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Convective Heat Transfer inside a Fluid-Filled Rectangular Cavity

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Abstract

Heat transfer is one of interesting fields of research investigated in many engineering applications. It relates to the amount of energy transferred due to temperature difference of two or more surfaces of materials at a particular mode of transfer in respect of time. Heat transfer has several modes of delivery including convection, conduction, and radiation. Heat can be transferred through a medium or a combination of mediums which can be forms of solid, liquid, and gas or a combination of those forms. A number of researches have been carried out related to heat transfer concepts in a number areas of applications including energy, industry, health, etc. This research is to review on convective heat transfer inside a fluid-filled rectangular cavity and address a number of conditions affecting convective heat transfer of the systems including: effect of partially active wall, effect of nanoparticle fluid, effect of magnetic field, and effect of thermo-sensitive gels & functional particles. The conclusions are also presented based on the explanation of the information and data collected.

Keywords: Heat transfer, natural convection, negative thermal expansion, rectangular cavity, polymer solution, thermo-sensitive gel

INTRODUCTION

Heat transfer is considered as one of interesting fields of research and its applications recently can be found in many engineering and commercial products including an electric blanket to maintain comfortable body temperature for post-surgery patients, environmentally friendly insulation materials for buildings and clothes in extreme weather conditions, hot furnaces for pig iron purification in steel industries, nuclear reactors, etc.

In general, heat can be transferred through several modes of delivery including convection, conduction, radiation, and variations of the modes through a medium or a combination of mediums which can be in forms of solid, liquid, and gas [1-3]. A number of research has been done so far by many scientists that investigate about natural convective heat transfer within particular fluids as a research interest including to observe the effect of active wall's position (heat source) and geometrical size of the cavity containing the fluids on some parameters of heat transfer such as temperature profiles, Nusselt number, and thermal conductivity.

Convective heat transfer can be understood as heat transferred due to the movement of fluid which can be forms of liquid or gas triggered by its temperature difference (natural convection) or the fluid motion can be generated by one or more external sources such as fan, compressor, and other suction devices (forced convection). Especially for natural convection, the movement is due to the interaction of gravity and density difference within the fluid affected by temperature gradient of the hotter area and the colder area, concentration, or composition [2].

Including natural convection within rectangular cavity is heat transfer between various surfaces of a rectangular parallelepiped cavity without interior solids defined by an angle term of θ measured from the horizontal. For this condition, fluid inside the cavity is surrounded by two different parallel isothermal walls (upper and lower plates) that incline at the angle of θ from the horizontal and are separated at a particular distance (L). By terminology, term of $\theta = 0^\circ$ is associated to horizontal plates heating from the below and term of $\theta = 90^\circ$ is referring to vertical plates heating from the sides. For a particular condition, temperature of the upper plate can be higher than that of at the lower plate and for this condition, θ will equal to 180° that correlates to the horizontal wall heated from the above [2]. According to Bergman et al. [1], heat flux transversely through the fluid-filled cavity depends on convection heat transfer coefficient of the fluid (h) and difference temperatures of the two opposing walls (ΔT). In addition, an aspect ratio (H/L) and the value of θ described above also strongly affect heat flux of the cavity.

EFFECT OF PARTIALLY ACTIVE WALL

Partially active wall refers to a condition where a heat source is located on one particular wall of the rectangular cavity. In fact, the rectangular cavity can have more than one heat sources mounted on its different wall. Some applications of the system can be found in heating and cooling of buildings, and cooling system of electronic heaters [4].

A number of research have been done especially based on this matter. Yigit et al. [5] investigated aspect ratios (AR) of the sample fluid which followed the model of Bingham fluid and studied about the influence of *AR* parameters on natural convection inside rectangular enclosures heated from the below. In the research, ratio of enclosure height ($AR = 0.25$ to 4) and nominal Rayleigh number ($Ra = 10^3$ to 10^5) for a single value of Prandtl number ($Pr = 500$) were set for the experiment. By comparing the Newtonian and Bingham fluids, it revealed that convective heat transfer was increasing with the increase of nominal Rayleigh number for the both fluids. In fact, the value of mean Nusselt number of the fluids following the Bingham model remained smaller than that of the Newtonian fluids for the set values of *Ra* and *Pr*.

According to the research, it was due to increasing viscous resistance that occurred from yield stress in the Bingham fluids. Apparently, the mean Nusselt number decreased with the elevation of Bingham number (*Bn*) until thermal transfer was driven by conduction for larger values of *Bn*. In addition, effect of convection was weakening with the increasing of *AR* at a given value of *Ra* and *Pr* for both Bingham and Newtonian fluids. For *AR* above the values (i.e. for tall enclosures), the heat was mainly transferred by conductive mode of delivery.

A study about natural convection in rectangular cavities heated on one vertical wall where other five surfaces were considered adiabatic had been performed by Karatas & Derbentli [6]. In the research, aspect ratio (*A*) of each rectangular cavity was set to 1, 2.09, 3, 4, 5, and 6 respectively with a constant height of 340 mm and a depth of 210 mm. To obtain specific shape, length of cavity was varied according to a particular aspect ratio which referred to a height-length ratio (*H/L*). Thirty five positions of temperature distribution were set on the length direction and were vertically distributed in 3 positions: bottom, middle, and top. Only one line of temperature distribution was applied in respect to the depth of the cavity. The research revealed that slightly temperature changes near the central region and concentration of isotherms were formed near the active wall. In fact, local Nusselt number varied along the height of cavity for Rayleigh number ranging from 2.6×10^5 to 5.06×10^7. There were increasing temperatures from the left to the right wall and the temperature gradient at the left wall was higher than that of the right wall due to a local heat sink on the left wall. At the central area of the cavity, temperature profile showed a linear variation with lower temperature gradient compared to that of at the near wall region where the heat was transferred by a conductive mode of delivery. Moreover, near the central area of the cavity, the temperature profile was almost flat for $A=1$ and $A=2.09$ but the gradient of temperature profile slightly increased with the increasing of aspect ratios (*A*) from 3 to 6. In case of the left wall for $Y=0.125$ (bottom line), temperature gradient was almost horizontal for all aspect ratios and it decreased when the aspect ratio was increased.

A numerical study of double-diffusive natural convection was investigated by Corcione et al. [7]. The research set vertical square enclosures having two opposite horizontal temperature and concentration gradient. The author solved conservation equations of energy, mass, momentum, and species by using computational codes based on SIMPLE-C algorithm for the combining pressure-velocity. In simulation of the experiment, some of independent variables were applied including buoyancy ratio, Lewis number, the Rayleigh number, and Prandtl number. The research revealed that mass and heat transfer were increasing if the Prandtl number and thermal Rayleigh number were expanded. Unlike the rate of mass transfer which was elevated with the augmented of Lewis number, heat transfer rate was fairly uncorrelated with the Lewis number provided that the buoyancy ratio was lower than the number at which the littlest heat transfer existed. Settings parameters of the experiment were performed for buoyancy ratio (*N*) ranging from 0.1 to 100, thermal Rayleigh number (Ra_T) ranging from 10^3 to 10^6, Prandtl (P_r) number ranging from 1 to 10, and Lewis number (L_e) ranging from 1 to 1000.

The research showed that rate of heat transfer increased when Ra_T and P_r were augmented and effect of *Pr* number on heat transfer was less than that of Ra_T at higher number of buoyancy ratio (*N*). Other characteristics which worth to be addressed by the research was that the distribution of N_u Vs *N*, showed a minimum graph at Nusselt number equal to 1. Apparently, for $L_e = 1$, the Nusselt number (N_u) exactly equalled to unity and for $Le > 1$, N_u was only slightly higher than unity. At the value of *N* which was a minimum, denoted by $N_{T\text{-}min}$, there was a clockwise flow generated by the temperature gradient and the flow was then balanced by anti-clockwise fluid motion generated by opposed solutal gradient. As a result, motionless fluid was formed through which mass and heat was principally base on pure conduction. It also revealed that $N_{T\text{-}min}$ was increasing if both Ra_T and L_e were increased. By this condition, the thickness of concentration boundary layer became thinner as the Lewis number elevated. Consequently, when solutal driving force expanded to develop thinner area of velocity boundary layer near to the cavity wall, the intensity of the solutal flow was decreasing and implied that higher buoyancy ratio was demanded to counteract the thermally-driven flow. What is more, flow generated by the temperature gradient remained more intense when the thermal Rayleigh number increased, and again, a higher buoyancy ratio was required to counteract it and the rate of heat transfer slightly depended on Lewis number for the buoyancy ratio lower than $N_{T\text{-}min}$.

By considering aspect ratio (*AR*) of the enclosures, Nithyadevi et al. [8] performed a numerical study related to effect of the ratios on natural convection of a water-filled rectangular cavity. Active walls were on both vertical walls (temperature of the left wall was higher than that of the right wall) on which 9 non-identical positions were installed as a combination of heating and cooling pairs. The research revealed that if hot source was placed at the top side of the left wall and cold source was mounted on bottom of the right walls, there was no significant heat transfer occurred. Around the centre of the cavity, heat transfer was dominated by conduction mode of delivery and convective heat transfer existed nearby the active walls. In fact, when hotter source was put on the bottom side of the vertical wall and colder source were mounted on the top side of another opposed vertical wall, then heat transfer rate was augmenting significantly as seen on Figure 1.

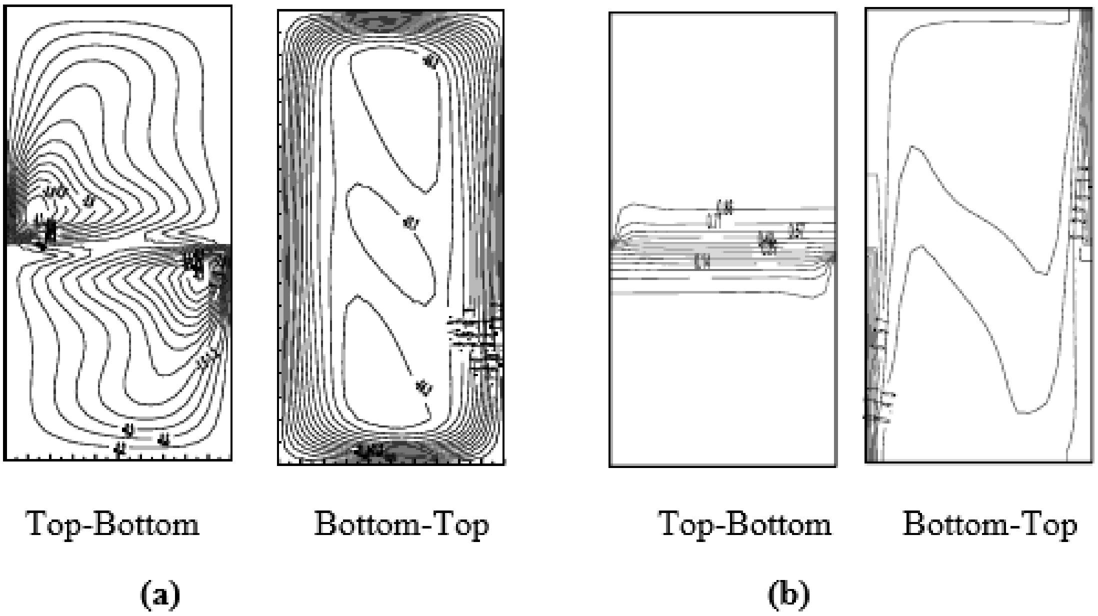

Figure 1: Stream Lines for *AR*=2 & *Gr*=10^5 (a) and Isotherms Lines for *AR*=2 & *Gr*=10^5 (b) [8]

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According to Kandaswamy et al. [9], natural convection occurred in a fluid-filled enclosure was due to the different density of the fluid triggered by dissimilar distribution temperatures of the fluid. Actually, most of assumptions used to describe temperature profile inside the cavity were based on a linear temperature-density relation. However, it was proved by the research that it was not exist in a real situation. Indeed, temperature-density's trend in practice was a non-linear pattern. In addition, position of heat source on the vertical wall also affected heat transfer rate inside the cavity.

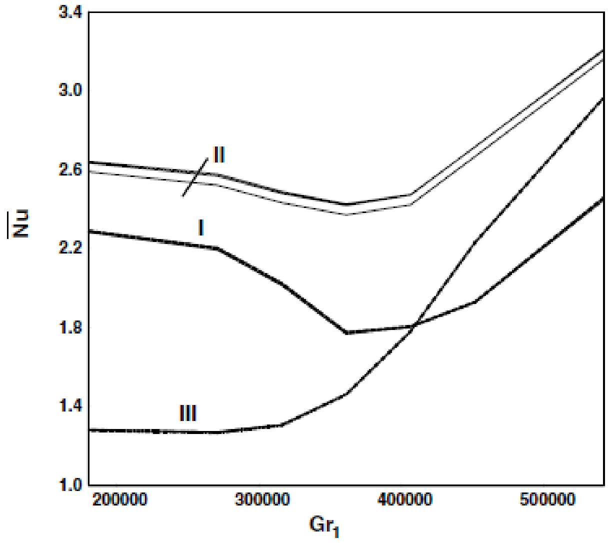

Figure 2: Average Nusselt Number versus Grashorf Number [9]

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In case the hot source was mounted on left side of the cavity and the cold source was put on right side of the cavity, the important results of this research was that the heat transfer rate increased if heating source was placed at the middle of the hot wall and when the heat source was placed on the upper and the bottom area of the vertical cavity, heat transfer rate was less than that of at the middle of active wall.

The rate of heat transfer was decreasing up to the density maximum (at the lowest value of the average Nusselt number), and then heat transfer was increasing significantly with the increasing of the Grashof number for every position of the heat source (I, II, and III) as seen on Figure 2.

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EFFECT OF NANOPARTICLE FLUID

The term of nanoparticle fluid or nanofluid refers to the base fluid that has suspended nano-scale solid particles inside it without causing formation of sedimentation and has zero increase in pressure drop during the fluid flow [10-11].

Nano particle fluid or nanofluid has been investigated widely in laboratory and industrial scale as an alternative way to enhance convective heat transfer of any particular systems [12-15]. Hence, its application can be found mainly in heat exchangers, buildings heating, phase change materials, automotive cooling systems, and also in plants applications such as solar cells, solar collectors, nuclear reactor, micro-channels [15-16], etc.

The significance of this type of fluid being used as heat transfer agent has been studied by a number of researchers especially in convective heat transfer field of interest and has been investigated based on various interesting topics including: effect of inclined nanoparticle-filled enclosure [17-18], effect of volume fraction quantity of nanoparticle on temperature gradient, streamlines, and isotherm of the fluid [19], etc.

Heat transfer and flow of Al_2O_3-water nanofluid inside a square enclosure were investigated numerically and experimentally by Hu et al. [20]. The research revealed that heat transfer enhancement was only effective at the lower mass fraction of nanoparticles (1wt %) compared to the pure water and was almost constant at 2wt %. Additional nanoparticle mass fraction i.e. at 3wt %, led to reduction of heat transfer and these facts also concluded that for nanoparticle fluid, thermal conductivity was more dominant than viscosity in affecting heat transfer at low nanoparticle mass fraction. In fact, heat transfer was more influenced by viscosity than thermal conductivity at higher fraction of nanoparticle fluid.

Contrast to the above results, similar nanoparticle fluid (alumina-water) was also investigated by Ho et al. [21] by considering thermal conductivity and unpredictability in effective dynamics viscosity of nanofluid in respect to natural convective heat transfer inside a square cavity. This research revealed that additional nanofluid inside the base fluid did not always increase heat transfer performance as it depended basically on the formula used in determining the effective dynamic viscosity and the Rayleigh number. Conductive heat transfer dominated through the alumina-water filled rectangular cavity at *Ra* equal to 1000, this condition led to the fact that increasing the amount of alumina volume fractions could increase the average Nusselt number reflecting an enhancement of thermal conductivity of the nanofluid. In fact, for higher value of Rayleigh number ($Ra \geq 10^4$), heat transfer across the cavity was dominated by convection mode and average Nusselt number showed increasing and decreasing patterns with the particle volume fractions for model I-III and model II-IV respectively. The difference between these two models curves was due to the difference of effective dynamic viscosity enhancement of the fluid extracted from two adopted formulas used to determine Nusselt number.

In respect to the dispersion of nanoparticles inside the fluid-filled cavity, Celli [22] proposed the possibility of a non-homogenous model to study spatial distribution of the nanoparticles inside the cavity and to investigate heat transfer performance of the fluid in respect to a natural convection phenomenon. Based on this research, non-homogenous distribution of nanoparticle occurred at lower values of Rayleigh number. In fact, fairly homogenous distribution was established in the core of the cavity at the Rayleigh number higher than 100. Similar to other research, the increasing of volume fraction of nanoparticle led to the decreasing of heat transfer at the vertical boundary.

Regarding the position of the enclosure, a research on an incline rectangular cavity was investigated by Bouhalleb et al. [23] that investigated about the correlation between Rayleigh number (*Ra*) and nanofluid flow pattern by applying various low aspect ratios (*AR* = 0.5, 0.25, 0.125, 0.1, 0.08) on the CuO-water nanofluid filled cavity cooled from the above and heated from one side of other wall. Aspect ratio of this case referred to a ratio of cold wall and hot wall surface. Based on the research, effect of Ra number was less significant to heat transfer for lower value of the aspect ratios. In fact, significant effect of heat transfer was clearly seen for higher aspect ratio and higher number of *Ra*. In addition, increasing of nanoparticle volume fractions led to increasing heat transfer performance significantly. If the dilute nanofluid concentration was set at 4% and at a value slightly greater than 2.5%, coefficient of heat transfer was increasing by 5% and 25 % respectively comparable with the pure water.

Inclination of the cavity also provided trends to heat transfer's coefficient in respect to volume fraction of nanofluid particles as seen on Figure 3. It described that heat transfer was gradually increasing until reaching a maximum point at a correlated inclination angle and then decreased moderately with the increasing of inclination angles.

This effect had the highest value of Nusselt number (*Nu*) at 2% of nanofluid concentration with an inclination angle of 30° and then lower values were represented by concentration of 4% and 0% (pure water) respectively. In addition, effect of aspect ratio was in great difference between the tall and the shallow cavity.

Observation of 2% nanofluid concentration without applying inclination angle showed that, for lower *AR* (tall cavity), great slopes of *Nu-AR* curves were obtained for every particular of observed Rayleigh numbers.

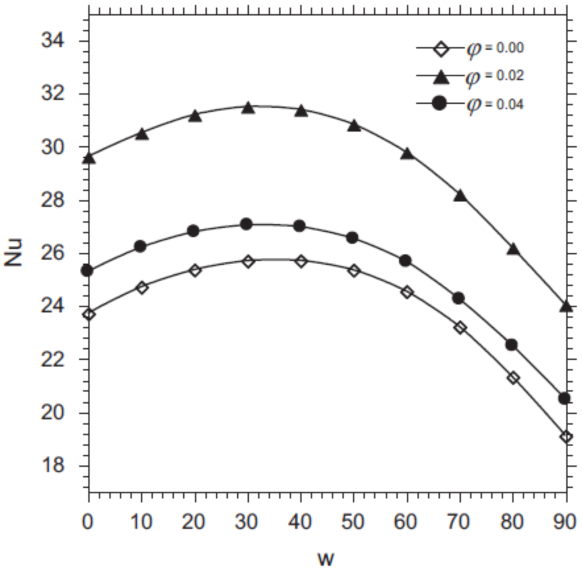

Figure 3: Nusselt Number and Inclination Angle for Various Volume Fractions at $Ra=10^7$ and AR = 0.1 [23] (Reprint from International Journal of Hydrogen Energy, with permission from Elsevier)

Contrarily, slopes of the curves were decreasing as the *AR* numbers were augmented. This fact showed that effect of convective heat transfer in the tall cavity was greater than that of in the shallow cavity.

EFFECT OF MAGNETIC FIELD

Effect of magnetic field has been considered as a significant factor affecting the rate of heat transfer inside the cavity and this fact has led to a complementation of magnetic field to fluid-filled systems as it could be found in engineering applications such as cooling mechanism of electronic components, combustion modelling, fire engineering, heat exchanger, and nuclear reactor [24]. Related studies have been done that used magnetic fields as a means of controlling crystal growth and structure development in the crystallization of alloys affected by convective heat transfer of the melting alloys [25].

In addition, a number of research also have been done regarding effects of magnetic field on heat transfer performance of a fluid-filled system including: effect of using magnetic-sensitive nanofluid and rotating magnetic field [26], implementation of Fe_3O_4 ferro-fluids interfered with single or double sources of magnetic field [27], magnetic nanofluid flowing inside circular pipe heated with a uniform magnetic field [28], interferences of constant and alternating magnetic field having two different intensities on convective performance of Fe_3O_4-water fluid inside a heated tube [29], etc.

Shaikholeslami et al. [30] investigated behavior of Fe_3O_4-water nanofluid in a cavity provided with a sinusoidal cold-wall under the influence of external magnetic field by considering effect of the ferro-fluid's volume fraction, Hartmann number (*Ha*) and Rayleigh number (*Ra*). The research revealed that, if the distance of hot and cold wall was shortened (i.e. higher value of cold wall's amplitude), temperature gradient of the fluid increased significantly under low effect of buoyancy force. In addition, by increasing Lorentz forces, which was related to higher number of *Ha* due to the increasing of magnetic field, average Nusselt numbers (Nu_{ave}) tended to decrease because the fluid velocity became retarded and conduction mode of delivery dominated the heat transfer. In fact, as the buoyancy forces and Rayleigh number increased, average Nusselt number was raising and the temperature gradient closed to the right wall was augmented.

Effect of a uniform magnetic field to buoyancy driven convective heat transfer inside a rectangular enclosure was investigated by Wang et al. [31]. The research showed that at the beginning, Nusselt number was increasing for the lowest value of Hartmann number (*Ha*) until it reached the peak before decreasing again with the increasing of Hartmann number. This behavior was applied to all the three Grashof number selected in the experiment: the lowest Grashof number represented the lowest Nusselt number for all range of Hartmann numbers. A correlation between vertical velocity of the fluid (*v*) and magnetic field intensity (*Ha*) was also identical to that of *Nu* and *Ha* number. Similar to the previous study by [29], Lorentz forces due to the induced current could cause deceleration of liquid metal flow inside the cavity. Effective heat transfer was only obtained from moderate Hartmann number (*Ha* = 211.91) where energy transport process was more effective. For further increasing of Hartmann number, the fluid velocity became more stagnant and pure conduction of heat transfer then existed.

In addition, externally imposed magnetic field was investigated by Oreper and Szekely [32]. The research revealed that natural convection could be restrained by magnetic fields depending on the intensity of magnetic field, geometry and size of the system. The presence of external magnetic field could change temperature and velocity fields with the provision of large magnetic fields. If the magnetic fields were set transversal to the gravitational force, the induction slightly greater than hundreds Gauss would cause apparent effects on the patterns of temperature and velocity of the observed system.

Complement to the above results, Gangawane [33] investigated effect of magnetic field's angle and heater size on free convection inside an open ended enclosure having one vertically left active wall. The research revealed that magnetic field applied at 45° of the normal provided the highest constraint effect on convective heat transfer comparable to that of 0° and 90°. In more specific, heater size (L_H), Hartmann number and Rayleigh number were set equal to 0.25, 50 and 10^3 respectively. For this condition, buoyancy force was obviously small and conductive mode of delivery dominated convection of heat transfer. The flow structures separated into two areas: one main region circulated near heated wall and the other minor region flowed near the open end of the enclosure. Obviously, when *Ra* number was raised up to 1000, by setting a higher power of the heat source, circulation flow of the fluid moving in from the open end existed. The flow then reached the hot wall before flowing out again to the open end surface. In fact, this circulation was limited toward walls' surfaces and caused a vortex in the middle of enclosure. In addition, by increasing the heater size to $L_H = 0.5$ and $L_H = 0.75$, buoyancy force became strong supporting the fluid to circulate throughout the enclosure. Significant changes existed for magnetic angle direction (θ_m) of 45° as circulating flow patterns were more skewed to the heated wall and secondary vortex existed near the open end. As a result, split fluid zones formed in the between and caused stagnant motion of fluid in the middle of cavity. This fact indicated that effect of Lorentz forces due to magnetic fields were maximum for this angle and provided the highest restriction to convective heat transfer.

EFFECT OF THERMO-SENSITIVE GEL & FUNCTIONAL PARTICLE

Thermo-sensitive gel can be used as a heat transfer agent due to its sensitivity to the very low environment temperature changes. The gel can be utilized to several applications including drugs delivery system in the human body as the material can be transformed from liquid to gel at the near human body temperature [34], artificial scaffold inside human's tissues to trigger growth of the new bone [35-37], smart material for flow control and mechanical micro-valve [38-39]. Terminology of 'gel' refers to a soft-solid-like material which consists of a number of components including polymeric materials and aqueous fluid presented in a substantial amount of quantity [40]. One type of thermo-sensitive gel, Poly (*N*-isopropylacrylamide), has LCTS at around 32˚C that could be determined by the temperature where a dramatic volume change begins to occur [41].

The role of thermo-sensitive gel as a heat transfer agent is supported by its swelling-shrinking characteristic (i.e. swelling ratio) affected by internal properties and external stimuli such as crosslinking density [42], pores size [43], temperature changes of its surroundings fluid, salt concentration [44], UV radiation, and alkalinity (*pH*) of solutions [45].

Behaviour of thermo-sensitive gel has been investigated by Hasegawa et al. [46] at Kanazawa University and some of related results could be depicted from Figure 4 that showed the appearance of NIPA gels inside the cavity within the interval of 1 minute and represented the condition of 145 minutes after the commencement of the recorded data. Thermocouple was mounted at the left side of the wall inside the cavity to measure the middle point temperature which was observed stable at 25˚C.

Location of the four particles observed i.e. A, B, C, and D can be clearly seen corresponding to red, yellow, blue, and green circle respectively. Observation of the gels showed that the gels maintained repetitive movements in up and down direction in the certain period of time inside the rectangular cavity heated from the above and cooled from the below as shown on Figure 4.

When the gels swelled at near the hot top surface of the cavity, the gels absorbed the heat and caused the diameter of the gels became larger because particular amount of solution was absorbed by the NIPA gels.

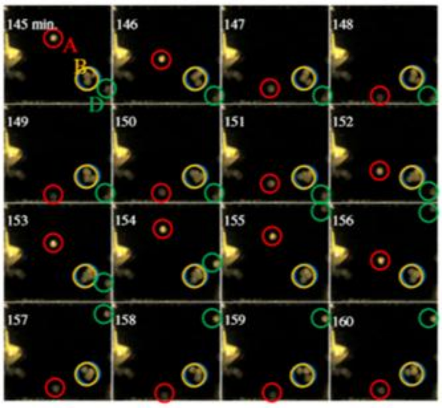

Figure 4: Gels Particles Movement Inside the Rectangular Cavity [46]

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As a result, density of the gels became larger than that of surrounding PAA solution and immediately caused the gels to be shrinking and dropped to the bottom area i.e. cold area of the cavity. During the shrinking process until the gels were reaching at the bottom cold surface of the cavity, NIPA networks blocked the PAA polymer solution preventing it to penetrate the NIPA network. As a consequence, density of the gels became smaller than that of surrounding solution and this phenomenon created a buoyancy force on the surface of the gels and pushed the gels to move upward. The up and down movements would still continue provided the density differences existed between the gels and the polymer solution.

In case of a fluid-filled cavity where the hot wall was on the upper side and the cold wall was on the below, application of such thermo-sensitive gels could boost the intermixture of hot and cold fluid region. As a consequence, it could support convective heat transfer inside such a condition. The size of the gels being used also could affect dynamics of gels inside the cavity and according to Tanaka et al. [47], the rate of response was actually inversely correlated with the square size of the gels.

Functional particles also could be applied as a heat transfer agent and could increase convective heat transfer rate [48]. The functional particles behaved contrary to the common materials when heated and exhibited inversely thermal expansion behaviour as the material contracted and shrank its volume when heated. Including in this type of functional particles are negative thermal expansion (NTE) capsule applying phase change material (PCM) and shape memory alloy (SMA) particles.

Regarding the shape memory alloy particles, Kataoka & Yoshida [49] proposed particle implementing SMA spring inside the particle to promote natural convection within the thermally stratified fluid region of the rectangular cavity. By using the particles, natural convection existed in the inverse direction i.e. the hot fluid moved down and the cold fluid went up due to the back and forth movements of the functional particle. The experiment showed significant difference of temperature profile along the vertical height of the cavity when comparing case 1 (without functional particle) with case 2 (with functional particle). The slope of temperatures in the case 2 was greater than that of in the case1 and the stratified fluid region diminished gradually.

In addition to the above results, Yamaguchi and Takanashi [50] promoted NTE capsule supported with PCM (L-Type and S-Type). The research revealed that the movements of NTE Capsule inside the one-meter-depth of water tank were influenced by temperature contour of the ambient water by which could affect density of water and buoyancy force acting on the NTE Capsule. In principal, when the particle was in the hot fluid region, steam pressure of PCM (using RC318) inside the smaller cylindrical vessel elevated significantly and pressed the larger cylindrical vessel filled with pressurized air. Thus the larger cylindrical vessel became shorten but the cumulative length of the both vessels was kept on the constant automatically. As an effect, volume of the larger vessel decreased significantly when the temperature raised and decreasing its buoyancy force acting on the vessel. This fact triggered the NTE Capsule to move down and exhibited a negative thermal expansion.

CONCLUSION

A number of research have been reviewed in respect to convective heat transfer phenomena inside a fluid-filled rectangular cavity and have contributed to some significant factors affecting the heat transfer performance. Effect of partially active wall, effect of magnetic fields, and effect of applied thermo-sensitive gels and functional particles were investigated for this purpose. It was obvious that position of heat source along the vertical wall and the heat source facing direction on the horizontal axis as well as its intensity could affect performance of convective heat transfer inside the cavity. Direction, continuity, and intensity of applied magnetic field also had apparent effects on the convective heat transfer performance. The applied of thermo-sensitive gels and functional particles obviously could support natural convection of heat transfer inside thermally-stratified fluid region of the rectangular cavity.

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REFERENCES

[1] Bergman, L.T., Lavine, S.A., Incopera, P.F., and Dewitt P.D., 2009, “Heat and Mass Transfer”, 7th Edition, John Willey & Sons Publisher, USA.

[2] Rohsenow, W.M., Hartnett, J.P., and Cho, Y.I., 1998, “Handbook of Heat Transfer”, 3th Edition, McGraw-Hill, New York.

[3] Holman, J.P., 2010, “Heat Transfer”, Tenth Edition, McGraw-Hill, New York.

[4] Oztop, H.F., and Abu-Nada, E., 2008, “Numerical Study of Natural Convection in Partially Heated Rectangular Enclosures Filled with Nanofluids”, International Journal of Heat and Fluid Flow, 29, pp. 1326–1336.

[5] Yigit, S, Poole, R.J., and Chakraborty, N., 2015, “Effect of Aspect Ratio on Natural Convection of Bingham Fluids in Rectangular Enclosure with Differentially Heated Horizontal Walls Heated from Below”, International Journal of Heat and Mass Transfer, Vol. 80, pp 727-736.

[6] Karatas, H., and Derbentli, T., 2017, “Natural Convection in Rectangular Cavities with One Active Vertical Wall”, International Journal of Heat and Mass Transfer, Vol.105, pp. 305-315.

[7] Corcione, M., Grignaffini, S., and Quintino, A., 2015, “Correlation for the Double-diffusive Natural Convection in Square Enclosures Induced by Opposite Temperature and Concentration Gradient”, International Journal of Heat and Mass Transfer, Vol. 81, pp. 811-819.

[8] Nithyadevi, N., Kandaswamy, P., and Lee, J., 2007, “Natural Convection in a Rectangular Cavity with Partially Active Side Walls, International Journal of Heat and Mass Transfer, Vol. 50, pp.4688-4697.

[9] Kandaswamy, P., Sivasankaran, S., and Nithyadevi, N., 2007, “Buoyancy-driven Convection of Water Near Its Density Maximum with Partially Active Vertical Walls, International Journal of Heat and Mass Transfer, Vol. 50, pp. 942–948.

[10] Abu-Nada, E., 2008, “Application of Nanofluids for Heat Transfer Enhancement of Separated Flows Encountered in a Backward Facing Step”, International Journal of Heat and Fluid Flow, Vol. 29, pp. 242–249.

[11] Daungthongsuk, W., and Wongwises, S., 2007, “A Critical Review of Convective Heat Transfer Nanofluids”, Renewable and Sustainable Energy Reviews, Vol. 11, pp. 797–817.

[12] Yu, G., Gao, D., Chen, J., Dai, B., Liu, D., Song, Y., and Chen, X., 2016, “Experimental Research on Heat Transfer Characteristics of CuO Nanofluid in Adiabatic Condition,” Journal of Nanomaterials, Vol. 2016, pp. 1-7.

[13] Kuznetsov, A.V., and Nield, D.A., 2010, “Natural Convective Boundary-layer Flow of a Nanofluid Past a Vertical Plate”, International Journal of Thermal Sciences, Vol. 49, pp. 243–247.

[14] Coudhury, P., Garg, P., and Jha, S., 2014, “Study of Nano Particles for Enhanced Heat Transfer Characteristics of Base Fluids for Cool Thermal Energy System”, International Journal of Engineering Research and Applications, Vol. 4 (4), pp. 97-101.

[15] Das, S.K., Choi, S.U.S., and Patel, H.E., 2006, “Heat Transfer in Nanofluids-A Review”, Heat Transfer Engineering, Vol. 27(10), pp. 3–19.

[16] Mansour, M.A., Mohamed, R.A., Abd-Elaziz, M.M., and Ahmed, S.E., 2010, “Numerical Simulation of Mixed Convection Flows in a Square Lid-driven Cavity Partially Heated from Below Using Nanofluid”, International Communications in Heat and Mass Transfer, Vol. 37, pp. 1504–1512.

[17] Heris, S.Z., Pour, M.B., Mahian, O., and Wongwises, S., 2014, “A comparative Experimental Study on the Natural Convection Heat Transfer of Different Metal Oxide Nanopowders Suspended in Turbine Oil Inside an Inclined Cavity”, International Journal of Heat and Mass Transfer, Vol. 73, pp. 231–238.

[18] Abu-Nada, E., and Oztop, H.F., 2009, “Effects of Inclination Angle on Natural Convection in Enclosures Filled with Cu–water Nanofluid”, International Journal of Heat and Fluid Flow, Vol. 30, pp. 669–678.

[19] Khanafer, K., Vafai, K., and Lightstone, M., 2003, “Buoyancy-driven Heat Transfer Enhancement in a Two-dimensional Enclosure Utilizing Nanofluids”, International Journal of Heat and Mass Transfer, Vol. 46, pp. 3639–3653.

[20] Hu, Y., He, Y., Qi, C., Jiang, B., and Schlaberg, H.I., 2014, “Experimental and Numerical Study of Natural Convection in a Square Enclosure Filled with Nanofluid”, International Journal of Heat and Mass Transfer, Vol. 78, pp. 380–392.

[21] Ho, C.J., Chen, M.W., and Li, Z.W., 2008, “Numerical Simulation of Natural Convection of Nanofluid in a Square Enclosure: Effects Due to Uncertainties of Viscosity and Thermal Conductivity”, International Journal of Heat and Mass Transfer, Vol. 51, pp. 4506–4516.

[22] Celli, M., 2013, “Non-homogeneous Model for a Side Heated Square Cavity Filled with a Nanofluid”, International Journal of Heat and Fluid Flow, Vol. 44, pp. 327–335.

[23] Bouhalleb, M., and Abbassi, H., 2014, “Natural Convection of Nanofluids in Enclosures with Low Aspect Ratios”, International Journal of Hydrogen Energy, Vol. 39(27), pp. 15275-15286.

[24] Hassan, A.R., and Maritz, R., 2016, “The Analysis of a Reactive Hydromagnetic Internal Heat Generating Poiseuille Fluid Flow through a Channel”, SpringerPlus, Vol. 5(1):1332.

[25] Mikelson, A.E., and Karlin, Y.K., 1981, “Control of Crystallization Processes by Means of Magnetic Fields”, Journal of Crystal Growth, Vol. 52, pp. 524-529.

[26] Fadaei, F., Dehkordi, A.M., Shahrokhi, M., and Abbasi Z., 2017, “Convective-heat Transfer of Magnetic-sensitive nanofluids in the Presence of Rotating Magnetic Field”, Applied Thermal Engineering, Vol. 116, pp. 329–343.

[27] Fadaei, F., Shahrokhi, M., Abbasi, Z., Dehkordi, A.M., and Abbasi, Z., 2017, “Heat Transfer Enhancement of Fe_3O_4 Ferrofluids in the Presence of Magnetic Field”, Journal of Magnetism and Magnetic Materials Vol. 429, pp. 314–323.

[28] Hatami, N., Banari, A.K., Malekzadeh, A., and Pouranfard, A.R., 2017, “The Effect of Magnetic Field on Nanofluids Heat Transfer Through a Uniformly Heated Horizontal Tube”, Physics Letters A, Vol. 381, pp. 510–515.

[29] Goharkhah, M., Salarian, A., Ashjaee, M., and Shahabadi M., 2015, “Convective Heat Transfer Characteristics of Magnetite Nanofluid under the Influence of Constant and Alternating Magnetic Field, Powder Technology Vol. 274, pp. 258–267.

[30] Sheikholeslami, M., and Ganji, D.D., 2016, “Ferrofluid Convective Heat Transfer under the Influence of External Magnetic Source”, Alexandria Engineering Journal.

[31] Wang, Z.H., Meng, X., and Ni, M.J., 2017, “Liquid Metal Buoyancy Driven Convection Heat Transfer in a Rectangular Enclosure in the Presence of a Transverse Magnetic Field”, International Journal of Heat and Mass Transfer, Vol. 113, pp. 514–523.

[32] Oreper, G.M., and Szekely, J., 1983, “The Effect of an Externally Imposed Magnetic Field on Buoyance Driven Flow in a Rectangular Cavity”, Journal of Cristal Growth, Vol. 64, pp. 505-515.

[33] Gangawane, K.M., 2017, “Effect of Angle of Applied Magnetic Field on Natural Convection in an Open Ended Cavity with Partially Active Walls”, Chemical Engineering Research and Design, Vol. 127, pp. 22–34.

[34] Hoare, R.T., and Kohane S.D., 2008, “Hydrogel in drug delivery: Progress and Challenges”, Polymer, Vol. 49(8), pp. 1993-2007.

[35] El-Sherbiny, I.M., Yacoub, M.H., 2013, “Hydrogel Scaffolds for Tissue Engineering: Progress and Challenges”, Global Cardiology Science and Practice, Vol. 38, pp. 316-342.

[36] Ziane, S., Schlaubitz, S., Miraux, S., Patwa, A., Lalande, C., Bilem, I., Lepreux, S., Rousseau, B., Meins, J.L., Latxague, L., Barthélémy, P., and Chassande, O., 2012, “A Thermosensitive Low Molecular Weight Hydrogel as Scaffold for Tissue Engineering”, European Cells and Materials, Vol. 23, pp. 147-160.

[37] Tozzi, G., Mori, A.D., Oliveira, A., and Roldo, M., 2016, “Composite Hydrogels for Bone Regeneration”, Materials, Vol. 9(4), 267; doi: 10.3390/ma9040267.

[38] Arndt, K., Kuckling, D., and Richter, A., 2000, “Application of Sensitive Hydrogels in Flow Control”, Polymers for Advance Technologies, Vol. 11, pp. 496-505.

[39] Baldi, A., Gu, Y., Loftness, P.E., Siegel, R.A., and Ziaie, B., 2003, “A Hydrogel-actuated Environmentally Sensitive Microvalve for Active Flow Control”, Journal of Microelectromechanical Systems, Vol. 12(5), pp. 613-621.

[40] Bromberg, L.E., and Ron, E.S., 1998, “Temperature-responsive Gels and Thermogelling Polymer Matrices for Protein and Peptide Delivery, Advance Drug Delivery reviews, Vol.31, pp. 197-221.

[41] Wang, H.D., Chu, L.Y., Yu, X.Q., Xie, R., Yang, M., Xu, D., Zhang, J., and Hu, L., 2007, Thermosensitive Affinity Behaviour of Poly(N-isopropylacrylamide) Hydrogel with *ß* Cyclodextrin Moieties, Ind. Eng. Chem. Res. Vol. 46, No.5.

[42] Oh, K.S., Oh, J.S., Choi, H.S., and Bae, Y.C., 1998, “Effect of Cross-Linking Density on Swelling Behavior of NIPA Gel Particles”, Macromolecules, Vol. 31, pp. 7328-7335.

[43] Yacob, N., and Hashim, K., 2014, “Morphological Effect on Swelling Behavior of Hydrogel”, AIP Conference Proceedings 1584, 153; 10.1063/1.4866123

[44] Mirdarikvande, S., Sadeghi, H., Godarzi, A., Alahyari, M., Shasavari, H., Khani, F., 2014, “Effect of pH, and Salinity onto Swelling Properties of Hydrogels Based on H-alginate-g-poly (AMPS)”, Biosciences Biotechnology Research Asia, Vol. 11(1), pp. 205-209.

[45] De, S.K., Aluru, N.R., Johnson, B., Crone, W.C., Beebe, D.J., and Moore, J., 2002, “Equilibrium Swelling and Kinetics of pH-Responsive Hydrogels: Models, Experiments, and Simulations”, Journal of Microelectromechanical Systems, Vol. 11, No.5.

[46] Hasegawa, M., Kamikido, T., Kawabata, N., 2016, “Behaviour of Thermosensitive Gel in Polymer Solution”, International Communications in Heat and Mass Transfer, Vol. 76, pp. 55-58.

[47] Tanaka, T., and Fillore, J., J. Chem. Phys. 1979, 70, 1214.

[48] Zhang, Y., Rao, Z., Wang, S., Zhang, Z., Li, X., 2012, “Experimental Evaluation on Natural Convection Heat Transfer of Microencapsulated Phase Change Materials Slurry in a Rectangular Heat Storage Tank”, Energy Conversion and Management, Vo. 59, pp. 33-39.

[49] Kataoka, I., Yoshida, K., 2002, “Development of Inverse Natural Convective Fluid and Its Thermo-hydrodynamics Characteristic”, Experimental Thermal and Fluid Science, Vol. 26, pp. 345-353.

[50] Yamaguchi, Y., and Takanashi, K., 2004, “Estimation of Buoyancy Change of an NTE Capsule Using PCM”, Proceedings of ASME International Mechanical Engineering Congress and Exposition, Anaheim, California USA.