| S.No | Number of Elements | Maximum velocity (m/s) | % difference |
|------|--------------------|------------------------|--------------|
| 1    | 29895              | 9.710 x10^{-3}         | -            |
| 2    | 38580              | 9.743 x 10^{-3}        | 0.339 %      |
| 3    | 44640              | 9.777 x 10^{-3}        | 0.348 %      |
| 4    | 53398              | 9.794 x 10^{-3}        | 0.173 %      |
| 5    | 96013              | 9.821 x10^{-3}         | 0.275 %      |

4.2. Validation

The flow patterns in a cylindrical geometry of layer depth \( d = 3.9 \times 10^{-3} \) m and a temperature difference \( \Delta T = 9.9 \) K is compared with the results of [12]. The velocity contours of the present study are compared with the literature as shown in Fig. 4. The oil is heated from the top using a copper rod that creates a temperature gradient as the bottom and side walls are kept at a lower temperature. This makes the surface tension of the heated region to be lower than that of the colder regions. Since the flow only moves from a region of lower surface tension to higher surface tension, the oil flows from the hot tip region to colder areas. This makes the surface velocity to be maximum near the heated region. The obtained contours and the literature accord fairly well. Figs. 5(a) and 5(b) compares velocity magnitude and temperature along the free surface with the literature, and the maximum percentage difference is found to be around 7 %. This may be due to the accuracy during the measurements in the experiments or the errors raised due to the chosen numerical method. The validation indicates that there is good agreement between the present simulation result and the literature.
Fig. 4 Velocity contour of [12] (top) with Present study (bottom) at $d = 3.9$ mm and $\Delta T = 9.9$ K

\[ \Delta T = 9.9 \text{ K} \]

\[ d = 3.9 \text{ mm} \]
4.3. The effects of Marangoni convection on Temperature, Streamline and velocity profiles

Figs. 6(a) and 6(b) show the temperature contours with and without Marangoni convection respectively for $d = 4 \times 10^{-3}$ m and $\Delta T = 14$ K. The silicon oil in the cylinder is heated from the top using a copper rod. Hence the temperature near the top surface is significantly more than the bulk of the fluid. The temperature in the bulk fluid is close to the temperature of the side and bottom walls which are kept at 298.15 K. The region near and around the heating rod tip has higher temperature contours. When the flow gets past that region, the temperature starts to drop down and reaches the bulk temperature quickly. Temperature distribution in non-Marangoni convection is more uniform, and there is not much distortion visible. Higher temperature contours are visible only in regions near the heating tip and the lower temperature contours away from it. The majority of the bulk oil temperature is close to the wall temperature. Along the free surface, the temperature of the oil reaches the wall temperature rather quickly. In Marangoni flow, distortion of the contour is more evident. Lower temperature contours are visible even higher up, closer to the tip, and around the axis of symmetry. This can be attributed to the presence of Marangoni convection. Due to the intense recirculation of the oil around the heating tip, temperature contours are found to be distorted. From these contour plots, it is evident that a temperature gradient forms in the fluid, producing significant Marangoni shear stresses that speed up the flow close to the surface. As the flow moves away from the hot rod tip, temperature gradients decrease further, which in turn decelerates the flow.
Figs. 6(a) and 6(b) show the temperature contours for d = 4 × 10^{-3} m, ΔT = 14 K respectively. The temperature contours demonstrate the movement of oil from the hot tip to the cold sidewalls along the free surface and its return flow. The bulk flow towards the top of the side wall and the return flow from its bottom constitutes the main cell. As the circulation flow near the sidewalls develops further, secondary cells appear within the main cell [24]. The flow without Marangoni convection is unicellular in nature (only the main cell is present) and follows a parallel flow state in the central region of the layer. Close to the hot tip, the flow gets accelerated and near sidewalls, it gets decelerated. Since the flow is unicellular the secondary cells are not affecting the flow and the fluid follows a more uniform path.

In the presence of Marangoni convection, when the surface tension at the center drops, the free surface flow is carried from the hot center towards the colder sidewalls. From Fig. 7 (b) the presence of secondary cells (cell 1 and cell 2) within the main cell is clearly visible. These cells and the region between are responsible for the sudden deceleration and acceleration of the fluid in the bulk region. Hence the flow is distorted and is not following a uniform path.
Similarly, the velocity contours with and without Marangoni convection is shown in
Figs. 8(a) and 8(b). The fluid velocity is found to be maximum at the hot rod and along the
free surface near to it. From Fig. 7, it is observed that the flow circulates in a clockwise
direction, and the fluid moves away from the tip region towards the side wall. The flow gets
decelerated as it moves closer to the sidewall and accelerates again in the return flow when it
reaches the heating tip. From Fig. 8(a), the flow appeared to be accelerating and decelerating
more uniformly in the absence of Marangoni convection. Velocity is maximum at the heating
tip and its nearby areas and is found to be $0.32 \times 10^{-3}$ m/s. In Marangoni flow, velocity is
maximum near the tip and along the free surface due to steep temperature gradients as shown
in Fig. 8(b). As the fluid moves towards the side walls, the velocity suddenly drops and the
fluid achieves bulk velocity rather quickly. The maximum velocity in the entire fluid domain
is approximately around $1.5 \times 10^{-2}$ m/s. Therefore, it is clear that huge temperature gradients
result in large Marangoni stresses, which cause the flow to accelerate close to the hot tip area.
The sudden drop in velocity afterward can be attributed to the smaller temperature gradients.
From the comparative study, it is evident that the overall velocity for Marangoni flow is
much higher than that of non-Marangoni flow and it can be credited to the convection driven
by surface tension.
Fig. 8 Velocity contours (a) without Marangoni convection, (b) with Marangoni convection for $d = 4 \times 10^{-3} \text{ m, } \Delta T = 14 \text{K}$
Fig. 9 Comparison of (a) Free surface velocity magnitude (b) Free surface temperature and (c) Velocity magnitude at $z = 2.5 \times 10^{-3}$ m with and without Marangoni convection at $d = 4 \times 10^{-3}$ m, $\Delta T = 14$ K

Comparison of velocity magnitude along free surface with and without Marangoni convection is shown in Fig. 9(a). Velocity magnitude of free surface is plotted against radial coordinate $r$. Since there is a huge variation in velocity magnitudes of models with and without Marangoni convection, two different y-axes are chosen. The surface velocity
obtained along the radial coordinate for non-Marangoni flow is much lower than that of Marangoni flow.

The maximum surface velocity is obtained near the heating tip for both Marangoni and non-Marangoni flow. The surface velocity of the oil slowly decreases as it further moves along the radial coordinate. Deceleration of fluid, when compared with Marangoni flow, is more uniform and at a slower rate. In Marangoni flow, fluid reaches its maximum velocity of $15 \times 10^{-3}$ m/s at $r = 0.8 \times 10^{-3}$ m, which is very close to the hot tip and decelerates immediately till $r = 4.8 \times 10^{-3}$ m. Further, the flow decelerates more uniformly at a slower rate till it reaches the cold side wall. At the wall, the velocity again drops suddenly from $0.9 \times 10^{-3}$ m/s to wall velocity. This might be due to the presence of secondary cells which is visible in both temperature and velocity plots. Fig. 9(b) compares the free surface temperature with and without Marangoni convection. Free surface temperature is plotted against radial coordinate $r$. The side and bottom wall temperatures were maintained at 298.15 K. The maximum temperature of 312.15 K is obtained at the hot rod tip. In the absence of the Marangoni effect, the temperature reduced gradually until it reaches the sidewall temperature. In Marangoni flow, the maximum temperature is near the hot tip region and it falls suddenly to 301.5 K till $r = 2.5 \times 10^{-3}$ m. After that, the drop in temperature is more gradual till it reaches bulk temperature.

Fig. 9(c) shows the velocity magnitude plotted against radial coordinate $r$ across $z$ position of $2.5 \times 10^{-3}$ m with and without Marangoni convection. $z = 2.5 \times 10^{-3}$ m represents the secondary cells and the region below the tip. Hence from this plot, the variation of velocity magnitude in the lower bulk fluid and at the secondary cells can be determined. Without Marangoni convection, the velocity magnitude rises to a maximum value of $0.15 \times 10^{-3}$ m/s at $r = 2 \times 10^{-3}$ m. The flow slowly decelerates and is not disturbed further as the flow in the fluid layer is unicellular in nature. In Marangoni flow the maximum velocity obtained is $2.5 \times 10^{-3}$ m/s at $r = 2.2 \times 10^{-3}$ m. When the flow crosses near the center of cell 1, the velocity decreases (as shown in Fig. 7). Further away from the center of cell 1, a marginal increase in the velocity magnitude is observable before dropping again as the flow approaches the sluggish cell 2 regions. Once the flow gets past cell 2 an increase in the velocity is noticeable before decelerating to its minimal value.
4.4. The effects of temperature gradient on Marangoni convection

The Streamline contours were plotted for three different temperature values: $\Delta T = 9.0$ K, 11.5 K, and 14.0 K for a depth of $4 \times 10^{-3}$ m in Fig. 10. For all temperature differences, along with the main cell, two other cells rotating in the same direction are visible. For 11 K and 14 K, cell 2 is clearly more separated than the temperature difference of 9 K.

Fig. 10 The effect of temperature gradient on stream lines contours for $d = 4 \times 10^{-3}$ m

Fig. 11 shows the velocity contours for three different temperature values of $\Delta T = 9.0$ K, 11.5 K, and 14.0 K for depth of $4 \times 10^{-3}$ m. Even though in bulk fluid there is not a significant change, the velocity at the surface is clearly getting increased when the temperature gradient increases. From this, it is evident that an increase in temperature difference increases the velocity of the flow thereby enhancing Marangoni convection.
Fig. 11 The effect of temperature gradients on velocity contour for $d=4 \times 10^{-3}$ m

Variation of free surface velocity with the presence of Marangoni convection is plotted against the $r$ coordinate for three different temperature values as shown in Fig. 12. As the temperature gradient increases the velocity magnitude at the free surface also increases. The maximum free surface velocity is found to be $9.8 \times 10^{-3}$ m/s, $12.7 \times 10^{-3}$ m/s and $15.5 \times 10^{-3}$ m/s for $\Delta T = 9.0$ K, 11.5 K, and 14.0 K, respectively. The deviation of velocity magnitude between the lowest and highest temperature gradients is approximately 45%. Hence it can be concluded that at a higher temperature gradient, the surface velocity will also increase and has a major impact on Marangoni flow.
Fig. 12 The variation of free surface velocity magnitude for different temperature gradients for a layer depth of $4 \times 10^{-3}$ m

4.5. The effect of layer depth on Marangoni convection

Fig. 13 shows the stream line contours for three different layer depths at a temperature difference of $\Delta T = 11.5$ K. For all layer depths, along with the main cell two other cells rotating in the same sense are observed. Cell 1 appears to be the largest at $\Delta T = 14$ K. Larger cell 1 indicates the flow will decelerate more but at a gradual rate. The effect of cell 2 is more sensed at $\Delta T = 9$ K as the increase in velocity near the cold wall after passing cell 2 is found to be small. For $\Delta T = 11.5$ K, free surface velocity for the three different layer depths is plotted with respect to the radial coordinate as shown in Fig 14. The maximum obtained surface velocity is $12.7 \times 10^{-3}$, $12.9 \times 10^{-3}$, and $13.1 \times 10^{-3}$ m/s respectively, and observed that the maximum velocity deviation is around 3% only. The marginal deviation obtained in the magnitude of velocity is due to the change in depth of the fluid domain. From the results, it is clear that for the present test condition, temperature difference has a greater influence on Marangoni convection than layer depth.
4.6. Impact of Meniscus on the Marangoni Convection

A meniscus can be termed as a curve in the surface of a molecular substance (fluids) when it touches another material or surface. All fluids possessing surface tension will make a meniscus by adjusting their shape to minimize surface energy. Also with the help of the meniscus, the surface tension of a particular fluid can be calculated. Hence the presence of meniscus can’t be ignored. The streamline contour in the presence of a meniscus is presented in Fig. 15. The Meniscus is modeled based on the experimental study of [12], where the oil is making a 90° contact angle with the hot tip. The Presence of the meniscus locally inclines the interface and temperature gradient [22]. Due to the presence of a meniscus fluid flows up the meniscus near the tip and accelerated along the other side. Away from the meniscus, the flow...
velocity drops and reaches the lower bulk fluid along the wall. The streamline patterns can be distinguished easily as secondary cells are not visible in the presence of the meniscus. Streamline near the tip is more inclined upwards as fluid tends to flow up the meniscus. Thus, it may be inferred that the meniscus plays a significant role in the heat transfer between the hot tip and the surrounding areas.

![Graph](image)

**Fig. 14** The variation of free surface velocity magnitude for different layer depths at $\Delta T = 11.5$ K.

![Streamlines](image)

**Fig. 15** Streamlines with meniscus for $d = 4 \times 10^{-3}$ m, $\Delta T = 9$ K

Fig. 16(a) compares the free surface velocity magnitude with and without meniscus. The velocity along the surface with a meniscus is observed to be significantly lower than without the meniscus. The meniscus makes the surface velocity smaller and thus reduces the ability of Marangoni convection in driving the flow. This may be due to the change in direction of shear stress along with the meniscus profile. Since the shear stress in normal flow has a fixed direction, the flow seems to have a higher surface velocity. Maximum velocity is found to be $5.2 \times 10^{-3}$ m/s and $9.8 \times 10^{-3}$ m/s for models with and without meniscus, respectively.
Velocity Magnitude (m/s)

\[ \Delta T = 9 \text{ K} \]
\[ d = 4 \times 10^{-3} \text{ m} \]

Temperature (K)

\[ \Delta T = 9 \text{ K} \]
\[ d = 4 \times 10^{-3} \text{ m} \]
Fig. 16 Comparison of (a) Free surface velocity magnitude (b) Free surface temperature and (c) Velocity magnitude at $z = 2.5 \times 10^{-3}$ m with and without meniscus at $d = 4 \times 10^{-3}$ m, $\Delta T = 9$ K

Fig. 16 (b) shows the comparison of free surface temperature plotted with radial coordinate in the presence and absence of meniscus. The peak value of temperature is obtained at the heating tip. In the presence of the meniscus, the heat is transferred to the oil from the bottom as well as the sides of the heating tip, whereas the meniscus is not considered, the oil gets heated only through the bottom side of the hot tip. Since the oil is getting extra heating from the sides, and the presence of high Marangoni stresses in the meniscus strong temperature gradients are maintained close to the tip. Hence the drop in temperature from its peak value is more gradual in the presence of meniscus. Once the flow moves further away from the influence of the meniscus, the deviation in temperature between the model with and without meniscus becomes very low. In Fig. 16(c), velocity magnitude with radial coordinate is plotted for models with and without meniscus at a distance $z = 2.5 \times 10^{-3}$ m. The values obtained show the velocity variation away from the surface, in the bulk fluid region. Velocity magnitude for the meniscus fluid is comparatively lower than that in the absence of meniscus. The maximum velocity magnitude obtained with and without meniscus is $0.85 \times 10^{-3}$ m/s and $1.6 \times 10^{-3}$ m/s respectively. Hence it is evident that the presence of the meniscus will reduce the velocity not only at the surface but also in the bulk fluid. Since cell 1 is not present when the meniscus is considered, the drop in velocity is more uniform and the sudden acceleration and deceleration of the fluid are not observed.
4.7. Presence of Microgravity on the Marangoni Convection flow

An environment where the earth’s gravity is very small, and the objects approach weightlessness can be termed microgravity. The value of gravity is almost negligible in microgravity conditions. Typical space gravity levels can range from 0.1 to 2,500 μg (Giangi et al., 2002), where, 1 μg = 9.81 x 10^{-6} m/s^2. Microgravity investigation is necessary for applications like crystal growth, where crystals can be made with very less defects, as gravity is not influencing the process. The presence of Marangoni convection can influence the defects and helps in growing low oxygen concentration crystals Nakanishi et al., (2002). Since Marangoni convection is the dominant convection in the absence of gravity, it can heavily influence the quality of the crystal. Numerical simulations are run with microgravity conditions to determine whether Marangoni convection is dominating the flow in the chosen shallow liquid layers. In order to achieve microgravity, 500 μg is selected as gravitational acceleration for the simulations in the negative z-direction. The effect of buoyancy is minimal in microgravity conditions since gravitational acceleration is negligible.

![Fig. 17 Streamlines under microgravity for d = 4 x10^{-3} m, ΔT = 9 K](image)

The streamlines are plotted in Fig. 17 for microgravity conditions. Flow patterns are similar in both normal and microgravity conditions, except for the presence of Cell 1 in the microgravity model. The presence of the meniscus made the flow patterns inclined towards it. Fig. 18 compares velocity magnitude at normal gravity and microgravity for ‘z’ position 2.5 x 10^{-3} m. The velocity of the oil under microgravity is slightly higher than that of normal gravity, even though the difference is not highly significant. The slight variation in the velocity magnitude observed might be due to the influence of gravity. The maximum percentage deviation in the velocity is observed to be only around 11%. The radial velocity profile for both normal and microgravity conditions at r = 5 x 10^{-3} m is shown in Fig. 19. The velocity changes its direction at around z = 2.7 x 10^{-3} m. Above this depth, the direction of the flow is from the hot tip towards the cold sidewalls and underneath, the flow returns back.
From the comparative study, it is clear that the velocity profiles for both normal and microgravity conditions are similar and Marangoni convection is indeed dominating the flow more than natural convection.

*Fig. 18* Comparison of velocity magnitude under normal and microgravity conditions for $d = 4 \times 10^{-3}$ m, $\Delta T = 9$ K at $z = 2.5 \times 10^{-3}$ m

*Fig. 19* Comparison of radial velocity profile under normal and microgravity conditions for $d = 4 \times 10^{-3}$ m, $\Delta T = 9$ K at $r = 5 \times 10^{-3}$ m
5 Conclusions

The combined buoyancy-Marangoni convection for a two-dimensional steady flow has been studied for shallow liquid layers. Numerical simulations were performed using COMSOL V5.6. Different layer depths and temperature gradient effects on Marangoni convection are investigated. The effect of the meniscus on the Marangoni flow is also discussed. Microgravity simulations are performed to prove that Marangoni convection is dominating the flow. From the present study, the following conclusions are obtained.

- The flow is observed to move radially from the hot tip area at the top towards the cold side walls and return back to the tip. Higher temperature and velocity contours are observed near the hot tip.
- Throughout the fluid domain the velocity obtained in the presence of Marangoni convection is significantly higher than that in its absence. The maximum surface velocity obtained with and without Marangoni convection is $15 \times 10^{-3} \text{ m/s}$ and $0.32 \times 10^{-3} \text{ m/s}$ respectively for $d = 4 \times 10^{-3} \text{ m}$, $\Delta T = 9 \text{ K}$.
- The flow without Marangoni is unicellular in nature, whereas in Marangoni flow two secondary cells are also visible. The presence of these cells makes the flow more distorted.
- The influence of temperature gradient and layer depth on Marangoni convection is studied for the selected range of $\Delta T$ and $d$. It is found that the maximum velocity deviation is around 45 % and 3 % respectively.
- It can be concluded that for the chosen conditions, the temperature difference is influencing Marangoni convection more than layer depth.
- The presence of meniscus causes the surface velocity to be smaller which makes Marangoni convection less effective in driving the flow. The peak velocity magnitude gets reduced by 60 % in the presence of the meniscus.
- Microgravity study proved that the layer depths selected are thin enough for Marangoni convection to be dominant.
- It was found that pure Marangoni convection dominates in the presence of microgravity that helps in improving the quality of the material produced such as a single crystal, welded joints etc.
Declarations

Ethical Approval
This declaration is not applicable.

Competing interests
The authors declare that they have no competing interests.

Authors’ contributions
Author 1 collected all information regarding the concept, found the novelty, and learned and handled the software tool. Author 2 proposed the concept, corrected, proofread, and submitted the manuscript.

Funding
The authors declare that no funding was received.

Availability of data and materials
VIT University has provided the licensed version of the software tool used.

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