# Effect of aspect ratio on basic-flow pattern induced by thermocapillary effect in free liquid film


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## Background

Thermocapillary-driven flow is realized by a surface tension difference due to non-uniform temperature distribution over the free surface. The fluid on the surface is generally driven from a region at higher temperature to that at lower temperature. Dr. Donald Roy Pettit, a NASA astronaut, demonstrated a series of experiments in the International Space Station in 2003 [1]. In this experiment, he formed a thin free liquid film of water in a metallic ring and placed a heated iron close to one side of the ring. From this experiment, he found that the fluid was driven from a colder region to a hotter region even though the fluid has a negative temperature coefficient of surface tension. After such unique demonstrations, Ueno and Torii [2] indicated there exist two major basic flows in a free liquid film; double-layered flow (DLF) and single-layered flow (SLF). The mechanism and selection of basic flows are discussed by numerical simulation[3-5], but little discussion has been done by experimental investigations except Fei et al.[6] .

In the present study, we focus on a multicellular flow structures in single-layered flow (SLF) by changing $\Gamma_{zx}$. In our experiments, a liquid film of 6-cSt silicone oil (Pr = 83.25) is formed in a rectangular hole in the aluminum plate. We discuss the **formation of the multicellular structures** by making comparisons with numerical results.

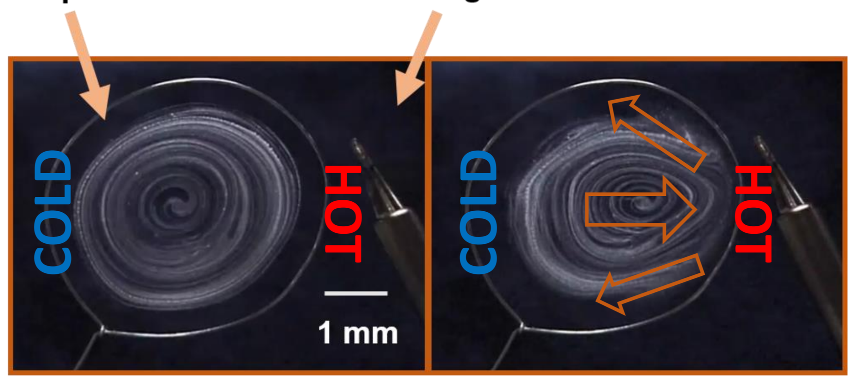



Fig. 1 Experiment on the ISS by Dr. Donald Roy Pettit in 2003 (©NASA) . The fluid was driven from a colder region to a hotter region.

## Symbols

**Nomenclatures**

| | | |
|---|---|---|
| $D_p$ | diameter of tracer particle | [m] |
| $d$ | depth of the film | [mm] |
| $L_x$ | end-wall distance | [mm] |
| $L_z$ | span-wise length | [mm] |
| $T$ | temp. | [°C] |
| $T_c$ | temp. at cold side | [°C] |
| $T_h$ | temp. at hot side | [°C] |
| $u$ | velocity of x component | [m/s] |
| $x$ | position in streamwise direction | [-] |
| $y$ | position in depth direction | [-] |
| $z$ | position in spanwise direction | [-] |
| $V$ | liquid volume | [m$^3$] |
| $V_0$ | volume of hole region | [m$^3$] |

**Geeks**

| | | |
|---|---|---|
| $\Delta T$ | temp. difference | [°C] |
| $\kappa$ | thermal diffusivity of fluid | [m$^2$/s] |
| $\mu$ | viscosity of fluid | [Pa s] |
| $\nu$ | kinetic viscosity of fluid | [m$^2$/s] |
| $\rho$ | density of fluid | [kg/m$^3$] |
| $\rho_p$ | density of particle | [kg/m$^3$] |
| $\sigma_T$ | temp. coefficient of surface tension | [N/(m K)] |

## Experimental apparatus

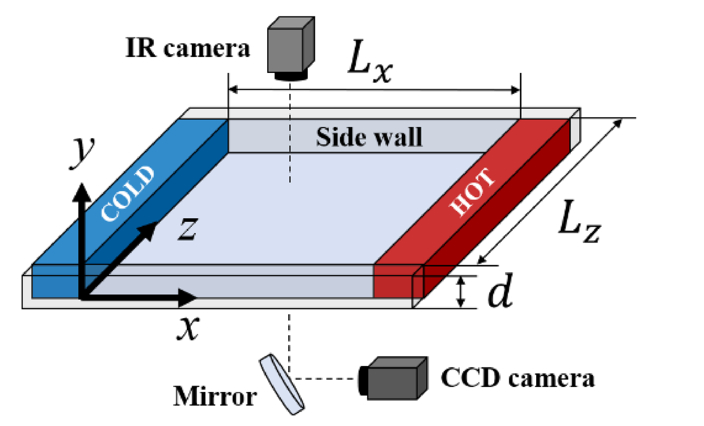



Fig. 2 Schematic of experimental apparatus. Temperature is taken by IR camera and the convection is taken by CCD camera.

## Experimental conditions

### Non-dimensional numbers

● Aspect ratio

$\Gamma_{zx} = L_z/L_x$

$\Gamma_{xy} = L_x/d$

$\Gamma_{zy} = L_z/d$

● Stokes number

$$\mathrm{St} = \frac{\rho_p {D_p}^2 u}{18\mu d} = 0\ (10^{-5} \sim 10^{-4})$$

● Marangoni number

$$\mathrm{Ma_L} = \frac{|\sigma_T|\,(\Delta T/L_x)d^2}{\rho\nu\kappa}$$

### Properties

● Test fluid [7]

| 6-cSt silicon oil (at 25 ℃) | | |
|---|---|---|
| Prandtl number | [-] | 83.25 |
| Density | [kg/m$^3$] | 916 |
| Kinetic viscosity | [m$^2$/s] | $6.0\times10^{-6}$ |
| Thermal diffusivity | [m$^2$/s] | $7.31\times10^{-8}$ |
| Thermal expansion coefficient | [1/K] | $1.09\times10^{-3}$ |
| Surface tension | [N/m] | $1.98\times10^{-2}$ |
| Temp. coeff. of surface tension | [W/(m K)] | $-5.79\times10^{-5}$ |

● Tracer particle

| Gold-coated acrylic particle | |
|---|---|
| Diameter [μm] | 15 |
| True specific gravity [-] | 1.80 |

● Test plate

| Material of the plate | Aluminum |
|---|---|
| Thermal conductivity [W/(m K)] | 236 |
| Thermal diffusivity [m$^2$/s] | $97.4\times10^{-6}$ |

### SLF (one of basic flow)

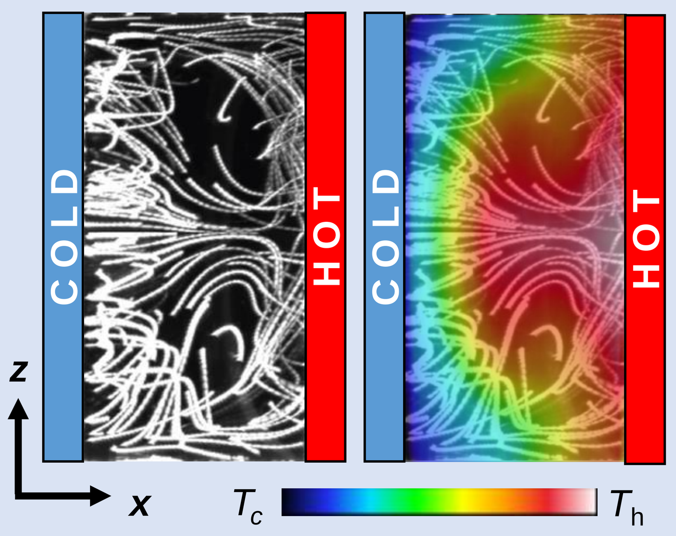



Fig. 3 Synthetic images of particle path lines and temp. distribution of SLF.

● Exp. conditions

(Length of liquid film)

$(L_x, d, L_z)$ [mm] = (2.0, 0.2, 4.0)

(volume ratio and Marangoni number)

$V/V_0 = 0.9$, $\mathrm{Ma_L} = 19$

(temp. difference)

$\Delta T = 6.7$ K

(frame rate)

CCD camera : 120 fps, IR camera: 60 fps

## Results (Experiment)

### Cell number in SLF of the free liquid film with $L_z$ (span-wise length)

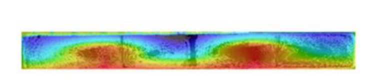
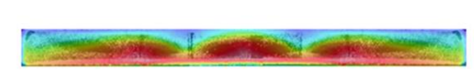
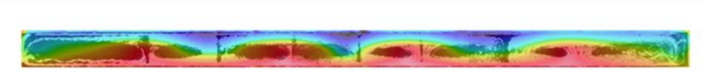
| | flow field and temp. distribution over free surface | $\mathrm{Ma_L}$ ($\Delta T$ [K]) | cell # (pair) |
|---|---|---|---|
| (a) |  | 25 (4.3) | 1(2) |
| (b) |  | 34 (10) | 2(4) |
| (c) |  | 47 (9.4) | 3(6) |
| (d) |  | 52 (15) | 4(8) |

Fig. 4 Flow and temp. filed over free surface. Each $(L_x, d, L_z)$ [mm] are (a)(1.0, 0.3, 6.0), (b)(1.0, 0.3, 9.0), (c)(1.0, 0.3, 12.0), (d)(1.0, 0.3, 18.0).

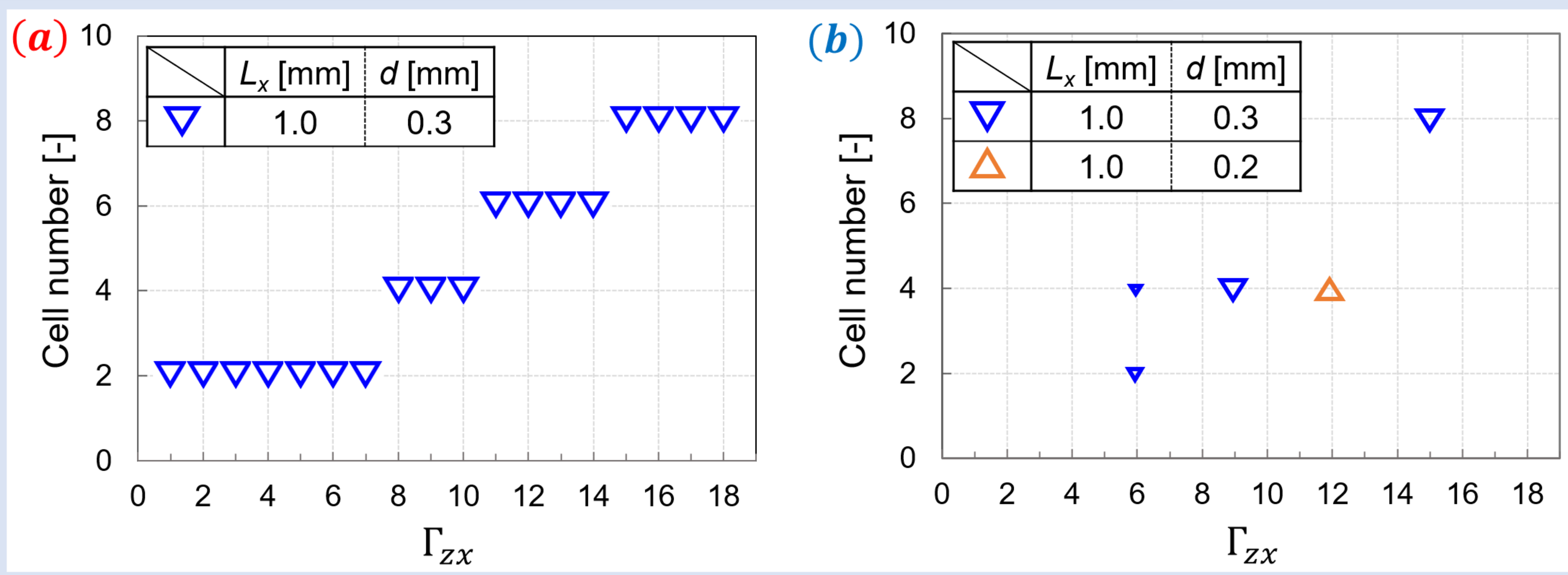



Fig. 5 Number of cell visualized over free surface of the film with $\Gamma_{zx}$ . (a) is $V/V_0 = 0.9$, (b) is $V/V_0 = 0.75$ .

▸ Figure 4 shows cell number of SLF is increased as the increase of span-wise length (which means, the structure of SLF flow is depends on aspect ratio of free liquid film).

▸ Figure 5 indicates cell number changes as aspect ratio to a threshold (ex. $\Gamma_{zx} = 8, 13, 15$).

▸ In the experiment up to now, the change of the cell structure has been confirmed even in the free liquid film with different volume ratio ($V/V_0 = 0.9$ and $V/V_0 = 0.75$).

### Cell size variation

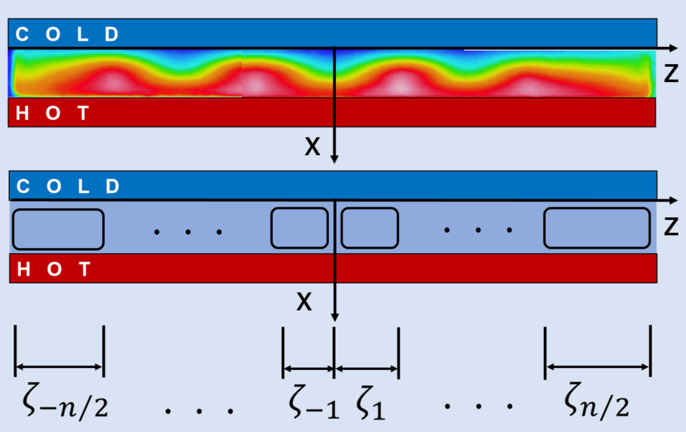



Fig. 6 Definition of cell length ($\zeta$).

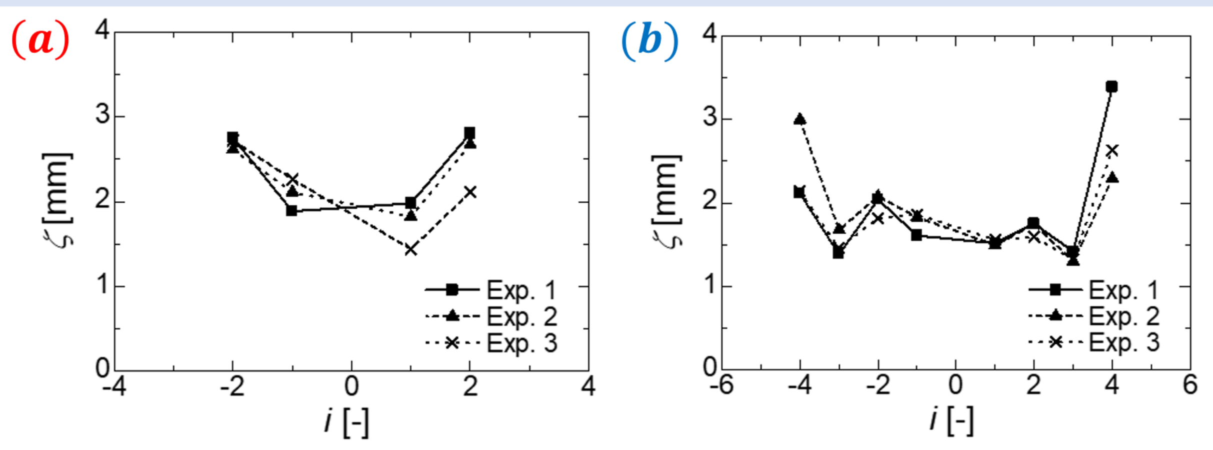



Fig. 7 Number of cell visualized over free surface of the film with $\Gamma_{zx}$ . (a) is (1.0, 0.3, 9.0), (b) is (1.0, 0.3, 18.0).

▸ In order to quantitatively evaluate each cell in SLF, each cell is defined as shown in Fig. 6.

▸ It is found that the size of the cells in the central region is almost constant and smaller than those near the side walls ($n \geq 4$).

## Summary

▸ Multicellular structures induced by the thermocapillary effect in the free liquid films are investigated experimentally and numerically. Correlation between the cell number/size and the liquid-film aspect ratio is illustrated.

▸ The size of cells expressed in SLF varies in location.

## Results (Numerical simulation)

▸ Numerical simulations also show that the number of cells increases from two to four when $\Gamma_{zx} \geq 4$. However, unlike experiments, no further increase has been confirmed until now.

▸ The flow from the cross-section direction ($x - y$) observed in the numerical calculation is different from the experiment (Fei et al. ).

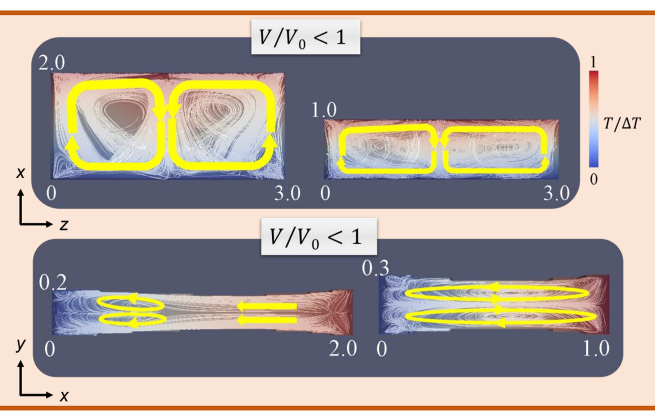



Fig. 8 Convection field and temperature field by numerical simulation of free liquid film (2.0, 0.2, 3.0) and (1.0, 0.3, 3.0).

## Future plans

▸ General criteria for the pattern formation in the free liquid film and its occurring condition will be indicated, and will be compared to those of such as Rayleigh-Bénard and Marangoni-Bénard convections.

▸ Effects of bottom walls on the thermocapillary-driven convection and pattern formation will be discussed taking account of the thermal-flow fields and the energy analysis.

## References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