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INVESTIGATION OF FLUID FLOW AND HEAT TRANSFER IN A CHANNEL WITH AN OPEN CAVITY HEATED FROM BOTTOM SIDE

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Abstract

In this study, laminar flow of air (Pr=0.71) and combined forced convection through a horizontal square duct having side length H with a cavity height D and length W placed below the duct is investigated. While the bottom surface of the cavity is kept at a constant temperature, all the other cavity and duct walls are adiabatic. Air at contant temperature enters to the duct with constant velocity. The problem is modeled in three dimensions (3-D) and continuity, momentum and energy equations are solved using FLUENT® software where Boussinesq approximation is used for the density difference. In differencing the convection terms, second order upwind scheme and SIMPLE algorithm has been adapted. Width to height ratio of cavity is taken as W/D=0.5 and 1 while duct height to cavity height ratio H/D is kept within 0.5-2 interval. The Richardson number is varied between 0.1 to 10. The numerical simulations and the analysis were carried out for Reynolds number values of 10, 100 and 200. The average Nusselt number is computed over the hot bottom cavity surface area and the effects of the Richardson number, Reynolds number, W/D and H/D ratios on the flow and heat transfer are investigated. It is observed that as the cavity width is increased, rotating cells are observed with increasing the Richardson number while for increased Reynolds numbers forced convection effects became more pronounced.
Keywords: Natural convection, forced convection, combined convection, cavity duct, laminar flow

ALT YÜZEYİNDEN ISITILAN AÇIK OYUK İÇEREN YATAY KANALDA ISI GEÇİŞİ VE AKIŞIN İNCELENMESİ

Özet

Bu çalışmada, yüksekliği ve genişliği H olan kare kesitli yatay şekilde konumlu bir kanalın tabanına yerleştirilen, yüksekliği D ve uzunluğu W olan bir oyuktan laminer akış koşullarında hava (Pr=0.71) akışı ile kombine zorlanmış ve doğal taşınım ile ısı geçişi sayısal olarak incelenmiştir. Oyuk alt yüzeyi sabit sıcaklıkta tutulurken, oyuk ve kanalın diğer duvarları yalıtılmıştır. Hava, kanala sabit hız ve sabit sıcaklıkta girmektedir. Problem, üç boyutlu (3-B) olarak ele alınmış ve süreklilik, momentum ve enerji denklemleri FLUENT® yazılımı yardımıyla çözülmüş ve yoğunluk farkı için Boussinesq yaklaşımı kullanılmıştır. Taşınım terimlerinin ayrıklaştırılmasında, ikinci dereceden ayrıklaştırma ve sayısal çözümde SIMPLE algoritması kullanılmıştır. Oyuk en/boy oranı, W/D=0.5 ve 1 alınırken, kanal yüksekliğinin oyuk yüksekliğine oranı H/D=0.5-2 aralığında tutulmuştur. Richardson sayısı 0.1-10 arasında değiştirilmiştir. Sayısal analizlerde Reynolds sayısının 10, 100 ve 200 değerleri için incelenmiştir. Nusselt sayısı, ısıtılan oyuk taban yüzeyi alanı boyunca ortalanmış değeri hesaplanarak Richardson sayısı, Reynolds sayısı, W/D ve H/D oranlarının değişiminin kanaldaki akışkan akışının ısı geçişine etkisi incelenmiştir. Oyuk genişliği arttırıldığında ısı geçişinde artış olduğu, Richardson sayısı arttırıldığında oyuk içinde dönel hücrelerin oluştuğu, yüksek Reynolds değerlerinde ise zorlanmış taşınım etkilerinin önem kazandığı gözlenmiştir.
Anahtar Kelimeler: Doğal taşınım, Zorlanmış Taşınım, Kombine taşınım, oyuk kanal, Laminer akış

1 Introduction

Numerous studies on the convective heat transfer in an enclosure have been studied because of its wide application areas. Solar collectors, cooling of electronic equipment, nuclear reactors etc are some of the application areas. The use of air as a cooling fluid in the electronic components are preferred due to low cost and simplicity to incorporate into designs. In these systems, the heat is transferred by natural, combined or mixed, convection. In low density systems, cooling by natural convection is widely used. For this reason, the numerical and experimental studies with open cavities are frequently encountered in the literature.

In two dimensional numerical studies, natural convection [1-4] and mixed convection [5,6] is also examined in a channel with an open cavity heated from below. Pallares et al. [7], numerically investigated natural convection in three dimensional cubic cavity heated from below and cooled from the top wall while other walls are adiabatic. Air was also used as a working fluid (Pr=0.71). As the Boussinesq approximation was used, the Rayleigh number (Ra) was varied between 3500 and 10000. This study results were found to be in compliance with the Nusselt correlations for those of the two parallel plates (heated from the bottom and cooled from the top) and the enclosed rectangular ones. Nakano et al. [8] studied three dimensional transient natural convection for the low Prandtl number fluid (Pr=0.01) and Ra=2000 in shallow rectangular cavity heated from below and cooled from the top. Transient response is seen first like regular oscillation and then becomes long revolving cells rotating around its own axis. Striba [9], investigated mixed convection in 3D horizontal channel with an open cavity heated from left cavity wall. The effects of Reynolds and Richardson number on the flow in the duct and inside the cavity are studied for $100 \le Re \le 1500$ and $0.001 \le Ri \le 10$. It was observed that for every Reynolds number, the Nusselt number increased with the Richardson number. Andreozzi et al. [10] studied three-dimensional transient natural convection in a horizontal channel heated from below for constant heat flux 120 W/m² and 240 W/m² and the Rayleigh number 1.11×10^6 and 2.21×10^6. The main flow created C-loop pattern and from the temperature profiles secondary motion is observed inside the channel. Buonomo et al. [11] numerically studied three dimensional mixed convection in a horizontal channel with the heated lower wall at uniform heat flux. The analysis is performed for the heat flux 150 W/m² and 300 W/m² and the Reynolds numbers of 5 and 150. In the study, for low Reynolds number, the presence of backflow was noticed.

In this study, the fluid flow and heat transfer is investigated for 10≤Re≤200, 0.1≤Ri≤10, duct height to cavity height 0.5≤H/D≤2, cavity width to cavity height (W/D) 1.5 and 1.

2 Physical Problem and Mathematical Formulation

The geometry investigated in this study is illustrated in Figure 1. An open cavity with a width W and height H is placed at the bottom of the 8×W long duct of square cross section H×H . The entrance length is 4×W and the length passed cavity is 3×W. The bottom surface of the cavity, only, is imposed a constant temperature, while all the remaining walls are assumed to be adiabatic. The air (Pr=0.71), which is a working fluid, enters the duct with a uniform velocity U_0 and ambient temperature T_0. Also the flow is assumed to be steady, laminar and incompressible. All thermo-physical properties are assumed to be constant except the density where the Boussinesq approximation is used to compensate for the density variation.

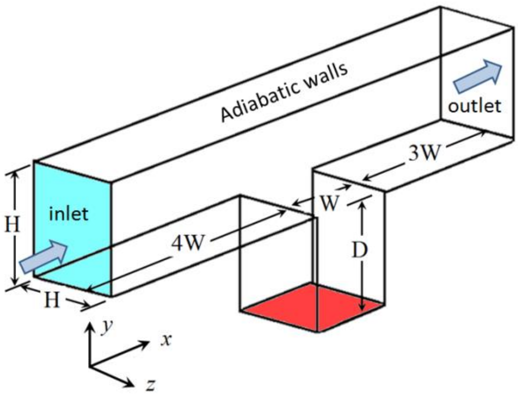

Figure 1. Schematic diagram of the geometry

Under these assumptions, the governing equations can be stated as;

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\beta g\left(T-T_0\right) \tag{3}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial z}+\upsilon\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

where ρ is the density, P is the pressure, υ is the kinematic viscosity, β is the thermal expansion coefficient, T is the temperature, g is the gravity and α is the thermal diffusivity. The boundary conditions can be stated as follows:

duct inlet	$T=T_0$, $u=U_0$, $v=w=0$
duct outlet	$\frac{\partial u}{\partial x}=\frac{\partial v}{\partial x}=\frac{\partial T}{\partial x}=0$
adiabatic walls	$\frac{\partial T}{\partial n}=0$, $u=v=w=0$
Heated cavity bottom wall	$T=T_H$, $u=v=w=0$

The dimensionless numbers encountered here which are Reynolds, Grashof, Richardson and Prandtl numbers defined as $\mathrm{Re}=U_0H/\upsilon$, $\mathrm{Gr}=g\beta(T_H-T_C)H^3/\upsilon^2$, $\mathrm{Ri}=\mathrm{Gr}/\mathrm{Re}^2$, $\mathrm{Pr}=\upsilon/\alpha$ respectively.

The mean Nusselt number is computed as an average over the isothermal heated surface area according to

$$\overline{\mathrm{Nu}}=\frac{\bar{h}H}{k}=\frac{1}{A_H}\iint_{A_H}\mathrm{Nu}\,dA \tag{6}$$

where k is the conductivity of air, A_H is the heated surface area and $\overline{\mathrm{Nu}}$ is the mean Nusselt number.

3 Numerical Solution

In the discretization of the convection terms, the second order upwind, and as for the solution algorithm, SIMPLE is used. The Boussinesq approximation is employed to account for the density variations. In the study, the duct height to cavity height ratio is varied between 0.5≤H/D≤ 2 and cavity aspect ratio (W/D) is 0.5 and 2. Richardson number is varied from 0.1 to 10 and the Reynolds numbers are taken 10, 100 and 200. In order to check the solution for grid independence, four different grid configurations were tested (20^3, 40^3, 50^3, 60^3). It was determined that 50^3 was the optimum grid.

To determine the accuracy of the study, the numerical solutions are compared with the available numerical studies in the literature, and the comparisons are provided in Table 1.

Table1. Comparison of Nusselt Number

Gr	Re_w	Ri	(Leong et. al.)[6] Nu_w	Study Nu_w	Relative %
10^2	10	1	2.209	2.369	6.7
10^2	100	0.01	3.837	4.006	4.2
10^3	100	0.1	4.510	4.010	11
10^3	10	10	3.644	3.321	9.7

4 Results and Discussion

For Ri=0.1 and 1, W/D=0.5, H/D=1, the pathlines (by tempera-ture) are depicted for Re=10, 100 and 200 in Figure 2. For

Re=10 (Figure 2a), heating is effective in the lower half of the cavity.

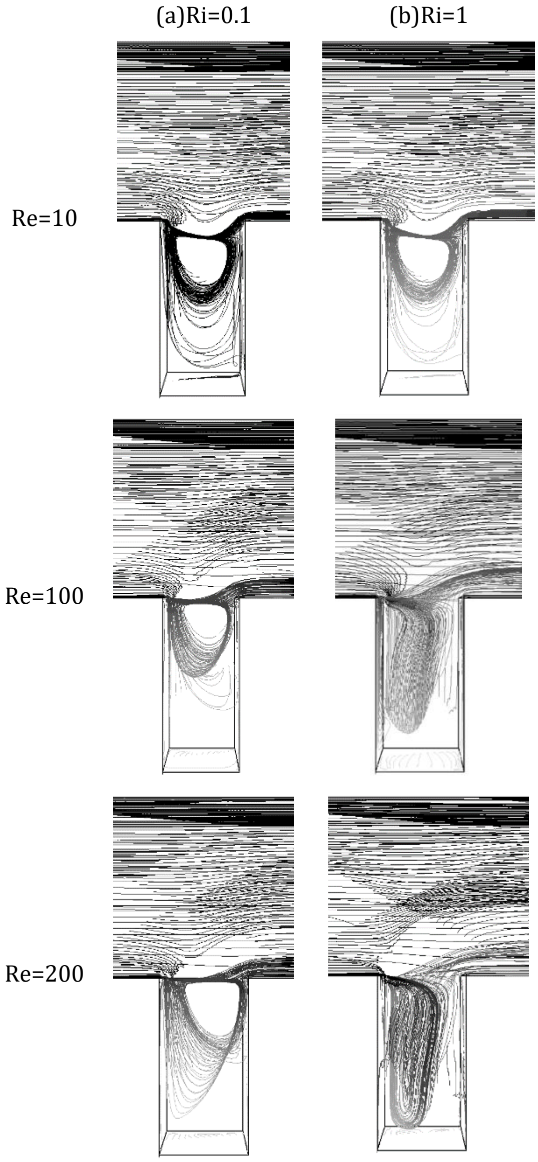

Figure 2.Pathlines (by temperature) for W/D=0.5 and H/D=1 and Re=10, 100 and 200 for (a)Ri=0.1, (b) Ri=1.

Due to the low duct flow, the air does not fully penetrates into the cavity; just a small dip from the top of the cavity is observed. At the upper portion of the cavity, a clockwise circulation is observed. For Re=100 (Figure 2a), weak motion in the lower portion of the cavity disappears and the fluid becomes almost motionless. As the circulation becomes stronger, the dip at the upper part of cavity disappeared. For Re=200 (Figure 2a), due to the increased velocity (higher Re values), the diameter and the magnitude of the circulation also increased and is most effective in the left lower part of the cavity. Except the right lower part of the cavity, the duct flow almost covers in the entire cavity.

For the Richardson number at low Reynolds number (Figure 2b), the pathlines are alike in Figure 2a. As the circulation similarly occurred at the upper portion of the cavity, weak motions are observed at the lower part of the cavity. Due to the small fluid velocities, no significant effects are observed in changing the Richardson number. For Re=100 (Figure 2b), the fluid penetrates deeper into the cavity from left side, forming a circulation which is clustered along the left wall and mixes with the duct flow. At the cavity exit, the temperature of the fluid on the lower part of the duct is increased due to better mixing. For Re=200 (Figure 2c), the pathline is similar to Figure 2-2b. As the circulation gains strength with increasing Reynolds number, it extends downward and becomes more effective on the left bottom cavity. The fluid inside the right bottom remains motionless.

For Ri=1, W/D=1, Re=10 and 100, the pathlines with respect to H/D ratio (0.5≤H/D≤2) are depicted in Figure 3. For Re=10 and H/D=0.5 (Figure 3a), since the cavity top surface is not a impermeable wall, downward velocity gradient impels the flow downwards. The duct flow penetrates deeper into the cavity and leaves the cavity from right side. It is also more effective at the lower part of the cavity. For H/D=1 (Figure 3a), the flow gets into the half of the cavity and forms a right warped parabolic and leaves the cavity. Under this parabolic line, a clockwise circulation whose diameter approaches to the vertical sides is observed.

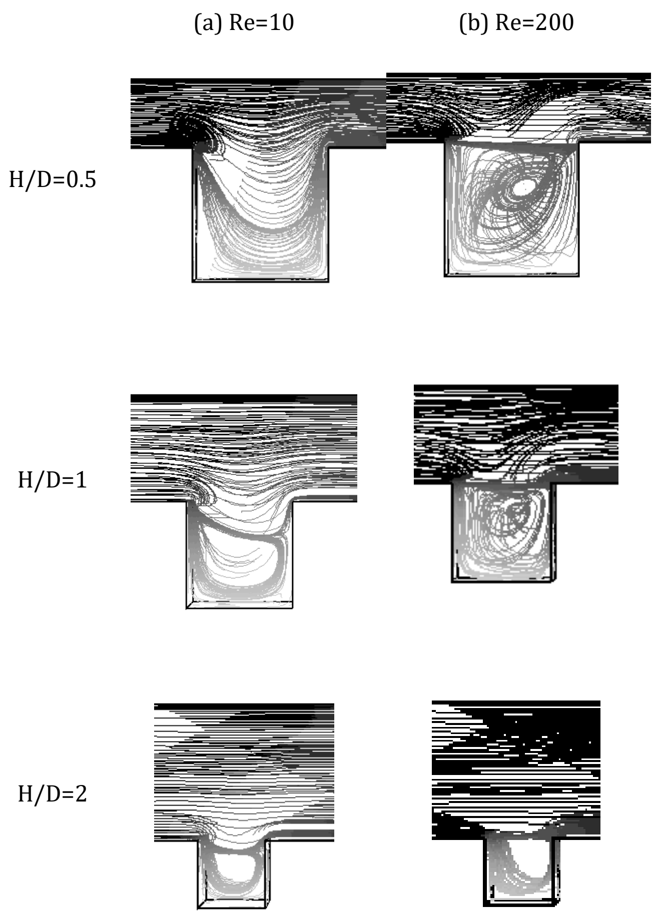

Figure 3.Pathlines (colored by temperature) for Ri=0.1 and W/D=1 and H/D=0.5, 1 and 2 for (a) Re=10, (b) Re=200.

For H/D=2 (Figure 3a), the flow enters the upper part of the cavity and forms a shallow bowl shape and then mixes back with the axial duct flow. Inside the cavity, it is observed that the diameter of the circulation is slightly decreased, and it is not effective at the right and left corners. For Re=200 and H/D=0.5 (Figure 3b), the fluid from the duct penetrates the cavity from right side, mixes with the hot fluid at the lower zone of the cavity and moves up from the left side. As a result of this a non-uniform circulation is observed inside the cavity. For H/D=1 (Figure 3b), the fluid penetrates into the cavity the same way, but the magnitude of the circulation becomes weak and less obvious. For H/D=2 (Figure 3b), the circulation fills the entire cavity and is clearer.

In Figure 4, the variation of the mean Nusselt number with the Reynolds numbers and H/D for Ri=1 and for W/D=1 is depicted. For all Reynolds numbers, the mean Nusselt number is increased as the H/D increases. For Re=10 and H/D=1, the mean Nusselt number is 0.76 and the conduction is more pronounced. In H/D=2, the mean Nusselt number is 1.30. For H/D=1, the mean Nusselt number for Re 10, 100 and 200 are 0.76, 1.83 and 3.37, respectively. For Re=10 and Re=100, the Reynolds number is increased 10 times but the mean Nusselt number is increased 2.4 times. This is because of the thermal boundary layers on the cavity walls which develop due to circulation in the cavity. For Re=200 and H/D=0.5, 1 and 2, the mean Nusselt numbers are 2.89, 3.37 and 3.96, respectively. In Figure 4, the lines for Reynolds are almost parallel to each other. As the H/D increase, the mean Nusselt numbers increase in proportion with each other.

In Figure 5, the variation of the mean Nusselt number with the Reynolds numbers and Ri for H/D=2 and for W/D=0.5 is depicted. As the variation in Nusselt numbers are examined, for Re=10 the increased in Ri number don't have a significant effect on the mean Nusselt number. For Re=100, the relative increase of mean Nusselt number is very small (0.6%) in the range of Ri=0.1 and Ri=1; for Ri=10 it increases 182%. For Re=200 and Ri=0.1, 1 and 10, the mean Nusselt numbers are 1.72, 2.72 and 6.20 respectively. At constant Richardson number, as the Reynolds number is increased, the mean Nusselt number is also increased.

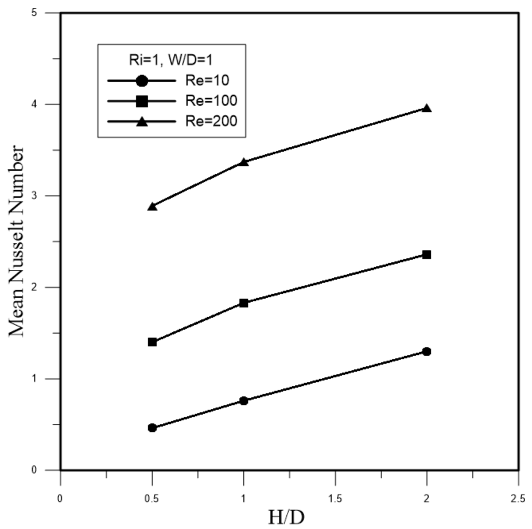

Figure 4. The variation of the mean Nusselt number with the Reynolds numbers and H/D for Ri=1 and W/D=1

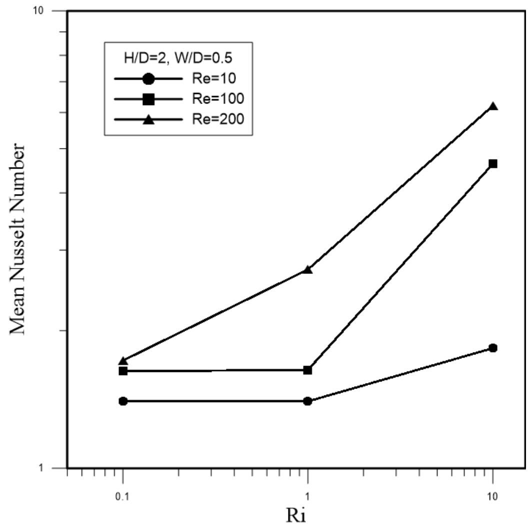

Figure 5. The variation of the mean Nusselt number with the Reynolds numbers and Ri for H/D=2 and W/D=0.5

In the range of Ri=1 and Ri=10, the mixed convection is dominant and the increment in mean Nusselt number is relatively larger at higher Reynolds numbers.

4 Conclusion

The heat transfer and fluid flow in an open cavity placed at the bottom of a straight duct is investigated numerically using three-dimensional models with respect to W/D and H/D, and dimensionless Richardson and Reynolds numbers. This study yields the following conclusions:

a) As the Reynolds number is increased, the circulation is observed inside the cavity.
b) As the H/D rate is increased, Nusselt numbers are increased proportionally.
c) At high Reynolds numbers, forced convection is more dominant.
d) At H/D=0.5, W/D=0.5 and in the range of Ri=0.1 and Ri=1 the mean Nusselt number is increased by %30 for Re=10 and %128 for Re=200.

5 Acknowledgment

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