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Complex Flow and Heat Transfer Behavior of Micro/nano Fluidics: Benard Convection Always Occurs in a NEMS World

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***Abstract*—In recent years, interest in the thermal-hydraulics at micro/nano scale keeps increasingly growing owning to the rapid technology thus enabled. It was now accepted that, the classical thermal or fluidic theories working well for "macro bulk systems" may become invalid for micro/nano scale geometry. On the contrary, some phenomena seldom occur in the large scale may frequently happen as a routine event in the small word. This study is aimed to theoretically predict a basic phenomenon that may always be encountered in the micro/nano fluidics devices, i.e. the previously well known Benard convection cell could easily be induced in a nano scale liquid film even by an extremely small temperature difference across such layer. It is this event that increases the complexity of the flow and heat transfer patterns in the MEMS/NEMS. Fundamental mechanisms related to this phenomenon will be interpreted and its implementations for developing useful tool will be suggested.**

Keywords-Benard convection; micro/nano fluidics; heat transfer

I. INTRODUCTION

Recent science and technology are witnessing a trend of miniaturization. Building systems as compactly as possible has become a major theme either for engineering practices or academic investigations [1]. Driven by this miniaturization trend, the microfabrication technology is maturing, more attention is paid on the exploitation of microsystem performance and fluid flow in microsystem is found significant in many practical situations [2][3]. Over the past few years, countless endeavors were made to develop superb ways for fabricating, designing and characterization of new micro/nano fluidics device and system, consisting of the core elements of many "micro or nano-machines". Among many disciplines to develop the new emerging technologies in this area, the fundamentals arise from the micro/nano fluidics and heat transfer science especially aroused dramatic attentions.

This article is aimed to reveal a generalized phenomenon, i.e. the complex Benard convective flow and heat transfer pattern in nano fluidics devices. In the classical/macro fluid mechanics, the well known Benard convection, which refers to the instability of a fluid layer confined between two thermally conducting plates, and heated from below to produce a fixed temperature difference, was mainly observed in a much larger gap space and has been intensively studied before [4]-[8]. As will be seen from the present study, in a micro/nano electromechanical fluidics system, a fluid layer confined between two thermally conducting plates always exists and an extremely small temperature difference across this nano sized liquid layer would be strong enough to induce a large temperature gradient and thus easily trigger the nano scale Benard cell. To better understand this problem, numerical simulations have been carried out to investigate Benard convection, heat transfer and complex flow behavior of fluid heated from a horizontal fluid layer within various typical structures. Meanwhile, the theoretical model was discussed and some novel applications based on such effect were suggested.

II. THEORETICAL MODEL

Without loosing any generality, the calculation domain within a volume of $40\times40\times10$ nm3 for the nano liquid layer as displayed in Fig. 1 has been chosen for a preliminary investigation. It should be pointed out that, in such scale, the Navier-Stokes equation as well as its corresponding energy equation still approximately hold true for characterizing the flow and heat transfer across the nano scale film gap [9][10]. Numerical method was applied to calculate such three-dimensional thermal hydrodynamic problems. Water was used as the main liquid to be tested. The other physical parameters are set as: room temperature 300K; the temperature difference across the nano fluid layer is 0.1K; the temperature dependent water density reads as: $\rho=\rho_0[1-\alpha(T-T_0)]$, with the thermal expansion coefficient α ranging from 1E-3/K to 1E-4/K, ρ_0 is reference density at 1000kg/m3. Considering the scale effect, the viscosity for the water in the nano film gap was modified as 0.5poise. Initially, the water layer was treated as in steady state at room temperature.

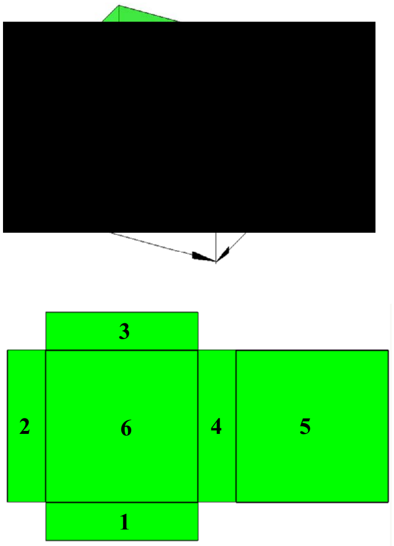

Fig. 1 Geometrical calculation domain

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To predict the Benard cell convection in various situations, several typical boundary conditions were prescribed as followed if particular treatments were not mentioned:

Case 1: The bottom surface of the cube (Face 5) is assumed as hot wall and the other surfaces are cold with the same temperature.

Case 2: The bottom surface of the cube (Face 5) is assumed as hot wall; Face 1 is used as input condition with a uniform velocity at 1E-20 m/s; Face 3 is set as outflow condition while the other surfaces are treated as cold wall with the same temperature.

Case 3: The bottom surface of the cube (Face 5) is assumed as hot wall; Faces 1 and 2 are set as input condition with a uniform velocity at 1E-20 m/s; Faces 3 and 4 are outflow and Face 6 is as a cold wall.

Case 4: The bottom surface of the cube (Face 5) is assumed as hot wall; Faces 1 and 3 are set as input condition with a uniform velocity at 1E-20 m/s; Faces 2 and 4 are outflow condition and Face 6 is a cold wall.

Here, the well established CFD tool—FLUENT was adopted for the numerical simulation.

III. RESULTS

Recently, advances in micro/nano technology provided many unique opportunities to fabricate miniaturized fluid devices, which have a variety of applications ranging from biomedical devices, lab-on-a-chip and other cases of practical interests [3][11]. The dense integration of microfluidic components for the construction of compact and monolithic chip-sized laboratories and reaction systems requests to combine many different functions on the same substrate. Some useful chip-based operations could include mixing, filtering, metering, pumping, reacting, sensing, heating, and cooling of nanoliter volumes of fluids [12][13]. Consequently, many interesting geometrical profiles such as micro channel, micro tube, microreactor, micro mixer, micro filter, micro container and micro heat exchanger are quite hackneyed. In accordance with the diverse structures and materials of these devices, the following studies were performed to comprehensively investigate the effects due to variable flow condition and circumstances, fluid mediums and complex internal construction, calculation domains, boundary conditions, etc. For brevity, only typical results will be given as follows.

A. Typical Benard convection

Some typical simulation results were depicted in Fig. 2. It was found that a very small temperature across the fluid gap will easily lead to Benard convection. Additional calculations by using the temperature difference such as 0.0001K, 0.001K and 0.01 K also gives the same conclusion. Fig. 3 presents the result by changing the temperature difference and physical parameter α. The shape of Benard convection cells for these circumstances doesn't distinguish with each other but the maximum velocity becomes larger along with the increasing temperature difference, and got lower with the decrease of the thermal expansion coefficient α.

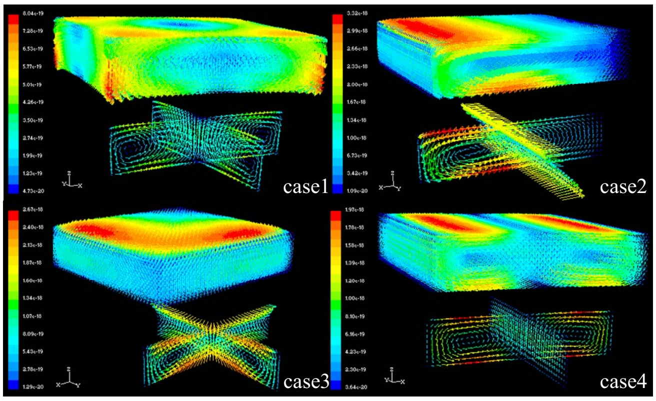


Fig. 2 Typical Benard cell induced in a rectangular channel

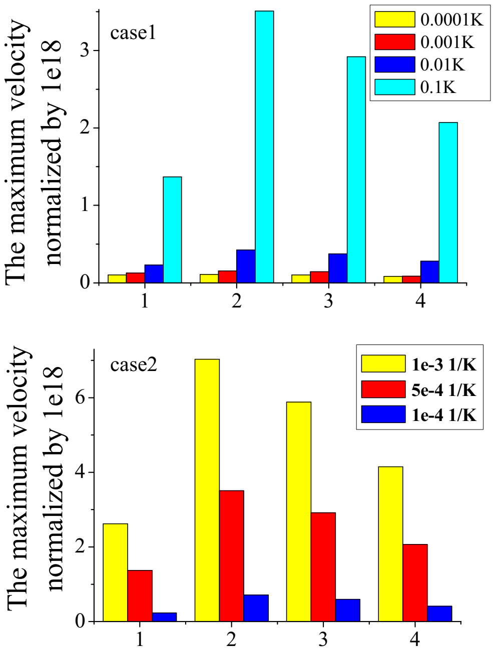


Fig. 3 Results obtained through changing physical parameters
Case 1: Various temperature differences;
Case 2: Various coefficient of thermal expansion.

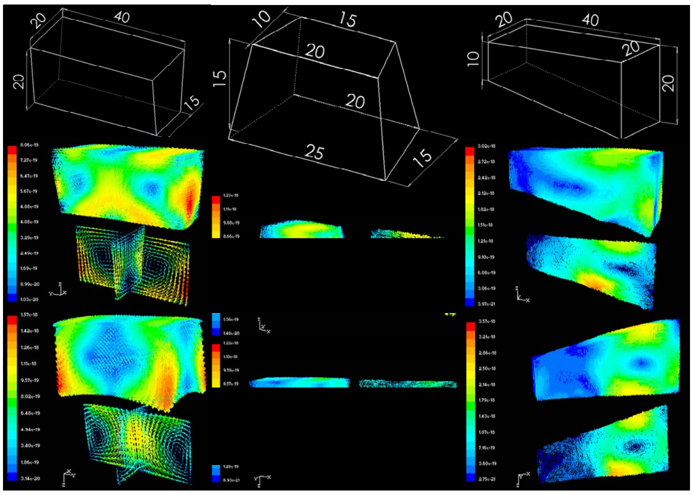
B. Irregular rectangular structures

Considering that in a micro/nanofluidic system, the flow channel and flow conditions are generally more complex than one may anticipate, several geometries with specific irregular structures were also tested, aiming to disclose and compare the different behaviors of the Benard convection cells thus involved. Such flow channel may appear more close to the reality. For example, in a small world, precisely fabricating an exactly rectangular or triangle channel is often extremely difficult, if not impossible.

Fig. 4 presented the Benard convection results at several different architectures as calculation domains. Among these, case 1 is for that obtained in a nano rectangular channel. In the micro fabrication, because of the crystal structure of materials, the angle between two faces may not always be 90 degree. In this case, the cross section will not be a rectangle but a trapezium. When the long hemline is on the top, the Benard convection cells congregate at the central place; and when it is on the bottom, the cells would disperse to both sides.

What reflected by case 2 is for the result obtained in nano terrace. It was interesting to note that, when the large underside was at the bottom, there is only one Benard cell at the cross section. However, when the large underside was on the top, there would possibly appear two Benard cells simultaneously. Consequently, different structure modes could be generated based on practical requests.

The structure design as depicted in case 3 is stimulated from classical books and references which said that the Rayleigh−Benard convection is the motion of the fluid that lies between two horizontal plates. Now, it is obviously that no matter where the declining plate is, on the top or bottom, the Benard cell appears all the time. And the clearest Benard cell is always located in the right part on the across section.



case 1 case 2 case 3

Fig.4 Different geometries as calculation domains

C. *Effects of inlet velocity*

Fig. 5 reflected the results by changing the velocity at inlet of the channels already tested in the Fig. 4. The calculation started from prescribing the inlet velocity at 1e-20 m/s. For the normal channels, when the velocity reaches a high level such as 1e-17 m/s, the fluid would just flow through the domain without circulation, as indicated in case 1. However, for the other two cases, the get through velocity doesn't keep in line any longer. Here, the get through velocities are 1e-15 m/s and 1e-17 m/s for case 2 and 3, respectively. Thereby, if both inlet velocity and Benard cell were required simultaneously, it would have more choices with the channel in case2. And when the velocity is 1e-20 m/s, the Benard cells appeared on the across section are inconsistent, one in case 2 and two in case 3.

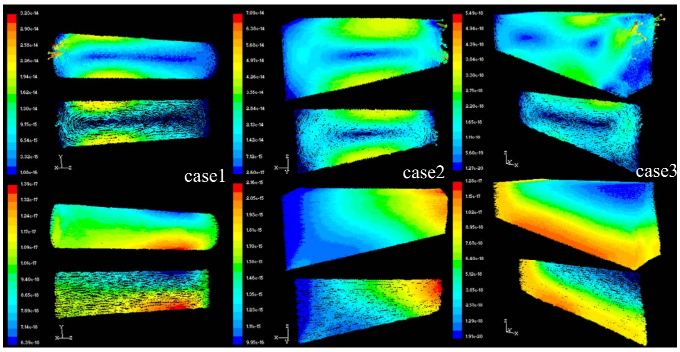


Fig. 5 Effects of velocity at inlet boundary on the Benard convection

D. *Effects of boundary conditions*

Fig. 6 indicated the results by changing the thermal boundary condition on the erect faces. For the case 1, the first class thermal boundary condition T=301K was used, while case 2 is for the first class thermal boundary condition at T=299K. Case 3 reflects the Second Class thermal boundary condition using zero heat flux q=0. Case 4 is for the Third class thermal boundary condition through considering a convection heat transfer coefficient h=1e6 W/m2K, at T0=300. These are two orthogonal sections in the middle of the calculation domain. In the first class condition, the location and shape of Benard cells do not vary greatly from each other, but the direction of rotation in T=301K is opposite to T=299K. And in the other two conditions, although the figure and different central position of Benard cell are distinctively different, the direction of rotation is uniform. It's also obviously that Benard cells appear at both across section in the first class condition, but only one in the other two conditions.

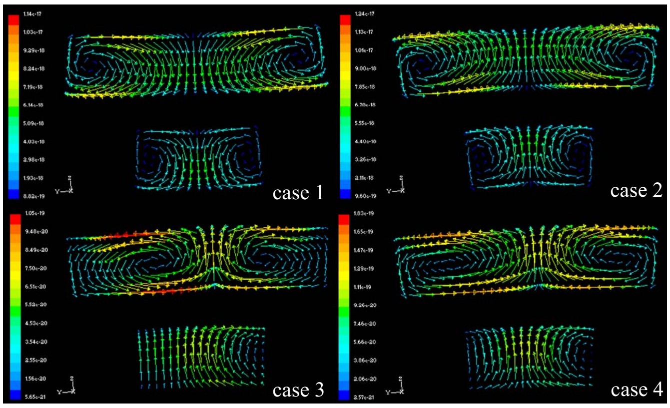


Fig. 6 Effects of changing the thermal boundary conditions on the erect faces;

E. *Domain with structures embedded inside*

Fig. 7, 8 represent the cases when certain geometrical structures were embedded inside the calculation domains. Inspiration for choosing such structures comes from the micro heat exchanger with fin, whose existence plays an important role in the fluid flow and heat transfer.

In Fig. 7, for case1, the additive structures didn't prong the underside; Benard cells congregated in the central place and occurred at only one across section. On the contrary, in the case 2, the embedded structures prong the underside and Benard cells did not only appear at both across section, but also disperse to both sides.

In Fig. 8, the surface temperatures of added configuration are 300K and 300.1K for case 1 and case 2, respectively. Benard cells appeared on the across section are inconsistent, one in case 1 and two in case 2 with same rotation.

Clearly, arrangement of different structures in the flow channel will induce very different results.

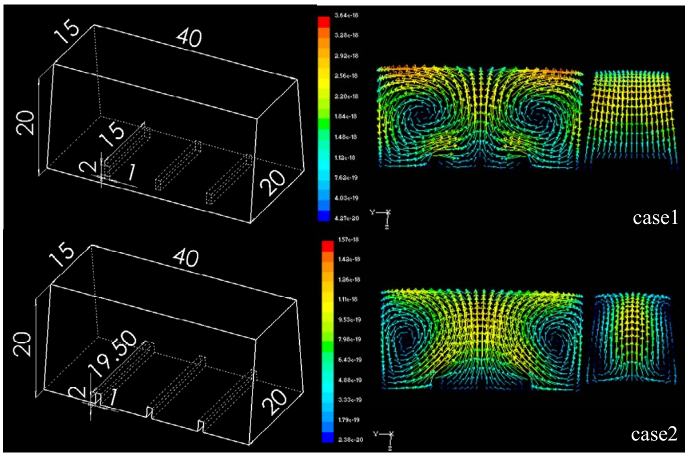


Fig. 7 Results for cases with typical geometric structures embedded inside the calculation domains.

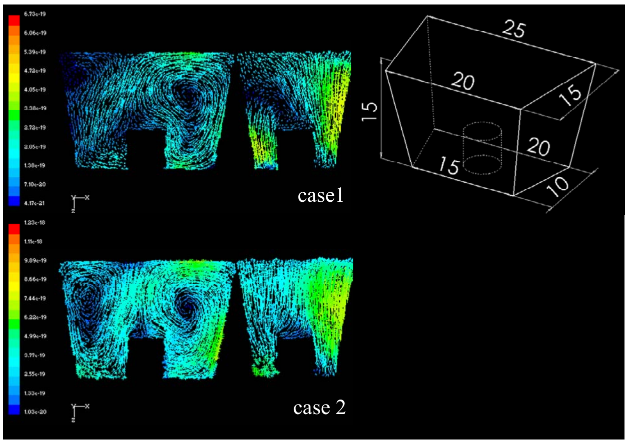


Fig. 8 Results by setting different temperature across the embedded structure
Case 1: The temperature across the cylinder is 300K;
Case 2: The temperature across the cylinder is 300.1K

F. *Effect with different fluid medium*

Fig. 9 calculated the effect due to changing different fluid medium in the calculation domains. In some chemical process, the fluid medium is not water, but some organic reagent. Therefore, we choose to consider other four fluid organic mediums for calculation examples. Case 1 is benzene (liquid); case 2 is for methyl alcohol (liquid); case 3 is fuel oil (liquid); while case 4 is for ethyl alcohol (liquid). For the liquid benzene, Benard cells appeared on each across section symmetrically and conformably. For the rest liquids, the form and location of Benard cells also appear abnormal.

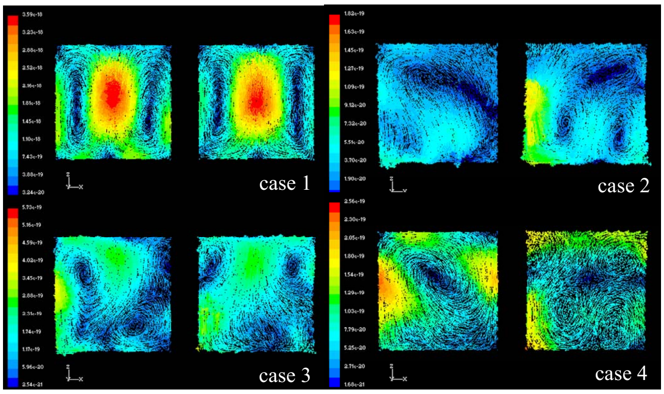


Fig.9 Results by adopting different fluid medium in the calculation domains

IV. DISCUSSION

Convective flows are ubiquitous in nature and play a central role in a wide variety of transport processes occurring in industrial processes involving heat transfer, chemical reactions, and crystal growth. Therefore, it is not surprising that the same is true in miniaturized fluidics in the micro/nano world [13][14]. Benard convection occurred in nanoscale presents a novel and greatly simplified mechanism for sensing slender thermal gradient and performing thermally activated biochemical reactions. The comprehensive numerical simulations as given above have revealed that Benard convection in nanoscale is quite sensitive to temperature difference across a small channel, no matter what its geometry appears as. A surprisingly enough conclusion lies in that, even an extremely small temperature difference such as 0.0001K would induce the Benard convection. For an unsteady state, even smaller thermal gradient could induce such phenomenon instantaneously. In the context of slender thermal gradient and speedy establishment of thermal equilibrium in nanoscale, no temperature device currently could achieve such high precision and sensitivity. Due to this magic precision and sensitivity, a new sensing effect on temperature can possibly be developed in the near future.

Recently, some investigators also have demonstrated a novel device designed to harness the circulatory flow field established by Rayleigh-Benard convection to realize the temperature cycling necessary to perform polymerase chain reaction (PCR) [13]. The experimental result indicated that such performance gain a distinct advantage over conventional thermocyclers. Therefore, existing of Benard convection in micro/nano fluidic devices for administrating chemistry and biology reaction, i.e. lap-on-the-chip, enabled some new biochip devices. Clarification on the mechanism of the complex Benard convection and implement it to the micro/nano world would be helpful in improving the performance of micro/nano fluidic device.

V. CONCLUSION

From the present CFD simulation, it can be found that only a very small temperature difference, which is easily available in an electromechanical fluidics system, would induce the well known Benard convection cell over the nano domain. On the macro scale bulk structures, such occurrence however generally requests a much large temperature difference. At the present stage, only a small temperature difference down to 0.0001K could arouse the Benard convection. Therefore, it is safe to say that, Benard convection may always occur in the fluidics world of a MEME/NEMS unless a uniform temperature over the whole system is strictly guarantied, which is not easy however.

In addition, all the above results reveal that no matter what inlet boundary condition, or distinct thermal boundary condition are considered, the Benard convection appears all the time, although the rotation direction and the shape of vertex may be variable for different cases. The fundamental insight into the micro/nano fluidics device appeared much complex than what was anticipated from the viewpoint of the large world. It is this event that increases the complexity of the flow and heat transfer patterns in the MEMS/NEMS. Clarification of the mechanism about Benard convection in nano world would be helpful in improving the performance of micro/nano fluidic device. In this sense, tremendous theoretical as well as experimental researches are strongly needed in the near future.

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