Numerical and Experimental Study Of Air Flow By Natural Convection In A Rectangular Open Cavity Cooled Top and Bottom Surfaces

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Özet
Bu çalışma ile ilk olarak kapalı kübik hacmin ön yüzeyinin çevreye açılmasıyla kübik boşluk haline gelen hacimde, alt ve üst yüzeyinden soğutma sınır şartında, laminer durumda doğal taşınım deneysel ve teorik olarak araştırılmıştır. Elde edilen ölçümler Fluent 6.3 paket programı yardımı ile çözülmüş ve deneysel veriler ile karşılaştırılmıştır.
Doğal taşınım şartlarını sağlayabilmek için bu deneysel çalışma ile 2x2x1,8m ebatlarında bir şartlandırma odası uygulamaya dahil edilmiştir. Ayrıca deney düzeneğinin giriş ağzı bu şartlandırma odasına verilmiştir. Son olarak bu çalışma ile sıcaklık değişimi, hız vektörleri ve akım fonksiyonu grafikleri elde edilmiştir. Buna ek olarak Nusselt sayısının zamana bağlı değişimi teorik ve deneysel çalışmalar sonucunda elde edilmiştir.
Anahtar kelimeler: Doğal taşınım, Laminer akış, Açık hacim, Kübik kapalı hacim.

Abstract
Initially, the front surface of a cubic volume of the opening to the environment has become a cubic volume of cavity in the top and bottom surfaces cooled by natural convection laminar boundary conditions that have been examined in experimental and theoretical case. Numerical analysis was completed by using the Fluent (CFD) software; and experimental results were compared.

A conditioning chamber in this experimental study 2x2x1,8m size to provide the natural convection conditions are included in the application. Also the inlet of the experimental setup is given to the conditioning room. Finally, in this work, temperature change, velocity and current function chart were obtained. In addition to time-dependent change of the Nusselt number were obtained as a result of theoretical and experimental studies.
Key words: Natural convection, Laminar flow, Open cavity, Rectangular cavity.

1. Introduction

Heat transfer with convection can be inspected in two groups. The first is forced convection provided via outside affects such as flow fan, bottom and wind. The second one is natural convection. However, in this, there is no flow movement created by outside affect. In such cases, the reason for fluid movement is the density difference occurring substantially due to temperature and concentration differences. The velocity of flow movement in natural convection is bottom compared to forced convection.

Nonetheless, heat transfer applications by means of natural convection are employed more in everyday life. Therefore, it is necessary to consider this effect in system design. Moreover, in general, natural convection applications are preferred in reducing heat transfer and relevant operating costs.

NOMENCLATURE

A	area (m^2)
g	acceleration due to gravity (=9.81 m/s^2)
h	enthalpy (J/kg)
k	thermal conductivity of the fluid (W/mK)
l	weight of evaporation (m)
L	characteristic length (m)
Nu	Nusselt number (—)
Nu	average Nusselt number (—)
P	pressure (Pa)
Ra	Rayleigh number (—)
S	source term in the difference equation
t	time (sec)
T	temperature (K)
T	temperature difference (K)
v	velocities in the y direction (m/s)
u	velocities in the x direction (m/s)
y	coordinate in the vertical direction (m)
Y	length in the vertical direction (m)
x	coordinate in the horizontal direction (m)
X	length in the horizontal direction (m)

Greek Symbols

α	thermal diffusivity (m^2/s)
β	volumetric coefficient of thermal expansion
ϕ	dependent variable
δ	length of control volume (m)
μ	dynamic viscosity (kg/ms)
Ψ	stream function (kg/s)
υ	kinematic viscosity (m^2/s)
ρ	density of the fluid (kg/m^3)
Γ	α or μ

Superscripts

n	value of the previous time step
$n+1$	value of the next time step

Subscripts

E	point of east grid
e	surface of east control volume
N	point of north grid
n	surface of north control volume
S	point of south grid
s	surface of south control volume
W	point of west grid
w	surface of west control volume
P	point of grid

If one or more than one surface of closed volumes is opened to the environment, there occur some spaces. What occurs in closed volumes and spaces owing to density concentrations which natural convection cause is the holding strength. In this study, density differences occur as a result of heat changes of fluid in closed environment. The heat transfer applications in closed volumes and spaces are encountered in engineering and everyday life. For instance, spaces between the wings used for cooling electronic appliances, spaces between buildings and business centres due to architectural property and necessity, spaces needed for heating and ventilating the buildings and spaces in all labour vehicles and household items such as refrigerator are cases frequently encountered in everyday life. The objective of the study is to contribute to heating, cooling and ventilating problems we face in daily life.

There are numerous studies about natural convection in literature. Researchers investigated natural convection numerically and experimentally in a cubic cavity which is heated and cooled from several surfaces (Karakaya, 2010), in a closed volume being formed of different forms of heat resources (Sezai I. and Mohamad, 2000), in a prismatic cavity (Durmus, 2006), in an environment one of the vertical surfaces of which is in the form of rectangular (Chan and Tien, 1985a), in an environment one of the surfaces of which is open and heated from the back surface and other surfaces of which are isolated (Li et.al, 2001), in a rectangular shaped closed environment heated from a horizontal surface and cooled from the ceiling (Aydın, 1999), in an empty refrigerator model heated from the back and having heat transfer from of the other surfaces (Laguerre et.al, 2005).

On the other hand, in this study, cubic volume natural convection was investigated not only experimentally but also theoretically under the boundary conditions of cooling the top and bottom surfaces in temporary situations.

2. Experimental Method

The schematic appearance of experiment set is given in Figure 1. The experiment set consists of four different parts.

1- Cubic cavity
2- Heater and Robotic arm

3- Control Unit
4- Conditioning chamber

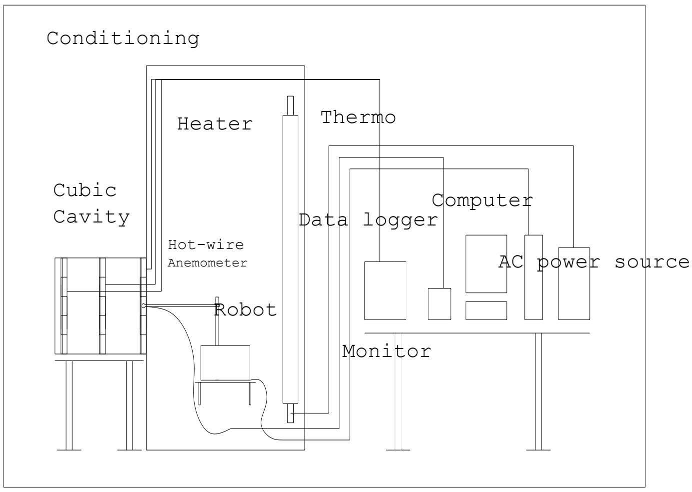


Figure 1 Schematic view of experimental setup

A cubic volume designed specifically and which we manufactured on our own has been employed so as to conduct natural convection experiments. The dimensions of the cubic cavity have been given in Figure 2.

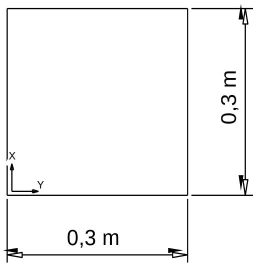


Figure 2 Dimensions of cubic cavity employed

The robotic arm used in experiment set can move in two dimensions, through the height and depth of cubic cavity. The heater in conditioning chamber is controlled by an AC power source. The maximum running limit of AC power source is 380 V and 8 A. The data measured in experiment set were collected via data collecting unit, ALMEMO 5990-0 model, which can collect measurements from many points of test area. To measure heat, T type cupper-constantan (Cu-CuNi) elements have been used. These thermo elements can measure the heat intervals between $200^{o}C$ and $+400^{o}C$. The diameter of thermo elements used for experiments are 0,5 mm and their sensitivity is $0,02^{o}C$. A TSI brand 8475 model velocity probe (hot wire anemometer) and a monitor were used to measure air velocity formed due to heat difference in the experiment. The cubic cavity used in the experiments was placed in a conditioning chamber with dimensions 2 x 1,8 x 2 m. Heat and velocity measurements were conducted in the experiment set. In this study submitted, natural convection in a cubic cavity whose side face is open was investigated. The cubic cavity obtained was used in the experiments since it offered a prism whose side face was open. As the fundamental objective was to investigate velocity and heat distribution in the cubic cavity whose side face was open to space, its parameters such as energy consumption, storing heat and performance were studied. At every stage of experiment, heat measurements were taken from different points of experiment set. Heat values were measured at three different distances towards the depth of cubic cavity by means of the robotic arm; besides, heat measurements were taken from totally 45 points, 15 points of which were on each face stuck to the surfaces. In addition, heat from surfaces to Δx - Δy distances was measured. On the other hand, the heat of conditioning chamber was kept constantan by measuring heat from 3 different points in conditioning chamber. By joining the cupper and constantan on one side of T- type cupper- constantan thermo elements used in heat measurements with point weld, it was isolated by metal varnish. The ends left open on the other side, however, were connected to ZA9000FST model connector element properly. Despite the fact that ALMEMO 5990–0 model data gatherer had calibration in its own programme, the measurement verification was proved after plunging the thermo elements ends into the mixture of boiling water and ice.

The velocity probe being able to measure the interval between 0,05 – 2,5 m/s was placed every point except for surfaces at every stage of experiment; and values were fixed. The velocity probe designed by us and mounted on the robotic arm was sent to the pre-introduced points via a programme written at Matlab 6.5 with the help of computer control; and then it was located at those points. Velocity probe was sent us after it was calibrated by ALMEMO Company. Velocity probe presents the mean velocity value of that point. While the experiments were being conducted, the surface opening to the conditioning chamber of cubic cavity was kept open. Therefore, a sliding glass door to close the surface of cubic surface was made. The cubic cavity was opened and closed via this glass door. So as to prevent air leakage from the contact point between cubic cavity and door, the edges were sealed by means of plastic seals. The entrance and front part of cubic cavity were fixed with wooden materials so that these parts would be flat and open; afterwards, it was mounted to the entrance of conditioning chamber. This case prevents the air movement and temperatures in conditioning chamber to change suddenly by continuously keeping the conditioning chamber door closed.

The opening and closing of conditioning chamber changes the temperature of conditioning chamber. Therefore, a thermostat controlled heater working on an AC power source was used to keep the temperature of the conditioning chamber constant at 18^{o}C. The experiments were carried out for the case when cubic cavity door was open. Thus, the door was closed fixing thermo elements in the cavity. We waited until the temperature change in the cubic cavity became nearly zero. Waiting time lasted approximately one hour and meanwhile the temperature of the conditioning room was kept constant at 18^{o}C. When surface temperature and cubic cavity inside environment temperature were nearly the same, it was accepted that the regime was achieved. In the regime case, it was witnessed that the maximum difference between the temperatures measured on surface and inside the cubic cavity was +0,5^{o}C. The set was made possible to convert into a cubic cavity firstly, by adjusting the velocity probe in Figure 3 to no 1 heat measurement point and by sliding the glass door from its sides at a certain velocity and by opening the front door of experiment set which was in the case of closed cubic volume. The data were started to be recorded within 5 second intervals by zeroing the time phase of data gatherers. Apart from these, running the chronometer on the velocity monitor, the values were recorded every 5 second.

Just after the cubic cavity door was opened, it was observed that there was temperature drop till 0,5^{o}C at the temperature of conditioning chamber. By increasing the voltage value 1 phase from AC power source, it was made possible to establish the 18^{o}C terms within 4 s. The position of velocity probe was adjusted as seen in Figure 3, and then the door was closed. After about 1 hour, when the regime conditions were recovered again, velocity values were recorded opening the sliding glass door. Meanwhile, the temperature values recorded under previous regime conditions were compared to the later values. When significant difference was observed at both time phases, temperature measurements were continued. The experiments were put an end after velocity values at every predetermined point inside the cubic cavity were found out.

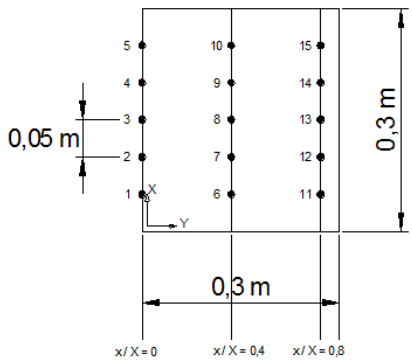


Figure 3 Temperature and velocity measurement points in cubic cavity

After the conditions of the regime were provided, the door was closed slowly by locating velocity probe at point 1 determined for closed door position. Velocity values were read on the monitor every 5 s while temperature values were recorded after the time value of data gatherer was reset.

Meanwhile, the temperature of conditioning room was constantly kept under control. In the case that heat change was zero or near zero at every point of the cubic cavity, it was understood that the system reached up to regime, and then sliding door was closed. The regime conditions for open position were provided after the position of velocity probe was changed from point 1 to point 2. The velocity values were determined slowly closing the sliding door. While the velocity values were determined at every point, it was returned to starting conditions. In addition, the temperature values determined at every time step were compared to the temperature values obtained at previous time intervals.

Top and bottom surfaces were designed as cooling surfaces; and they were kept constant at 0.5^{o}C, and experiments were conducted accepting the other surfaces as adiabatic.

3. Numerical System

The velocity and temperature values in the environment where experimental study was carried out were also found out as numerical to be able to investigate different parameters. For numerical solutions, FLUENT-6.3 software programme was employed. FLUENT is a computational fluids dynamics programme which uses finite volume method. This programme is extensively used for numerical solving pressurable and non-pressurable, laminar or turbulence flow problems. This programme can also conduct perfectly suitable numerical computation for mixed geometries.

In this study, for maximum temperature, Rayleigh number becomes $0{,}5x10^8$. The value of Rayleigh number gives laminar flow conditions ($Ra_L<10^9$).

Rayleigh number is defined as;

$$Ra = \frac{g.\beta.\Delta T.L^3}{\upsilon.\alpha} \tag{1}$$

Here g is gravitational momentum; β is thermal expansion coefficient; ΔT is the difference between environment and cool surface heat; v is kinematic viscosity; α is thermal diffusivity coefficient. The physical properties of air are defined in accordance with mean temperature, and characteristic length L is taken as the width of cubic cavity.

In numerical method, mass, momentum and energy equation sets are solved. The double dimensional projection of continuation or mass protection can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \tag{2}$$

For pressurable liquids, double dimensional, time related momentum equations are written as follows:

In the direction of x

$$\frac{\partial(\rho u)}{\partial t} + u\frac{\partial(\rho u)}{\partial x} + v\frac{\partial(\rho u)}{\partial y} = \rho g_x - \frac{\partial P}{\partial x} + \mu\left\{\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right\} \tag{3}$$

In the direction of y

$$\frac{\partial(\rho v)}{\partial t} + u\frac{\partial(\rho v)}{\partial x} + v\frac{\partial(\rho v)}{\partial y} = \rho g_y - \frac{\partial P}{\partial y} + \mu\left\{\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right\} \tag{4}$$

In both equation 3 and 4, Left side shows laziness strengths while right side shows gravitational, pressure and viscosity strengths, respectively.

For energy equation,

$$\frac{\partial(h)}{\partial t} + u\frac{\partial(h)}{\partial x} + v\frac{\partial(h)}{\partial y} = \frac{k}{\rho}\left\{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right\} \tag{5}$$

correlation is used. Here, h is enthalpy. On the other hand, the relation between heat and enthalpy can be given as follows:

$$\Delta h = \int c dT \tag{6}$$

For pressurable flow of computed current function in numerical solution has been defined as follows:

$$\rho u = \frac{\partial \psi}{\partial y}, \qquad \rho v = -\frac{\partial \psi}{\partial x} \tag{7}$$

Constant ψ lines are flow current lines. The changes in ψ

$$d\dot{m} = \rho(Vn)dA = d\psi \tag{8}$$

are equal to mass flow rates (White, 1999).

In differentiation of valid heat equations in solution area, implicit approach is employed. In this approach, the value at any network point at $t + \Delta t$ time is computed from the value of network point known as (t) at previous time stage. That is, the nodal temperature at the time is independent of the other nodal temperatures. Although the approach provides convergence, there is limitation in selection of Δt. This also necessitates the selection of small Δt. To shorten the computation period, implicit approach is used instead of explicit one (Incropera and DeWitt, 1996).

Implicit approach can be written as follows:

$$\frac{\partial \phi}{\partial t} = F(\phi) \tag{9}$$

$$\frac{\phi^{n+1} - \phi^{n}}{\Delta t} = F\left(\phi^{n+1}\right) \tag{10}$$

$$\phi^{n+1} = \phi^{n} + \Delta t F\left(\phi^{n+1}\right) \tag{11}$$

$$\phi^{i} = \phi^{n} + \Delta t F\left(\phi^{i}\right) \tag{12}$$

Here, ϕ is dependant variable n wanted to be calculated; the size value of that time $n+1$ is the size value of next time stage (Fluent, 2006). As seen, the new temperature of network point in implicit approach is related to the unknown point of neighbouring point. Implicit approach provides unconditioned convergence compared to explicit approach and this also, means that the solution is convergent without any limitation in length and time clearances (Incropera and DeWitt, 1996).

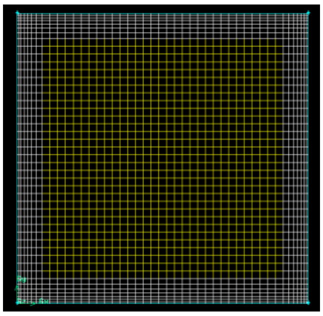


Figure 4 Distribution of grid used for computations

In this study, a non-linear distribution of grid is used. 7 networks with increase of 1.2 times starting from 0,002 m from the surfaces are constituted, afterwards, constant 0,008 m distribution of grid is applied (Figure 4). The inside of cubic cavity is divided 1724 networks totally. General differential equation used in numerical solution determines the values in these network points; and general differential equation is written as follows:

$$\frac{\partial}{\partial t}(\rho\phi)+\frac{\partial}{\partial x_i}(\rho u_i \phi)=\frac{\partial}{\partial x_i}\left(\Gamma\frac{\partial\phi}{\partial x_i}\right)+S \quad (13)$$

S in this equation shows source term, Γ in momentum equation shows viscosity while it shows heat emitting coefficient value, and ϕ shows any dependant variable (Durmus and Daloglu, 2008). For any network, control volume is given in Figure 5.

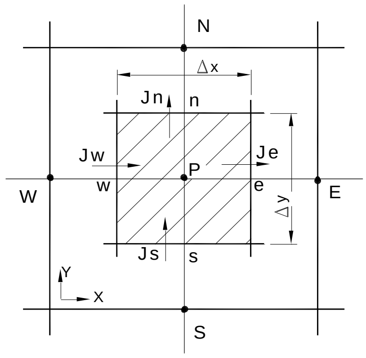


Figure 5 Control volume for two dimension flow area (Patankar, 1980)

While starting numerical solution, iteration convergence criteria are given in Fluent programme. In this study, 10^{-4} is used for continuity equation and velocity components, while 10^{-6} convergence criteria are used for energy equation.

3.1. Validity of Numerical Calculation

In this study, before starting numerical solution in cubic cavity being investigated, the validity of boundary conditions and the reliability of outcomes were searched (Chan and Tien, 1985; Bilgen and Oztop, 2005). Natural convection problem, which was in continuous regime with an open prismatic cavity whose side surface was investigated, was compared with the outcomes after being solved in the same geometry and in the same boundary conditions (Durmus and Daloglu, 2008). In these studies, while vertical surfaces opposite the open surfaces were heated at constant temperature, horizontal walls were isolated. In 10^3 and 10^6 intervals of Rayleigh number and mean Nusselt numbers obtained for 0,71 value of Prandtl numbers are given comparatively in Table 1.

Table 1 Comparison of results for a prismatic cavity whose lateral surface is open (Durmus and Daloglu,2008)

Ra	Nu (Chan)	Nu (Bilgen)	Fluent
10^3	1,07	1,31	1,33
10^4	3,41	3,53	3,54
10^5	7,69	7,85	7,68
10^6	15	15,2	19,35

The height change of horizontal velocity component investigated on open surface by Chan et al is given in Figure 6 (Chan and Tien, 1985b). In Figure 7, Fluent solutions are given for Rayleigh numbers in the same study.

As seen, Chan and Bilgen's studies and Fluent solutions show consistence (Durmus and Daloglu, 2008). In our study, numerical solutions were obtained for cubic cavity investigated after attaining similar outcomes.

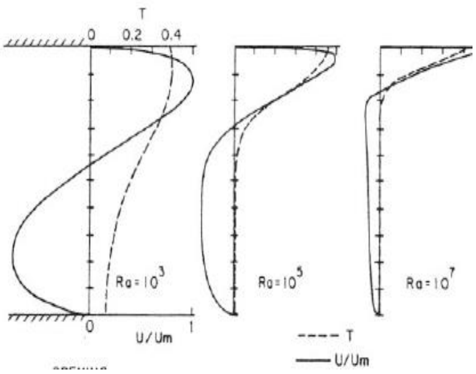


Figure 6 Height and change of horizontal velocity component for various Rayleigh numbers (Chan and Tien, 1985b)

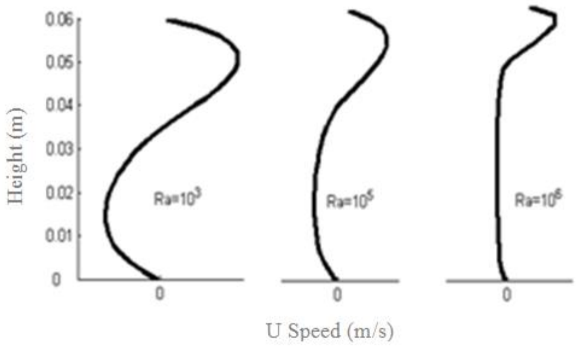


Figure 7 Height and change of horizontal velocity component obtained from Fluent solution (Durmus and Daloglu, 2008)

4. Findings And Discussions

Start and boundary conditions employed in numerical solution of the equations are shown in Figure 8. It was accepted that temperatures at the beginning was equal to the temperatures of cubic cavity surface temperatures. However, temperatures on the open surfaces were taken as zero at conditioning chamber temperature (18^{o}C) and velocity components. For under and top surface of cubic cavity, constant surface temperature (0,5^{o}C), boundary condition, was used. The other surfaces are accepted as adiabatic.

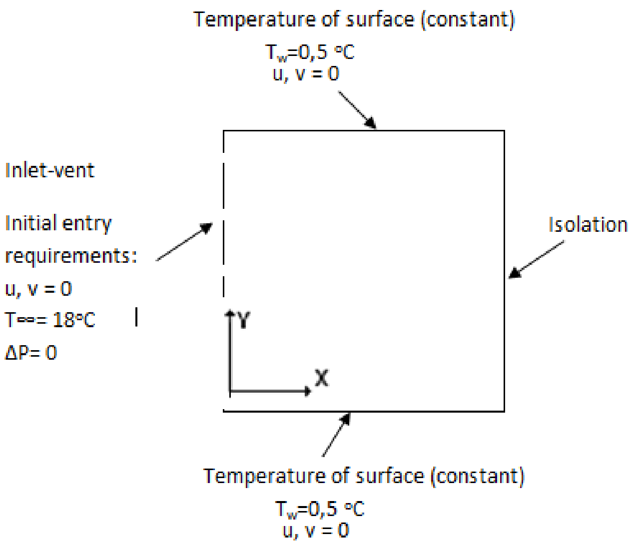
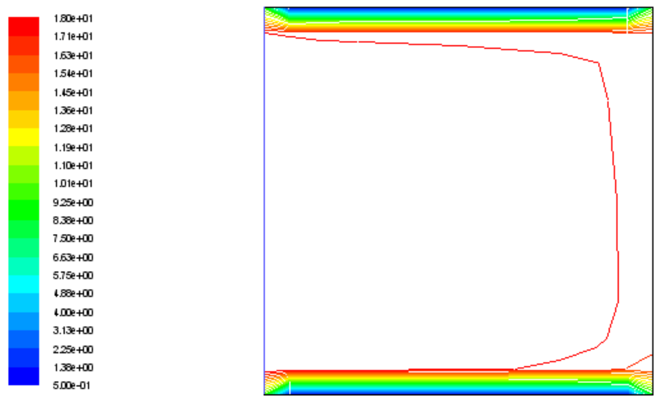


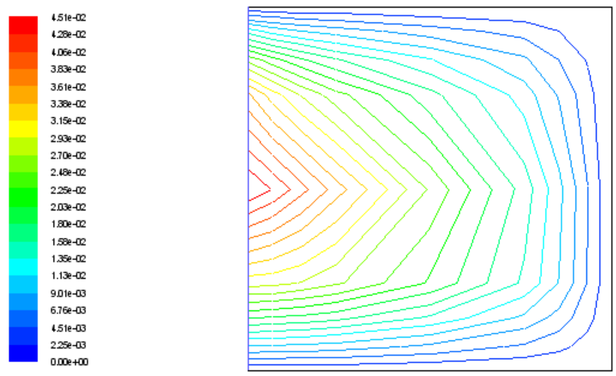
Figure 8 Boundary and initial conditions deployed for numerical solution

Figure 9 and Figure 10 give heat, flow function and velocity momentums at a second. Air entering at the velocity of 0,03 m/s at x/X=0 leaves the cubic cavity at the velocity of 0,48 m/s.

a)



b)



c)

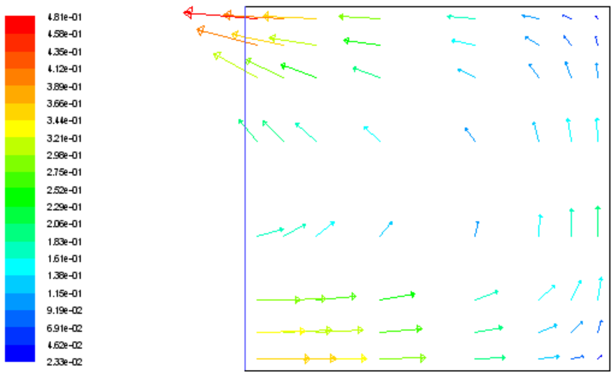


Figure 9 Equivalent curve distribution in cubic cavity for t=75.s

a) temperature, b) flow function, c) velocity vectors

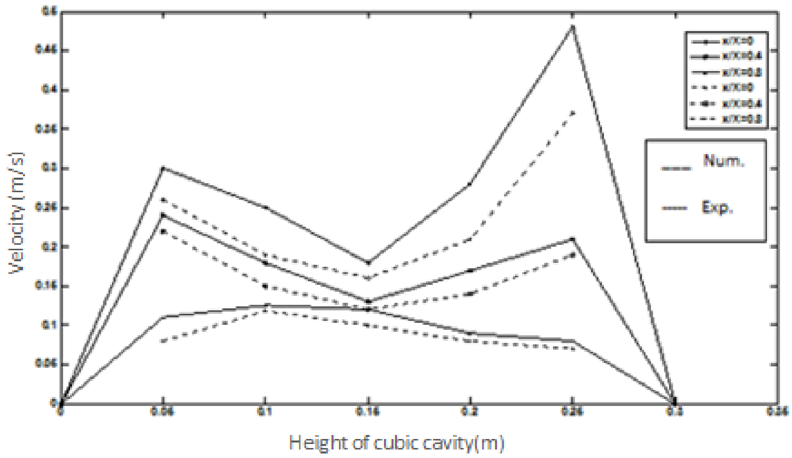


Figure 10 Change when cubic cavity rises of experimental and numerical product velocity values inside cubic cavity for t=75 s.

In Figure 11, in the entrance, numerical and experimental temperature distributions at different time intervals were submitted. The temperature in the cubic cavity started to drop. The temperature values obtained experimentally have considerably approximate values near numerical temperature values (Figure 11).

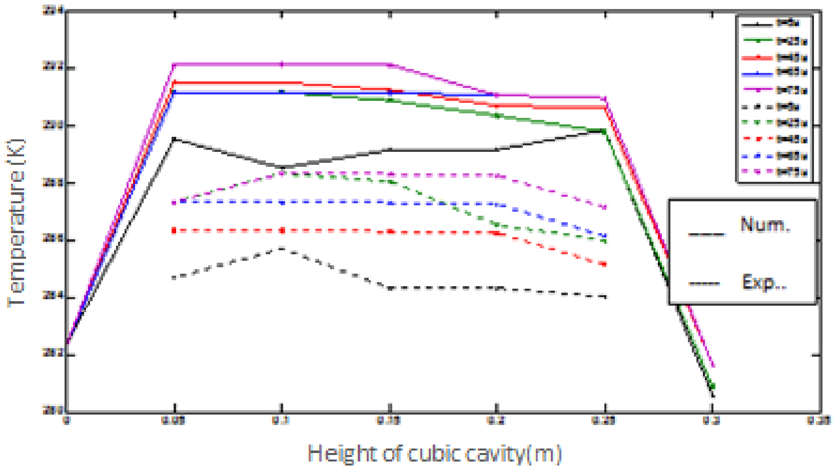


Figure 11 Change when cubic cavity rises of experimental and numerical temperature values for x/X=0.

In Figure 12, numerical and experimental temperature values at x/X=0,4 were presented. After twenty five second, a temperature rise was observed due to velocity change after the height of 0,05 m. At next time stages, this change did not occur; no considerable changes in temperatures were seen. Moreover, it is witnessed that regime conditions were approached after 55 second.

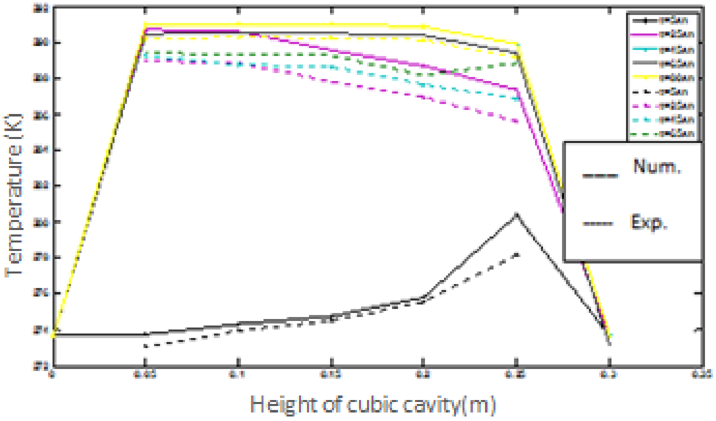


Figure 12 Change when cubic cavity rises of experimental and numerical temperature values for x/X=0,4

Numerical and experimental heat distribution is given in x/X=0,8 in Figure 13. As it can be seen, apart from the area near cool surface, temperature changes occurring as far as cubic cavity height are big at the beginning; however, they decrease as the time passes.

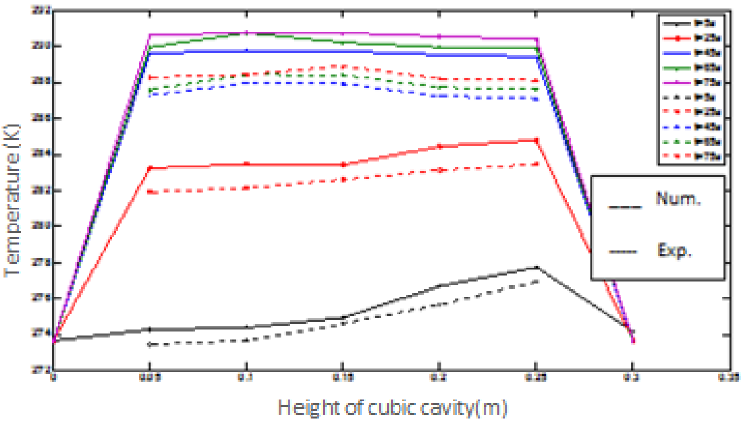


Figure 13 Change when cubic cavity rises of experimental and numerical temperature values for x/X=0,8

While Nusselt numbers are calculated during the heat pass between the surface kept at constant temperature and air, mean Nusselt number was obtained (Bilgen and Oztop, 2005). As known, Nusselt number is equal to dimensionless heat gradient on the surface (Incropera and DeWitt 1996; Genceli, 2002).

$$Nu_L = \frac{\partial \theta}{\partial \bar{X}}\Big|_{x=0} \tag{14}$$

In order to determine Nusselt number, the temperatures obtained from experimental and numerical solutions are made dimensionless as follows:

$$\theta = \frac{T_{(xt)} - T_\infty}{T_w - T_\infty} \tag{15}$$

Here, $T_{(xt)}$ temperature value is T_∞ environment temperature and T_w surface temperature. If remembered that Nusselt number was dimensionless, it is necessary that the distances be dimensionless, too.

x and y coordinates are made

$$\bar{X} = \frac{x}{L} \quad \text{and} \quad \bar{Y} = \frac{y}{L} \tag{16}$$

Dimesionless as $\overline{X}$ and $\overline{Y}$ and mean Nusselt number can be calculate:

$$\overline{Nu} = \int_0^l Nu_L . d\overline{X} \tag{17}$$

According to the above eqation.

The change of mean Nusselt number on cooled surfaces according to time was given in Figure 14.

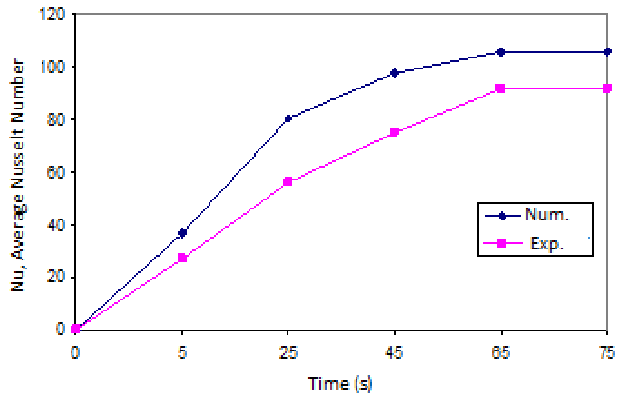


Figure 14 Variation of Nusselt number to time on the surfaces cooled

The Nusselt number obtained numerically at the fifth second is 37,18 (Figure 14). The Nusselt number increases very rapidly until forty-fifth second, and reaches the value of 98,30. Afterwards, though this rapid increase slows down, Nusselt number increases by time and reaches to the value of 106,43 and after this the change occurs very little. The Nusselt number obtained experimentally, however, starts nearly with 27,73 value at the fifth second, and until 45 second, it increases parallel with Nusselt number, and it rises approximately to the value of 75,60 at forty-fifth second. Experimental Nusselt number displays similar changes with numerical Nusselt number. It increases until sixty-fifth second and reaches the value of 92,24. After this time phase, it does not demonstrate much change. The differences seen between mean Nusselt numbers obtained experimentally and numerically may result from various reasons. The system located inside the cubic cavity to measure temperature may hinder, though very little, air movements and; therefore, the Nusselt number may decrease. Nevertheless, while the case is considered as two dimensional for numerical solution, in reality, it may affect the results if the case is considered as three dimensions. In addition, the errors that are possible to be made in temperature measurement due to radiation may lead to these differences.

5. Results And Discussion

In this study, flow and changes in a cubic cavity possessing different surface boundary conditions were investigated experimentally and theoretically and the following results were obtained.

- Changes were not observed in velocity and temperature distributions in cubic cavity after seventy-fifth second and the system became stable.
- When the entrance of cubic cavity was opened, air started to enter into the cubic cavity rapidly and the velocity of air decreased when it reached to the height of 0.15 m later, the air whose velocity increased according to starting point left the cubic cavity.
- It was observed that secondary and whirling flows appeared during processing time in partial areas in the cubic cavity. Generally, whirling flows occur in front of the surfaces cooled.
- When the cubic cavity was opened, the heat distribution inside the cavity was not homogeneous. When the cavity was opened, temperature rise was witnessed in the entrance, and then it started to decrease.
- Initially, numerical and experimental results were close to each other. However, as the time elapsed, some differences occurred.
- When the results were compared with the literature, increases in Nusselt numbers in double surface cooling boundary conditions were observed. So, this shows that the heat gradient inside the volume is higher.

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