University of Baghdad
College of Engineering
JE
JOURNAL OF ENGINEERING

Journal of Engineering
journal homepage: www.joe.uobaghdad.edu.iq
Number 4 Volume 28 April 2022

Mechanical and Energy Engineering

Numerical study of natural convection in an annulus between two concentric cylinders provided with metal foam fins.

Israa H. alkinani
Ph.D. Student
Mechanical Engineering Department
College of Engineering- Baghdad University
israaalkiinani@gmail.com

Asist. Prof. Luma Fadhil Ali
Mechanical Engineering Department
College of Engineering- Baghdad University

ABSTRACT

Natural convection in an annular space provided with metal foam fins attached to the inner cylinder is studied numerically. The metal foam fins made of copper were inserted in different axial sections with three fins in each section. The temperature of the inner cylinder is kept constant while the annular outer surface is adiabatic. The thickness effect of the inner pipe wall was considered. Naiver Stokes equation with Boussinesq approximation is used for the fluid regime while Brinkman-Forchheimer Darcy model is used for metal foam. In addition, the local thermal non-equilibrium condition in the energy equation of the porous media is presumed. The effect of Rayleigh number and number of foam fins in the axial direction, on fluid flow and heat transfer characteristics, were examined. The current model was valid with the available published results and good agreement is noticed. Results showed that as the Rayleigh number increases the dominated of convection mode increases and average Nusselt increases. It was found that at Rayleigh of 10^6 Nusselt reached its higher value which is 4.6 for the case of adding seven axial metal foams. A comparison between adding foam fins and copper fins was established for a range of Rayleigh numbers between 10^4 and 10^6. It showed a good enhancement in Nusselt number and the greatest enhancement percentage was 45.9% at Rayleigh equal 10^6 for the case of using seven sections of foam fins.
Keywords: Natural convection, metal foam, concentric cylinders, local thermal non-equilibrium, numerical investigation.

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2022.04.01

Article received: 16 /12 /2021
Article accepted: 17 /1/2022
Article published: 1/4/ 2022

دراسة نظرية للحمل الحر داخل فراغ حلقي بين اسطوانتين متحدتي المركز مزود بزعانف من الرغوة المعدنية

اسراء حميدالكناني
جامعة بغداد / كلية الهندسة / قسم الميكانيك

أ.م.د. لمى فاضل
جامعة بغداد / كلية الهندسة / قسم الميكانيك

الخلاصة

تم دراسة الحمل الحراري الحر في فراغ حلقي مزودة بزعانف من الرغوة المعدنية متصلة بالأسطوانة الداخلية عدديا. تم إدخال الزعانف المعدنية المصنوعة من النحاس في أقسام محورية مختلفة بثلاث زعانف في كل قسم. تم الحفاظ على درجة حرارة الأسطوانة الداخلية ثابتة بينما كان السطح الخارجي للفراغ الحلقي معزول حراريا. لقد تم أخذ تأثير سمك جدار الانبوب الداخلي بعين الاعتبار. استخدمت معادلةNaiver Stokes مع تقريب(Boussinesq)في منطقة المائع بينما استخدم نمط Brinkman-Forchheimer Darcy في منطقة الرغوة المعدنية. اضافة الى هذافقد تم اعتماد نمط التزان الحراري الغير متزن لتمثيل معادلة حفظ الطاقةالخاصة بالمادة المسامية. تم اختبار تأثير رقم ريلي وعدد زعانف الرغوة المعدنية الموزعة بالاتجاه المحوري للفراغ الحلقي على خصائص جريان المائع وانتقال الحرارة. تم مقارنة نتائج المودل الحالي مع نتائج البحوث المنشورة المتوفرة وقد لوحظ ان توافق النتائج جيد. لقد بينت نتائج هذه الدراسة انه بزيادة قيمة رقم ريلي يصبح طور الحمل الحر مهيمن ويزداد رقم نسلت. وقد وجد ان رقم نسلت يصل لاعلى قيمة له(4.6) عند رقم ريلي يساوي 106 في حالة اضافة سبع زعانف من الرغوة المعدنية بالاتجاه المحوري. تم اجراء مقارنة مع حالة استخدام زعانف نحاسية لمدى من رقم ريلي بين 104 الى 106وقد بينت تحسن جيد في رقم نسلت واعظم نسبة مئوية للتحسن كانت 45.9% عند ريلي يساوي 106 وبحالة استخدام سبع زعانف من الرغوة المعدنية بالاتجاه الطولي.

1. INTRODUCTION

Natural convection in a concentric annulus has a wide variety of practical applications such as gas-insulated electrical transmission systems, double-pipe heat exchangers, solar collectors, cooling of electronic components, thermal storage, pressurized and water reactors. Researchers began to shed light on such heat exchangers in **1976** where the researcher **Caltagirone** performed two researches for theoretical models and experimental tests for natural convection two-dimensional flow with a fixed radius horizontal annulus. He studied the performance of this type of heat exchanger and the ability to use it in such applications. Several studies were followed by the study of such heat exchangers, such as the researcher **(Hamad and Khan, 1998)** conducted an experiment on natural convection in horizontal and inclined annuli to investigate the effects of inclination angle and diameter ratio on heat transfer. They compared their experimental data with numerical results predicted using the FLUENT CFD package. At the beginning of the 21th century, researchers began to study ways to develop heat exchangers for various applications. One of these ways is to introduce metal foam to such heat exchangers. **(Mansour, 2008)** studied the effects of constant temperature variation on the outside and adiabatic conditions on the inner borders with constant volumetric heat flow on two-dimensional natural convection in a thin horizontal cylindrical annulus filled with a porous material. **(Targui and Kahalerras, 2008)** presented a numerical study of heat transfer and fluid flow in a double pipe heat exchanger provided with porous media blocks in the annular space. Hot fluid was passing in the inner pipe while the cold fluid was in the annular gap with the counter-flow model. The outer pipe was adiabatic. Two cases for porous blocks distribution in the annular space were investigated; first, the porous is attached to the outer surface of the inner pipe, while in the second case the porous is attached to both the outer surface of the inner pipe and the outer pipe inner wall with a staggered model. Forchheimer- Brinkman Darcy extended equation with local thermal equilibrium model was adopted with laminar, two-dimensional, steady, incompressible, and axisymmetric flow considerations. The influence of permeability, arrangement, and height of the blocks, and the thermal conductivity ratio were examined. They found that the Nusselt number increases by increasing block thickness for lower values of Darcy number and its increase by increasing thermal conductivity ratio. Moreover, they found that the second arrangement is more efficient than the first one. **(Xu, et al., 2011)** introduced numerically fully developed force convection in a circular tube partially filled with metal foam located aligned to the inner wall of the tube. They used the Brinkman flow model, local thermal non-equilibrium to represent heat transfer equation and interfacial coupling conditions for temperature and velocity at the foam-fluid interface. They concluded that the fluid temperature outlet increased with foam pore density increases. They also studied the influence of thermal conductivity ratio K_f/K_s and they found that decreasing this ratio would yield an increase in Nu followed by an increment in heat transfer as a result of the deterioration of heat conduction resistance. The theoretical and experimental study had been conducted by **(Abeed, 2012)** on two dimensions, laminar and steady-state then transient natural convection in the annular between two concentric cylinders filled with porous media. Two situations for the cylinders were considered; horizontal and inclined by an angle of 45^{0} . He adopted the Brinkman-extended Darcy equation and local thermal non-equilibrium model as governing equations and the Fluent program was used to simulate his problem. The theoretical part studied the effect of Ra and Nu numbers on dissipation ability while the experimental part studied the effect of Nu and inclined angle on heat dissipation. **(Qu, et al., 2013)** studied numerically natured convection in an annular partially filled with metallic foam. They adopted two equations for non-equilibrium heat transfer, a model I had the porous layer on the inner wall, while model II had it on the outside wall. Forchheimer and Brinkman’s model and local thermal non-equilibrium model were used to describe momentum and energy equations. They conducted that increasing Ra and Pr would strengthen convective performance and lead to an increment in Nu. By comparing Nu for the two models, they noticed that Nu of a model I is rather larger than Nu of model II. **(Sheremet and Trifonova, 2014)** considered their numerical results as standard guidelines for the use of the Darcy and Brinkman extended Darcy models in the case of transient conjugate natural convection in a vertical cylinder partially filled with a porous media and have heat-conducting solid walls of finite thickness in conditions of convective heat exchange with the environment. **(Senthilkumar and Palanisamy, 2015)** presented an experimental investigation of forced convection in an annular gap filled with porous media. The flow was turbulent with steady-state conditions. Four different porous media particles were examined in their study: cast iron, mild steel, copper, and aluminum They obtained the heat transfer coefficient and conducted a Nusselt number of correlations for the four tested porous media particles for Re>8500. **(Shehab, 2016**) presented experimental investigation of natural convection heat transfer in a gap between two concentric pipes filled with porous media. He used two types of porous media respectively; glass and plastic balls. The inner surface was subjected to constant heat flux using electrical heater while the outer surface was isothermally cooled. The effected parameters which examined in his study are the annular ratio, balls radius and porous media material. He found that average Nusselt number increase by increasing ball radius and the outer diameter of the annular, he also found experimental relations for average Nusselt number of both glass and plastic balls. **(Alhusseny, et al., 2017)** used the metal foam beside the rotation to enhance the heat transfer of a double-pipe exchanger. They studied the effectiveness, pressure drop, and the overall system performance and found that the thermal effectiveness could be enhanced, but extra caution should be taken to prevent the costs associated with an increase in pressure losses. A numerical study of natural convection for unsteady, laminar, and two-dimensional flow in a semicircular cavity filled with saturated fluid porous media was presented by (**Chamkha, et al., 2018)**. Boussinesq approximation and local thermal equilibrium were assumed. The finite difference method was used to solve the governing partial differential equations. They analyzed the effect of Ra and Darcy numbers, and thermal conductivity ratio on fluid flow and average Nu. They conducted that an increment in Ra or Da yield an increase in Nu and fluid flow resistance. (**Roy, 2019)** investigated the flow characteristics of natural convection in an annulus surrounded by two wavy wall cylinders generated by the exothermic reaction., their numerical results illustrate that the Frank-Kamenetskii number, the Rayleigh number for thermal diffusion, the buoyancy force parameter, the amplitudes of inner and outer wavy wall cylinders, and the Lewis number all affect the streamlines, isotherms, and isolines of concentration. (**Chen et al., 2020)** investigated a numerical study for forced convection in a double pipe heat exchanger filled with metal foam. The theoretical model was done using ANSYS FLUENT. This study was divided into two parts; uniform configuration and graded configuration. Results showed that for uniform configuration an increase in the effectiveness occurs with increasing thermal conductivity till a peck point then it reverses into decreasing. They noticed that effectiveness and pressure drop increases with increasing pore density and decreasing of porosity. For graded configuration, the best performance was held for the case in which lower porosity was attached to both sides of the inner pipe wall and at a small pore density nearby the inner pipe wall. Finally**,(Hamzah and Nima),** studied convection heat transfer and fluid flow characteristic in a double pipe heat exchanger with the presence of metal foam blocks in the annular gap numerically in **2019** and experimentally in **2020** . Hot water flows in the inner pipe that made of copper and cold air flows in the annular space. The outer pipe was made of Perspex. Finite volume method was adopted to solve the governing equation of the two-dimensional model. The heat exchanger flow was parallel with ten fins distributed in the gap between the two pipes. The numerical results showed that inserting foam blocks increase the heat transfer coefficient and Nusselt number. For the experimental study they adopted two thermal Teflon flanges to make the two pipes concentric together. Each flange has 12holes distributed with equal angles to allow the air to enter the annular gap and exit uniformly. Copper foam blocks of 40PPI were attached to the outer surface of the copper tube and inclined by angle of 30° with the tube entrance. These metal foams were distributed along the inner pipe as four blocks for each section. To make sure that air enters the annular uniformly, they used special manufactured chamber with four hoses and distributer. They examined the effect of inserting the foam blocks on heat transfer and fluid flow for a Reynold number range from 616 to 2343. Both parallel and counter flow arrangement were investigated. They concluded that adding the metal foam blocks Promote heat transfer coefficient and Nusselt number and that the highest value of Nusselt was for counter flow model. They also found that the presence of foam blokes had no significant influence on pressure drop.

By reviewing previous literary studies, we noted that few of them dealt with free or mixed convection within cylindrical annular with the presence of metal foam, especially for three-dimensional flow. Also, very few had studied inserting metal foam in the form of blocks distributed within the annular space and the suggested metal foam fin design had not been presented before. Moreover, we did not find in the researches presented in this chapter any study that tested the case of the constant inner surface temperature of the annular with the outer surface being insulated.

In this paper, a three-dimensional numerical study of natural convection in an annular space between two concentric horizontal cylinders partially filled with metal foam was introduced. The metal foam was partially distributed with both radial direction and angular direction as fins. Copper foam fins were arranged in the form of three pieces distributed on the surface of the inner tube in each section, allowing heat to be transferred from the inner tube to the fluid directly on one side and through the metal foam on the other. These pieces are designed in a way that allows the convection currents to move between them freely and smoothly. All of this contributed to promoting the heat transfer and fluid flow characteristics with respect to economic consideration.

2. MATHEMATICAL MODEL AND PROBLEM DESCRIPTION

The geometry of the problem under investigation is shown in **Fig. (1)**. It consists of two cylinders; the inner cylinder is maintained at a constant temperature while the outer cylinder is insulated. Metal foam is inserted as three pieces distributed with equal distances in the annular space aligned to the inner cylinder in different sections. Metal foam fin designed in a way that the surface area increases gradually with the radius toward the outer cylinder. This design leads to an increase in contact area between the fluid and the metal foam and helps in mixing the fluid passing through them. The annular test section length was 45 cm. The diameters of inner and outer cylinders are 10 cm and 5 cm respectively. The flow is assumed to be steady-state, three-dimensional, laminar and incompressible with constant thermophysical properties except for fluid density which follows the Boussinesq approximation. Metal foam is isotropic, homogeneous, and saturated with porosity of 0.9 and pore density w equal 10. Governing equations used for fluid and metal foam are:

Liquid region: **Jiji, 2009**

$$\rho(V\cdot\nabla)V = -\nabla P + \rho\vec{g}B\Delta T + \mu\,\nabla^2 V \qquad \text{Momentum Eq.} \qquad (1)$$

$$\rho c_p(V\cdot\nabla T) = k\nabla^2 T \qquad \text{Heat Eq.} \qquad (2)$$

Foam region: **Bejan, 2008**

$$\frac{\rho_f}{\varepsilon^2}(V\cdot\nabla)V = -\nabla P + \rho_f\vec{g}B\Delta T + \frac{\mu_f}{\varepsilon}\nabla^2 V - \frac{\mu_f}{K}V - \frac{\rho_f C1}{K^{\frac{1}{2}}}|V|\cdot V \qquad \text{Momentum Eq.} \qquad (3)$$

$$\rho_f c_f(V\cdot\nabla T) = k_{fe}\nabla^2 T \qquad \text{Fluid Heat Eq.} \qquad (4)$$

$$k_{se}\nabla^2 T = 0 \qquad \text{Solid Heat Eq.} \qquad (5)$$

3. MATERIALS AND METHODS

3.1 Numerical method

The numerical analysis is presented for steady state, three-dimensional, laminar and natural convection heat transfer. CFD ANSYS FLUENT software package (version 18.2), a computer package that uses a *finite* volume method to model fluid flow and how to transfer the heat in simple and collector geometric shapes that are difficult to solve in other languages (**Aziz and Nima, 2020**). The ANSYS FLUENT provided the ability to model, mesh, give appropriate boundary conditions and simulated the governing equations of the present case. To reduce the computational cost; a symmetric model was used. A grid independent test was made to choose the suitable mesh which contains 2665423 elements. A local thermal non-equilibrium model was considered for metal foam and air was used as a working fluid. Brinkman- Forchheimer Darcy model used to describe momentum equations in metal foam. Thus it is necessary to define both the reciprocal of permeability C1, and inertial loss coefficient C2, where : (**Ergun, 1952)**

$$C2 = 3.5\frac{(1-\varepsilon)}{d_p\varepsilon^3} \quad \text{.......... .. (6)}$$

3.2 Parameters definition

To predict the improvement of heat transfer using the new design of metal foam for natural convection in annular space several parameters were adopted. Rayleigh Ra number and permeability K are the most affected parameters and they defined as follows:

$$Ra = \frac{gB\Delta T\delta^3}{v\alpha} \quad \text{........... . (7)}$$

Where δ is the distance between the two cylinders; $\delta = r_o - r_i$, K is the permeability which defined as follows **Qu, et al., 2013**:

$$K = \frac{d^2\varepsilon^2}{150(1-\varepsilon)^2} \quad \text{............ (8)}$$

The local Nusselt number (Nu) can be expressed as follows **Al-Hattab, et al., 2008**:

$$Nu_{\mathrm{local}} = \frac{h_i r_i}{k} ln\, r_o/r_i \quad \text{........ .... (9)}$$

3.3 Validation

To ensure the validity of numerical work, a comparison was made with the results presented by (**Khanafer, et al., 2008)** for $Ra = 7.5 * 10^5$, $r_{porous}/r_i = 1.5$ $Da = 10^{-3}$and $k_s/k_f = 100$. **Fig.2** show results of the comparison for isotherms contours.

Another compression was done with the numerical results obtained by **Al-Hattab, et al., 2008** at $Ra = 7.12 * 10^2$, diametric ratio=2. **Fig.3** shows results of the comparison for streamline contours and isotherms patterns. **Table-1** shows the results of these comparisons for Nusselt number. These comparisons showed good agreements between the current results and other researchers’ work.

4. RESULTS AND DISCUSSION

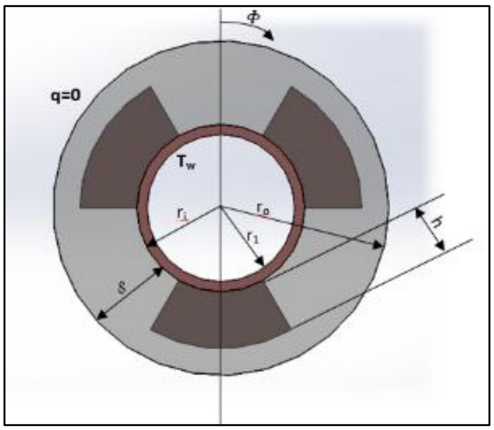
The considered problem has been analyzed at different values for Rayleigh numbers namely;$10^4. 5 * 10^4. 5 * 10^5 \& 10^6$ with metal foam fins distributed in four sections along the inner pipe then three other intermediate fins were added. The aim was to investigate the effect of these parameters on fluid flow and heat transfer inside the annuli space in presence of the suggested design of metal foam fin. In addition, a comparison has been established between the results of the percent case with a copper fins case to estimate the effect of using this design for metal foam in annular gaps.

Fig. (4 & 5) show the influence of the Rayleigh number on the temperature and velocity contours in fluid and metal foam regions at x/l= 0.55 for the case of 4 metal foam sections. Figure 4 illustrates that for both of Ra= (10^4 and $5*10^5$) the metal foam fins are isotherm and the upper fluid regions are at the highest temperature. The lower region temperature was graduated toward the outer cylinder. For Ra=10^4 the lowest temperature was trapped between the two fins and it look like semicircular around outer wall. The graduated temperature region for Ra=10^4 is large than that in case of Ra=$5*10^5$. For Ra=$5*10^5$ the lowest temperature region crawling downward. In figure 5 the effect of Ra on velocity contours was shown. The velocity is zero at the inner and outer walls for both Rayleigh numbers. A stagnation region appears at the upper region in case of Ra=$5*10^5$ since the temperature reached its maximum value. It can be noted from both figures that velocity and temperature values increases by increasing Ra.

Fig. 6 illustrated temperature and velocity contours along the annular for Ra=10^5 in the four foam fins case. It can be seen that the presence of metal foam fin in the bottom helped in improving heat transfer in this region. The other fin helped in improving heat transfer in the left side. They are both working on mixing the fluid and generating a movement in these weak heat transfer regions. It's also clear that both temperature and velocity were increasing toward the end of the annular.

Fig. (7&8) display the impact of Ra for 7 sections on temperature and velocity contours respectively. Similar to the case of 4 sections, **Fig. 7** shows the metal foam at the highest temperature. The foam fin at the upper region; which is the hottest region, transfers heat to the lower fluid which improves heat transfer. By increasing Rayleigh number, the temperature of inner pipe and metal foam solid matrix will increase which means an increase in temperature difference between solid and fluid. Based on the above; an obvious increase in heat transfer coefficient will occur. **Fig. 8** shows that an increase in Ra will enhance fluid flow characteristics. Metal foam fins geometry helps in mixing fluid between and through fins and transfers heat to fluid far from inner cylinder thereby increase its temperature, therefore its velocity will increase and turn from the stagnation status.
Influence of Rayleigh number on local Nusselt number along the annular length at $Ra = 10^4. 5 * 10^4. 10^5. 5 * 10^5 \& 10^6$ illustrated at **Fig. 9 and 10** for cases of 4 and 7 metal foam sections respectively. A significant increase in Nu appeared in the sections where foam fins were inserted. An increase in Rayleigh number led to an increase in Nusselt number along the annular. We can observe that Nu number decrease gradually along the annular as a result of temperature difference decrease. An exaptation for cases of Ra=$5*10^5$ &10^6 for the first case where Nu value remains constant after x/l=0.3 which belongs to the stability of temperature difference. These figures also showed that Nu number for clear fluid sections increase along the annular as a result of heat transfer improvement and fluid mixing that occurred due to the presence of foam fins.

Fig. 11 presents a comparison between the average Nusselt number for 4 sections of foam fins with a corresponding case of copper fins and the case of 7 sections of foam fins. All curves showed an increment in Nu number by increasing Ra number till Ra=10^5 where copper fins Nusselt number started to decrease by increasing Nu. That decrement gives an indication that the conduction heat transfer becomes the dominant mode. The reason for this phenomenon belongs to the disability caused by copper fins for the fluid movement which clearly appear by increasing inner wall temperature that presents an increase of Ra. On the other hand, the metal foam allows the fluid to move through it because of its high permeability. By increasing metal foam number along the annular heat transfer by solid matrix to the fluid and mixing of fluid will increase. As a result, the above average Nu number will increase.



Dimensions	Values
r_1	0.044m
r_i	0.05m
r_o	0.1m
□	0.05
h	0.02m
L	0.45m

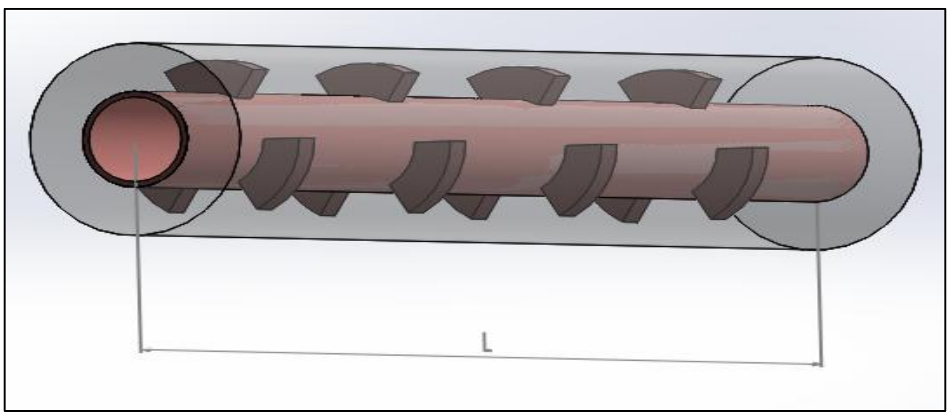


Figure 1. Physical geometry of the present problem; side view and three dimensional model with four metal foam sections with the necessary dimensions.

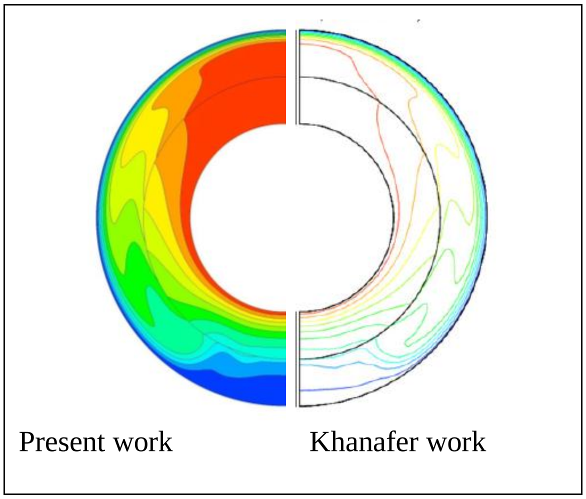


Figure 2. Comparison with **Khanafer, et al., 2008**for isotherms contours.

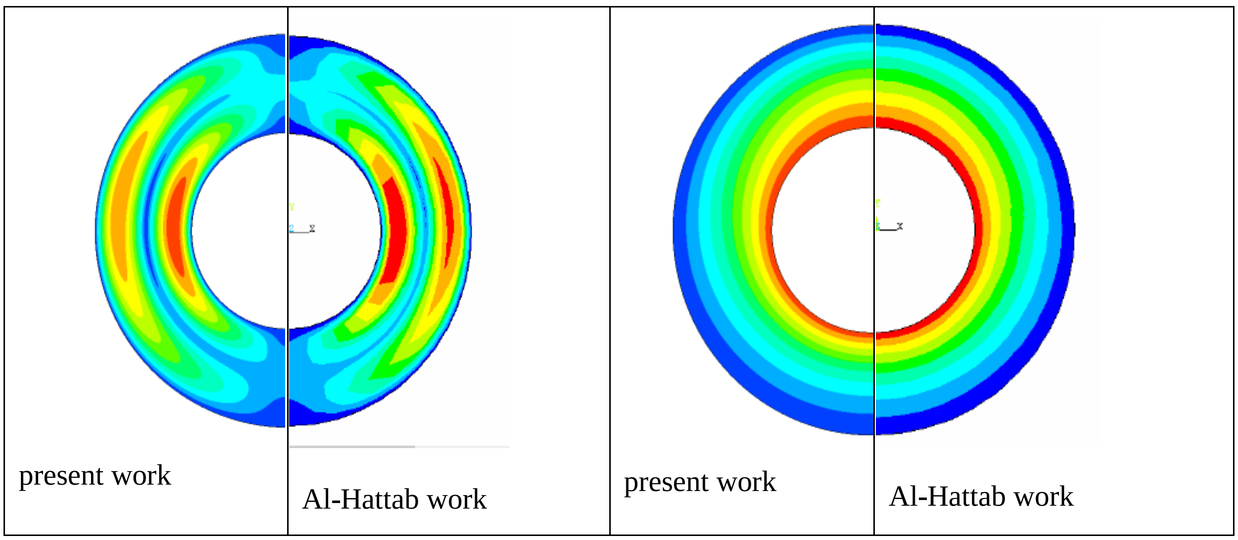


Figure 3.Comparison with **Al-Hattab, et al., 2008** for isolines and isotherms contours.

Tabel. Nusselt number of the present work and the corresponding researchers work.

Khanafer	Present work	Al-Hattab	Present work
8	8.2	0.96	1

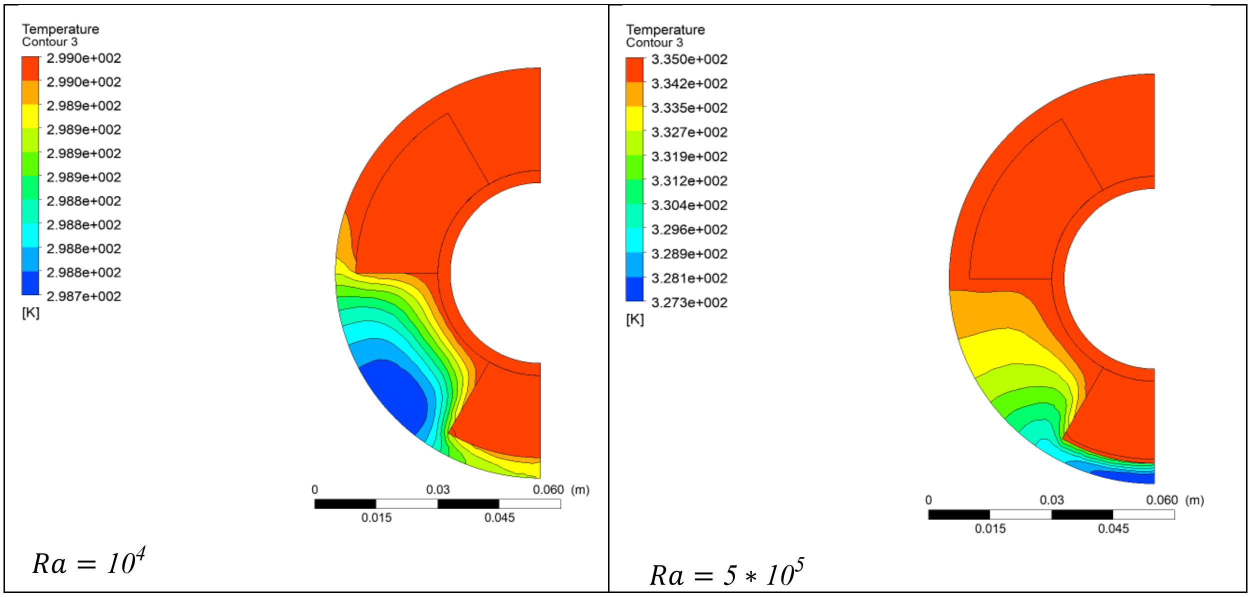


Figure 4. Effect of Rayleigh number on temperature contours at x/l= 0.55 for the case of four sections.

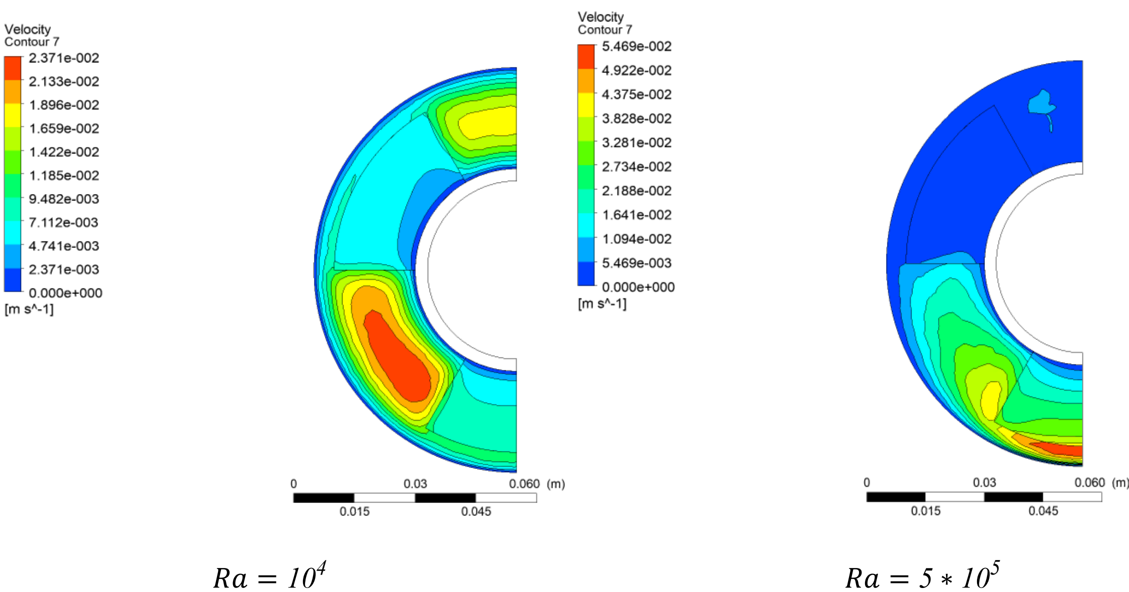
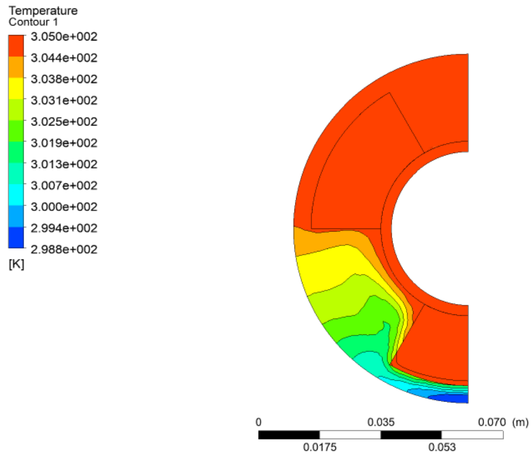
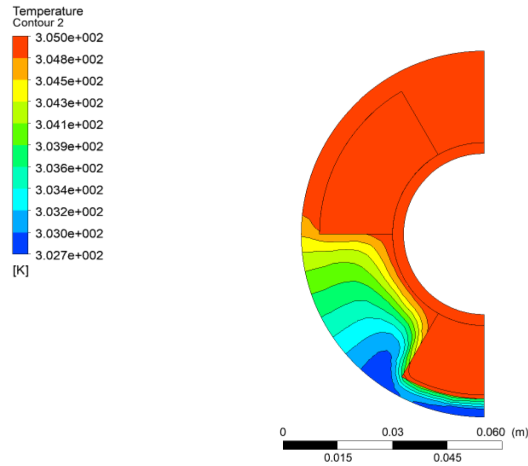


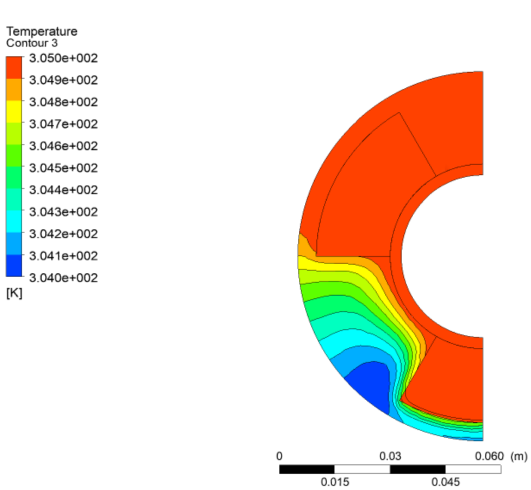
Figure.5 Effect of Rayleigh number on streamline contours at x/l= 0.55 for the case of four sections.



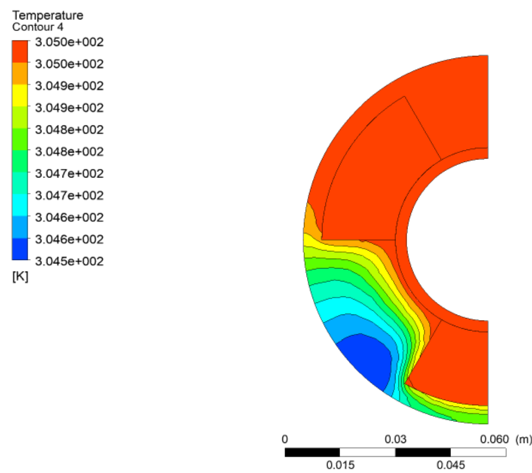
Section 1



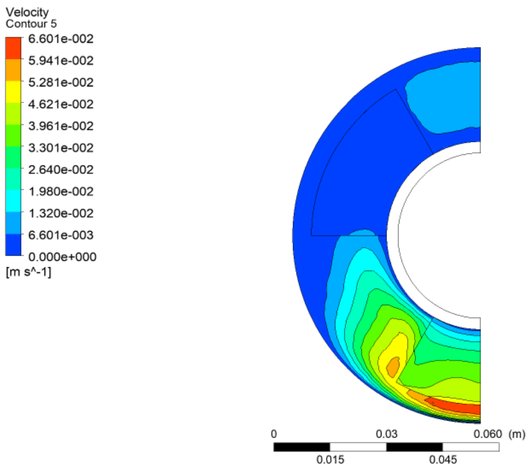
Section 2



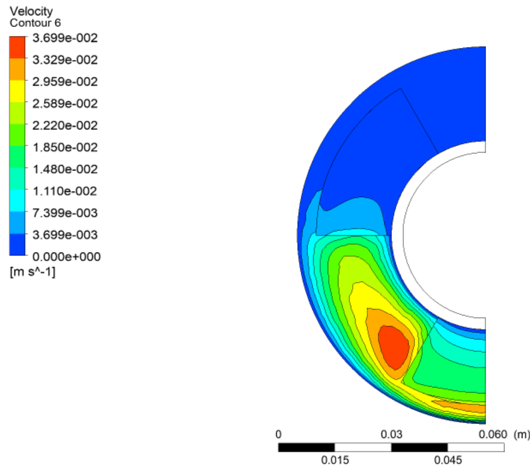
Section 3



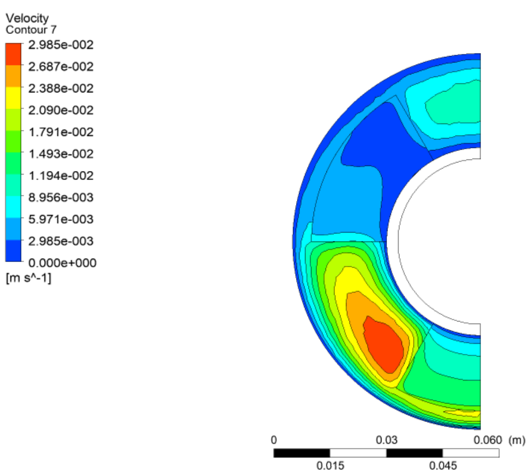
Section4



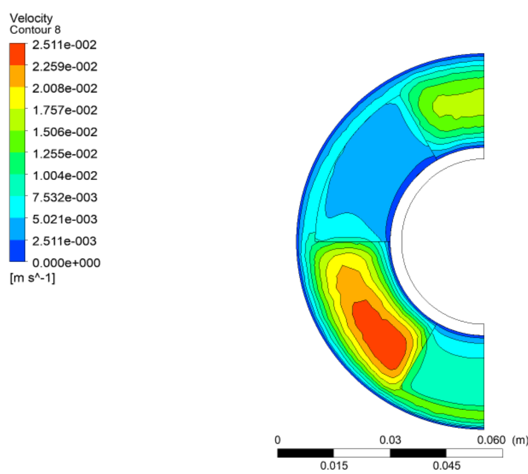
Section 1



Section 2

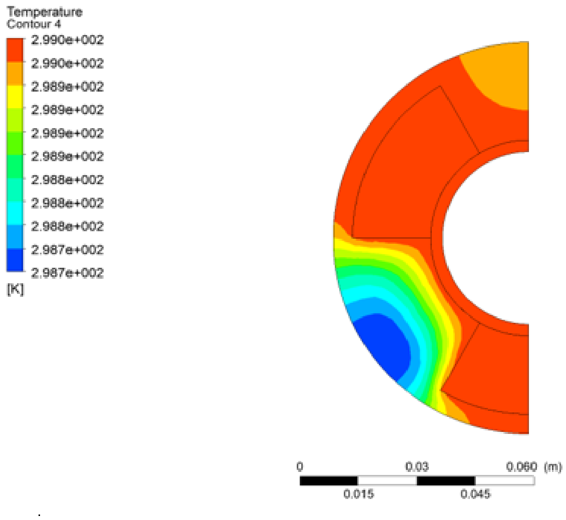


Section 3

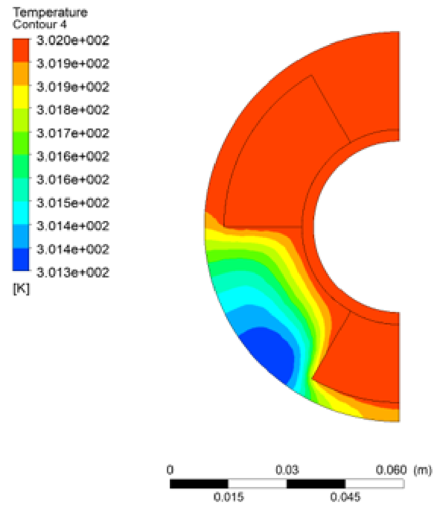


Section 4

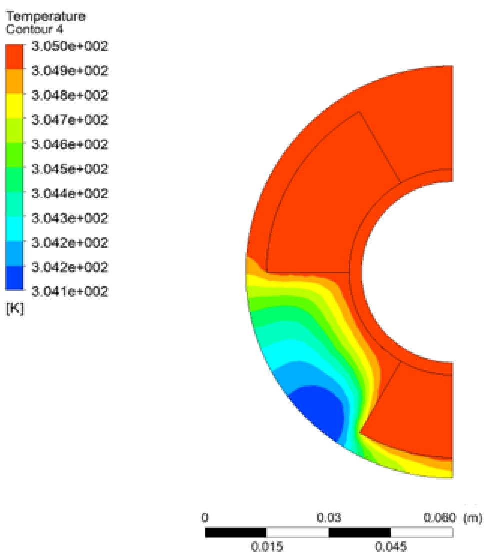
Figure 6. Temperature and Velocity contours along the annular at $Ra = 10^5$.



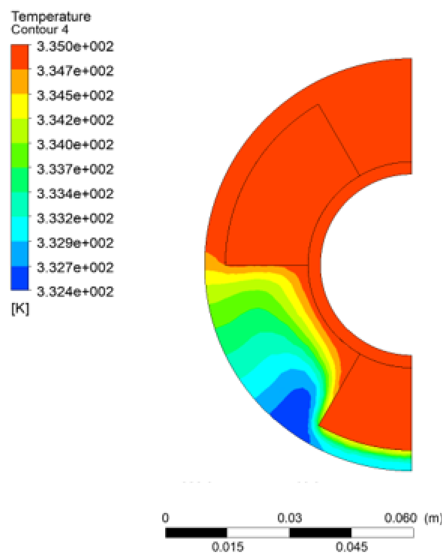
Ra=10^4



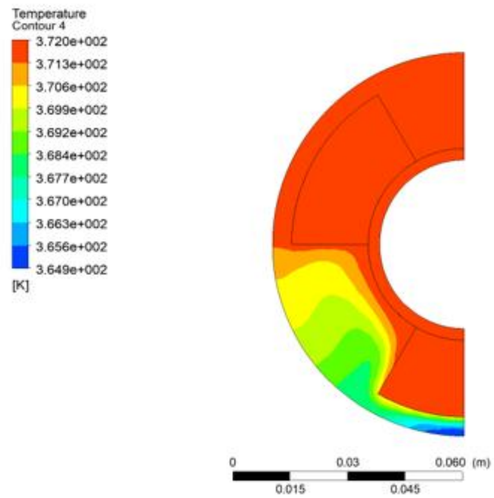
Ra=$5*10^4$



Ra=10^5

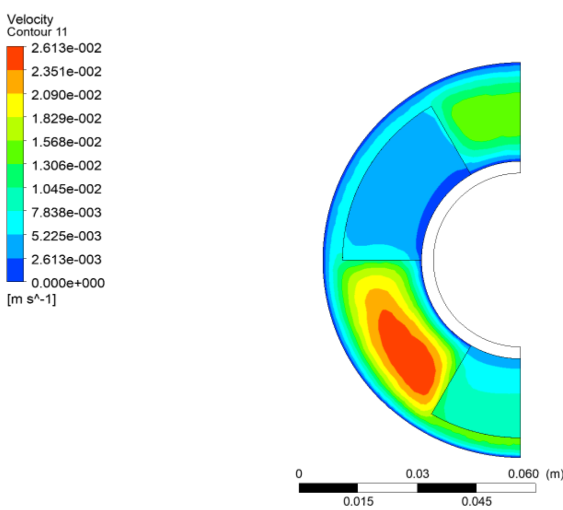


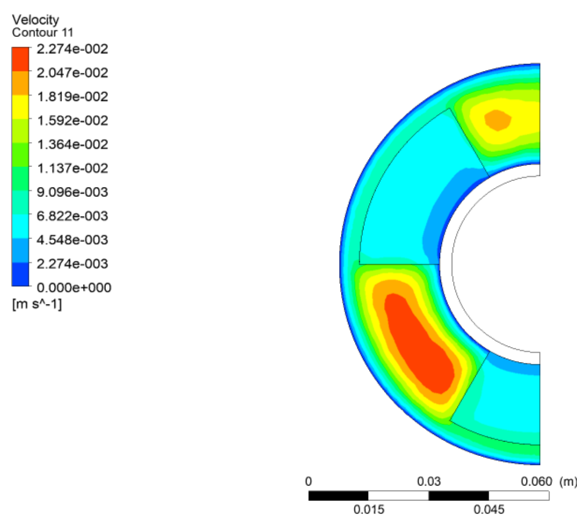
Ra=$5*10^5$



Ra=10^6

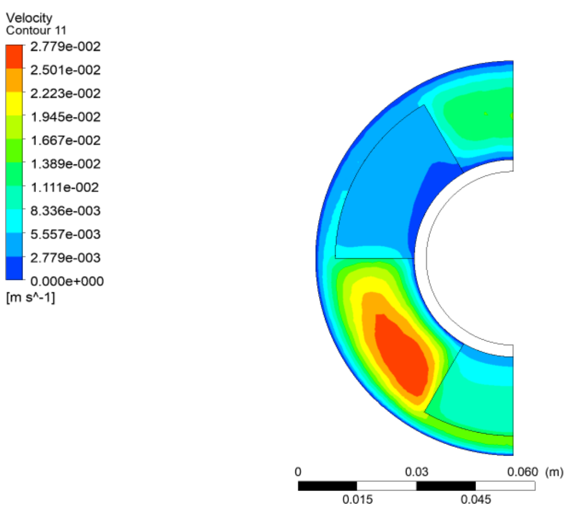
Figure 7. effect of Rayleigh number on temperature contours at x/l=0.45 for the case of seven sections.



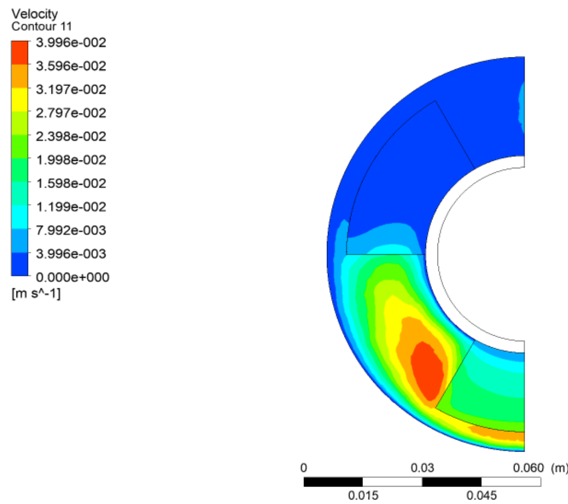


-

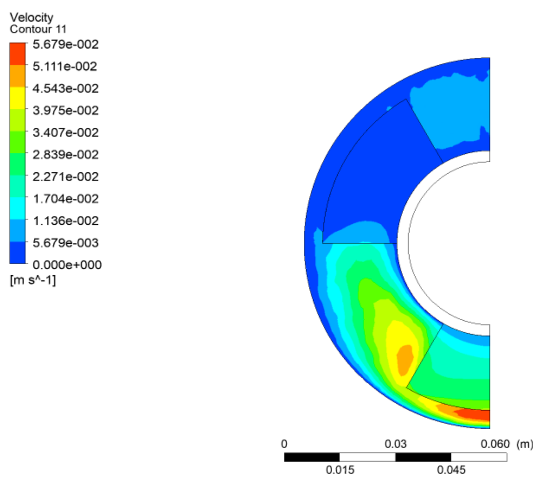
Ra=10^4 Ra=$5*10^4$



Ra=10^5



Ra=$5*10^5$



Ra=10^6

Figure 8. effect of Rayleigh number on velocity contours at x/l=0.45 for the case of seven sections.

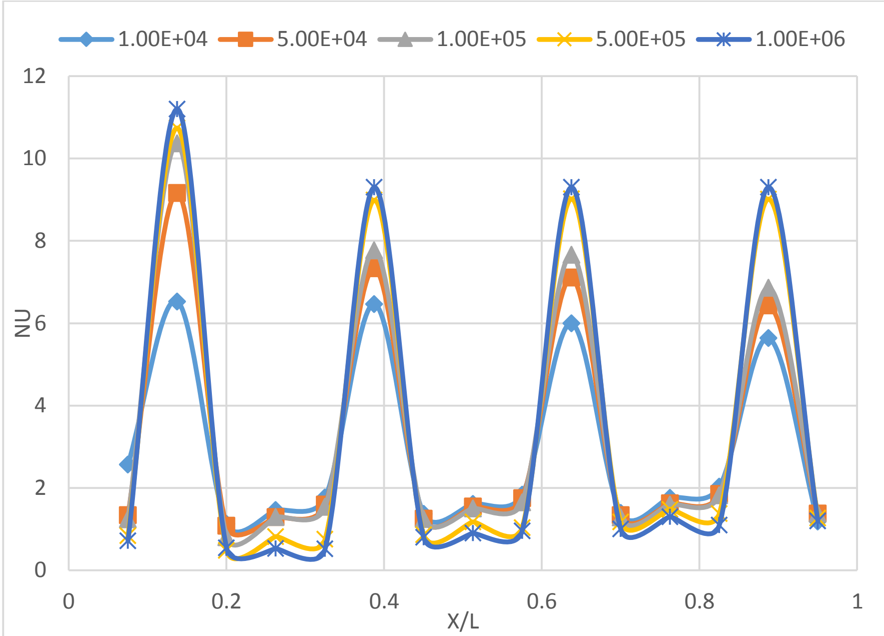


Figure9. Effect of Rayleigh number on local Nusselt number at different values of Ra for the case of four sections.

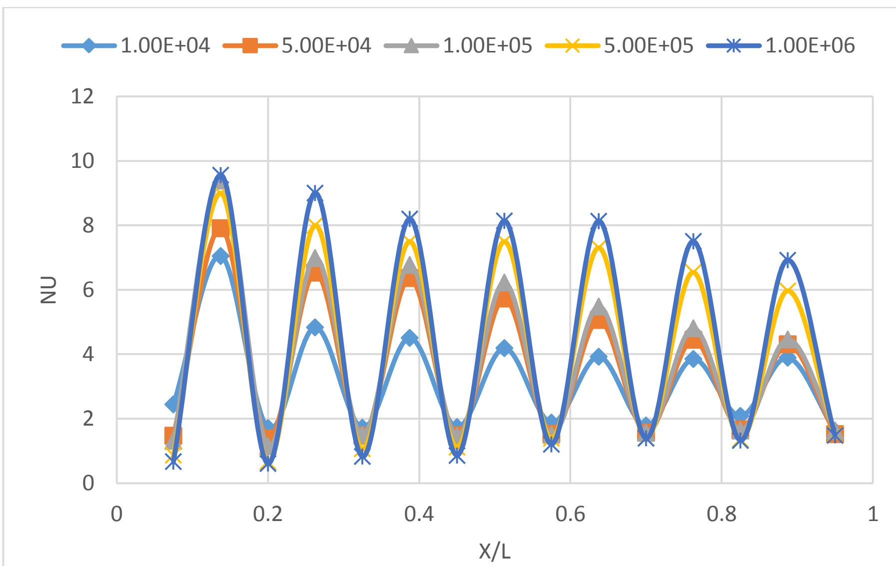


Figure10. Effect of Rayleigh number on local Nusselt number at different values of Ra for the case of seven sections.

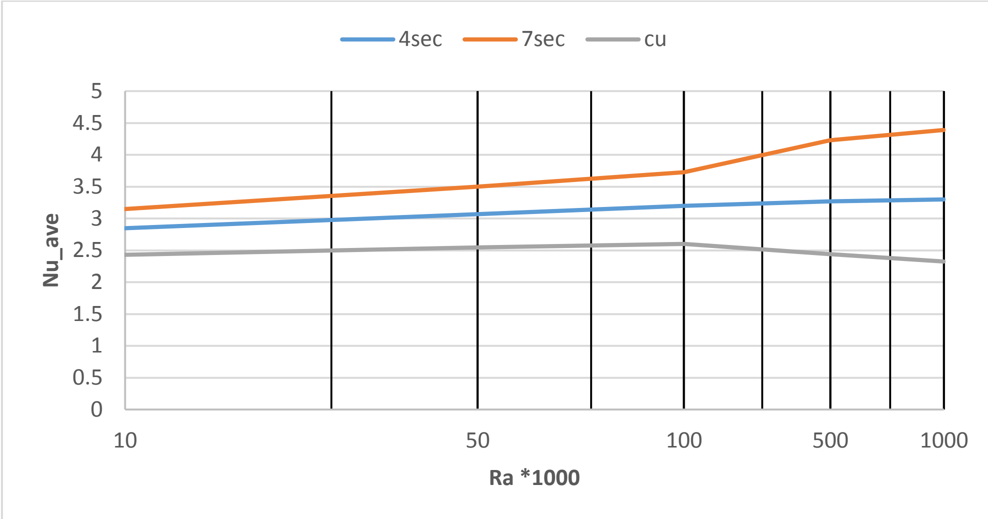


Figure.11. comparison between Nusselt number for foam fins in 4 and 7sections with copper fins.

5. CONCLUSION

Natural convection heat transfers in annular space between two concentric cylinders filled partially with metal foam was presented in this paper. Metal foam is inserted as three fins distributed with angle of 60^o around the inner surface. Different number of metal foam fins along the annular space was examined. That distribution would allow heat to be transferred from the inner tube to the fluid directly on one side and through the metal foam on the other. These fins are designed in a way that allows the convection currents to move between them freely and smoothly. All of this contributed to an increase in heat transfer in addition to reducing the amount of metal foam used and thus reducing the cost.

Three-dimensional laminar flow, steady state conditions with constant properties were assumed. Boussinesq approximation used for fluid density. The inner cylinder was kept at a constant temperature while the outer surface of the annular was insulated. ANSYS FLUENT software was used to solve this problem.

For this problem; the heat transfer is confined to the upper region of the annular and by increasing Rayleigh number the conduction will be the demotivate mode of heat transfer. The reason behind this behavior is that heat will transfer from the inner surface to the fluid which as a result will get hotter and raises to the top of the annular which is adiabatic. Here the hot fluid will remain at the top and prevent the lower fluid from rising. The lower fluid will be at stagnation status and thus convection currents will be stopped. From the results of adding metal foam fins with the suggested configuration, we concluded that the heat transfer by convection is improved. Results showed that adding foam fin in the lower region enhances heat transfer in this region which is the weakest region. Also, adding two additional fins distributing around the inner pipe with an angle of 60^o helps in transferring heat from the top to the rest of the annular thereby fluid turns from stagnation to a movable status. As a result; the average Nusselt number increases. We concluded that the local Nusselt number in metal foam sections decreases towards the end of the annular for all Ra values as a result of decreasing the difference in temperature between the solid and fluid. We also concluded that the average Nusselt number increases by increasing Rayleigh number and meatal foam fins along the annular.

The increase in Nusselt number by adding meatal foam fins is more than the increase which occurs when adding copper fins for the Ra number range between (10^4 and 10^6). The highest average Nu was for the case of 7 sections of metal foam which was 4.4 at Ra=10^6 while the lowest was 2.38 for copper fin case at Ra=10^6.

REFERENCES

- Abeed, M., A., 2012, Experimental and Theoretical Study of Natural Convection Heat Transfer between Two Inclined Concentric Cylinders Filled With Porous Media, Tikrit Journal of Engineering Sciences, 18(4), pp. 40–51.
- Al-Hattab, T. A., Majeed, M. H., and Abd-Saada, M. F., 2008, Heat Transfer By Free Convection Between Horizontal Concentric Pipes, The Iraqi Journal For Mechanical And Material Engineering, 8(3), pp. 219–236.
- Alhusseny, A., Turan, A., and Nasser, A., 2017, Rotating metal foam structures for performance enhancement of double-pipe heat exchangers, International Journal of Heat and Mass Transfer, 105, pp. 124–139. doi: 10.1016/J.IJHEATMASSTRANSFER.2016.09.055.
- Aziz, S. and Nima, M., 2020, Performance Analysis of Solar Tower Integrated with Flat Plate and Copper Foam Absorber, university of Baghdad.
- Bejan, A., 2008, Convection in porous media, Applied Mathematical Sciences (Switzerland). doi: 10.1007/978-0-387-76543-3_4.
- Caltagirone, J. P., 1976, Thermoconvective instabilities in a porous medium bounded by two concentric horizontal cylinders, Journal of Fluid Mechanics, 76(2), pp. 337–362. doi: 10.1017/S0022112076000669.
- Chamkha, A. J., Miroshnichenko, I. V. and Sheremet, M. A., 2018, Unsteady Conjugate Natural Convective Heat Transfer and Entropy Generation in a Porous Semicircular Cavity, Journal of Heat Transfer, 140(6). doi: 10.1115/1.4038842.
- Chen, X. et al., 2020, Performance evaluation of a double-pipe heat exchanger with uniform and graded metal foams, Heat and Mass Transfer/Waerme- und Stoffuebertragung, 56(1), pp. 291–302. doi: 10.1007/s00231-019-02700-3.
- Ergun, S., 1952, Fluid through packed columns, Chemical Engineering Progress, pp. 89–94.
- Hamad, F. A. and Khan, M. K., 1998, Natural convection heat transfer in horizontal and inclined annuli of different diameter ratios, Energy Conversion and Management, 39(8), pp. 797–807. doi: 10.1016/S0196-8904(97)10010-3.
- Hamzah, J. A. and Nima, M. A., 2019, Numerical Investigation of Heat Transfer Enhancement of Double Pipe Heat Exchanger Using Metal Foam Fins, Journal of Engineering, 25(6), pp. 1–18. doi: 10.31026/j.eng.2019.06.01.
- Hamzah, J. A. and Nima, M. A., 2020, Experimental Study of Heat Transfer Enhancement in Double-Pipe Heat Exchanger Integrated with Metal Foam Fins, Arabian Journal for Science and Engineering, 45(7), pp. 5153–5167. doi: 10.1007/s13369-020-04371-3.
- Jiji, L. M., 2009, Heat Convection. second. New York: Springer Berlin Heidelberg. doi: 10.1007/978-3-642-02971-4.
- Khanafer, K., Al-Amiri, A. and Pop, I., 2008, Numerical analysis of natural convection heat transfer in a horizontal annulus partially filled with a fluid-saturated porous substrate, International Journal of Heat and Mass Transfer, 51(7–8), pp. 1613–1627. doi: 10.1016/j.ijheatmasstransfer.2007.07.050.
- Mansour, K., 2008, Natural convection with porous medium in a narrow horizontal cylindrical annulus with linear heat generation, ASME 2011 9th International Conference on Nanochannels, Microchannels, and Minichannels, ICNMM 2011, 1, pp. 495–499. doi: 10.1115/ICNMM2011-58125.

- Qu, Z. G., Xu, H. J. and Tao, W. Q., 2013, Conjugated natural convection in horizontal annuli partially filled with metallic foams by using two-equation model, Journal of Porous Media, 16(11), pp. 979–995. doi: 10.1615/JPorMedia.v16.i11.20.
- Roy, N. C., 2019, Natural convection in the annulus bounded by two wavy wall cylinders having a chemically reacting fluid, International Journal of Heat and Mass Transfer, 138, pp. 1082–1095. doi: 10.1016/j.ijheatmasstransfer.2019.04.133.
- Senthilkumar, K. and Palanisamy, P., 2015, A study of concentric tube heat exchanger with different porous particles using Wilson plot analysis, International Journal of ChemTech Research, 8(10), pp. 138–147.
- Shehab, S. N., 2016, Experimental Investigation of Natural Convection into a Horizontal Annular Tube with Porous Medium Effects, Journal of Engineering, 22(12), pp. 103–117.
- Sheremet, M. A. and Trifonova, T. A., 2014, Unsteady Conjugate Natural Convection in a Vertical Cylinder Containing a Horizontal Porous Layer: Darcy Model and Brinkman-Extended Darcy Model, Transport in Porous Media, 101(3), pp. 437–463. doi: 10.1007/s11242-013-0253-8.
- Targui, N. and Kahalerras, H., 2008, Analysis of fluid flow and heat transfer in a double pipe heat exchanger with porous structures, Energy Conversion and Management, 49(11), pp. 3217–3229. doi: 10.1016/J.ENCONMAN.2008.02.010.
- Xu, H. J., Qu, Z. G. and Tao, W. Q., 2011, Analytical solution of forced convective heat transfer in tubes partially filled with metallic foam using the two-equation model, International Journal of Heat and Mass Transfer, 54(17–18), pp. 3846–3855. doi: 10.1016/j.ijheatmasstransfer.2011.04.044.

NOMENCLATURE

c: specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	ε: porosity
Da: Darcy number	ΔT: temperature difference
μ:dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)	υ: kinematic viscosity ($m^2 \cdot s^{-1}$)
k: thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	K: permeability (m^2)
Nu: Nusselt number	ρ: density ($kg \cdot m^{-3}$)
$\boldsymbol{\alpha}$: Heat diffusivity m^2/s	g: gravity acceleration (m/s^2)
ΔP: pressure difference ($N \cdot m^{-2}$)	**δ**: width of the annular gap (m)
h: heat transfer coefficient $W/(m^2.K)$	T: temperature (K)
Ra: Rayleigh number	ω: pore density [PPI (pores per inch)]
	V: velocity vector ($m \cdot s^{-1}$)
Subscripts	
e: effective	f, s: fluid, solid
i: inner	o: outer
r: radial position (m)	p: porous
Greek Symbols	
β: volume expansion coefficient (K−1) w wall	