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Numerical Study of Natural Convection in a Cavity Filled with Air and Heated locally from Below

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Abstract: Heat transfer from discrete heat sources has become a subject of increased interest because of advances in the electronics industry. Increased heat dissipation is the most important outcome of new generation electronic devices which are more and more miniaturized. Large heat flux densities, which need to be dissipated, are obtained as a result of this miniaturization. Electronic cooling has therefore generated increased interest in the analysis of heat transfer in locally heated cavities. Natural convection holds obvious advantages due to its low-cost and noise-free operating conditions. In this work, a numerical study of natural convection, in a cavity filled with air (Prandtl number, Pr = 0.71), which is heated by discrete sources, was carried out. The governing equations were discretized using the finite volume method and a hybrid schema. The resolution was carried out with the Simpler algorithm. Our procedure of simulation was validated by comparing our results with those of other authors. Temperature and velocity fields were obtained. Local and average Nusselt numbers were also calculated. The influence of various parameters (Rayleigh number from 103 to 105, positions of the sources, periods of the variable heat flux) was considered. Correlations between the Nusselt numbers and the various parameters were also obtained.

Keywords: *cavity, sources, heat, dissipation, convection, simulation.*

1. Introduction

The study of heat transfers by convection plays an important role in the design and improvement of various engineering systems. Among these systems, heat transfer in buildings and electronic component cooling can be cited as examples. In the electronics industry, the tendency to more miniaturization leads to an improvement of the performance of electronic equipments but on the other hand, the amount of heat to be dissipated becomes more important. A better thermal control is then needed in order to avoid overheating problems which can deteriorate the electronic components [1]. The electronic components being modelled as discrete heat sources and the study of natural convection in a locally heated cavity needs to be carried out.

There are a lot of papers devoted to natural convection in cavities heated by discrete sources. For example, Turner and Flack [2] were the first to study experimentally natural convection in a rectangular cavity heated by one source. The best position of the source which allows increasing heat transfer has been obtained as a function of the Rayleigh number. Subsequently, the experimental and numerical study of Chadwick and Heaton [3], carried out for three positions of a heat source, allowed to reach the conclusion that the lowest position leads to the best heat transfer. More recently, Ho and Chang [4] studied numerically the effect of the aspect ratio on heat transfer in a cavity heated by four sources with constant heat fluxes. The obtained results showed that the increase of the aspect ratio leads to a decrease of the heat dissipation causing heating of the sources.

As far as we know, most studies carried our by other authors considered sources with constant heat fluxes. The case of a cavity containing heat sources with periodically variable fluxes has not be considered while numerous applications such as electronic components, solar energy collectors, the heating and air conditioning in buildings involve intermittent heat fluxes. The aim of this work is to study numerically natural convection in a cavity heated from below by discrete sources with variable heat fluxes.

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2. Numerical Simulation Procedure

The governing equations are the continuity equation, Navier-stockes equations and the energy equation in 2D. The Boussinesq approximation has been used as in [5]. To establish dimensionless governing equations, the dimensionless variables are defined the same way as in [6].

By introducing the dimensionless variables, the governing equations become dimensionless equations with dimensionless numbers such as the cavity aspect ratio (A = H/L), Rayleigh (Ra) and Prandtl (Pr) numbers.

The heat transfer rate has been defined by the local Nusselt number as in [6]. The average Nusselt number is calculated by averaging the local Nusselt numbers obtained at the various nodes.

The governing equations were discretized using the finite volume method and a hybrid schema [7]. The resolution was carried out with the Simpler algorithm [8]. In this paper, a mesh with 50x50 elements has been used. The number of 2500 elements has been chosen thanks to a preliminary study with various mesh sizes. This number has also been considered as sufficient and was used by other authors [9]. The time step, between two successive iterations, has been taken equal to 10^{-2} seconds. The numerical program has been written using Fortran 6.0. The velocity and temperature fields being displayed using TECPLOT.

3. Results

As a first step, our numerical procedure has been validated by comparing the calculated results with those obtained by other authors. For that purpose, we considered the same conditions as B. Calcagni et al. [9] who obtained numerical results using Fluent and experimental ones by holographic interferometry.
In this work, two cases have been considered, at first the cavity is heated by only one source and in the second case two heat sources are considered.

3.1. Case 1: One heat source.

The cavity is filled with air (Pr = 0.71). The horizontal walls are adiabatic except at the sources. The heat flux may be constant (q_c = 3.5 W/m^2) or variable periodically (q_p = 3.5 W/m^2 or q_p = 0). Vertical walls are kept at the same constant temperature (T_f) (Figure 1).

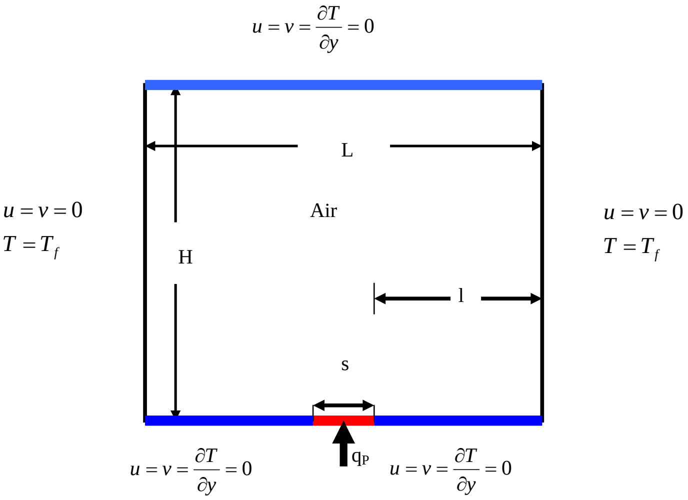


Figure 1. Geometry of the simulated case 1 with boundary conditions.

Velocity and temperature fields in a square cavity (dimensions: 0.05mx0.05m and aspect ratio A= 1) with a 1 cm length heat source which is located at the center of the lower plate, are shown in figures 2 and 3 for Ra number varied from 10^3 to 10^5.

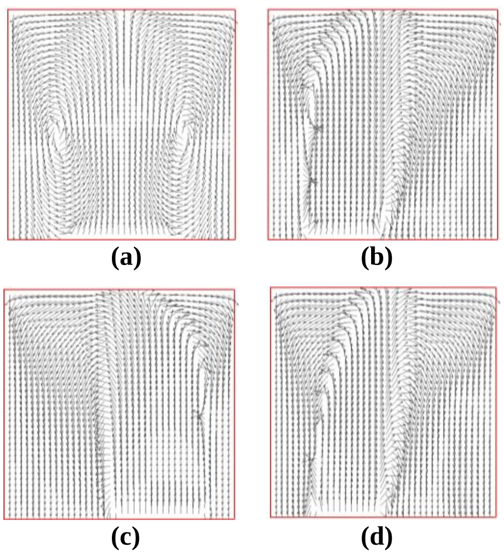


Figure 2. Velocity fields for various Ra numbers.
(a) : Ra = 10^3, (b) : Ra = 10^4, (c) : Ra = 5x10^4, (d) : Ra = 10^5.

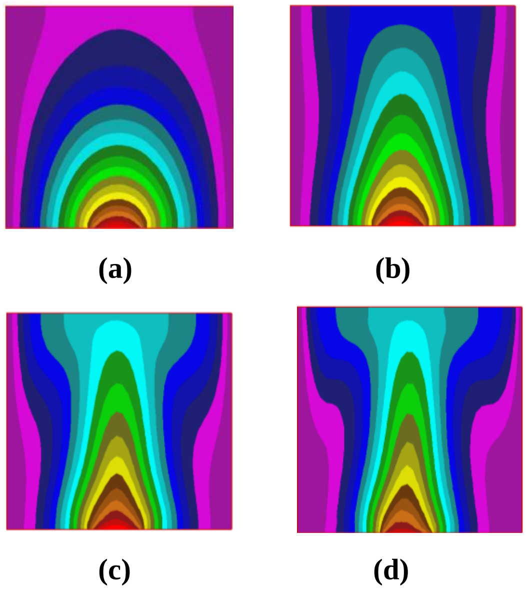


Figure 3. Temperature fields for various Ra numbers.
(a) : Ra = 10^3, (b) : Ra = 10^4, (c) : Ra = 5x10^4, (d) : Ra = 10^5.

Temperature as a function of (y), for x = 2.5 cm and various Rayleigh numbers, is shown in fig. 4. For all Ra numbers, temperature decreases from its maximum value (corresponding to y = 0) to its lowest value at y = 5 cm. As for the behaviour as a function of the Rayleigh number, at a same position (y), temperature increases with Ra.

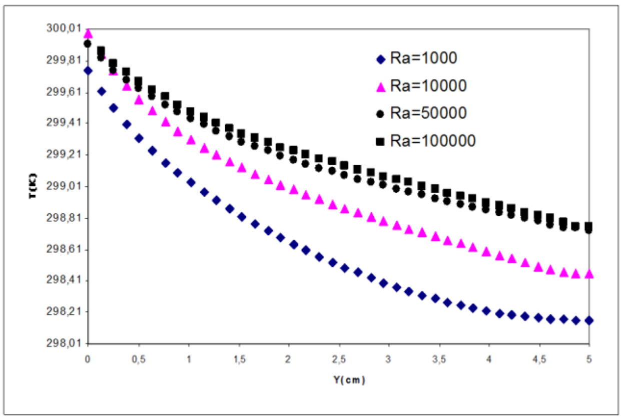


Figure 4. Temperature as a function of the position (y) for various Ra numbers.

The local Nusselt number is drawn as a function of (x) in figure 5 for Ra number ranging from 10^3 to 10^5. It can be noticed that for all Ra numbers, as in [9], the minimum value of Nu is reached at the center of the cavity, minimum value which increases with Ra number.

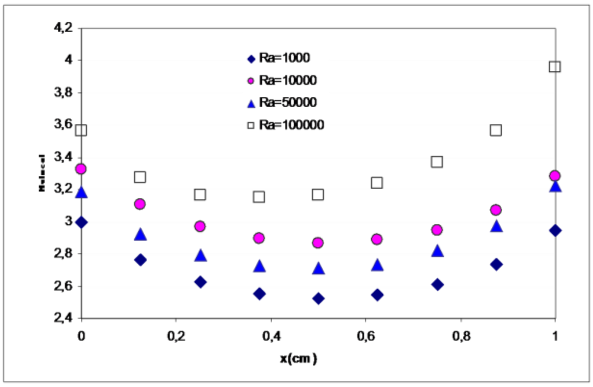


Figure 5. Local Nusselt number as a function of the position (x) for various Ra numbers.

As for the average Nusselt number, <Nu>, as shown in fig.6, it increases with (Ra) and the correlation equation (1) has been obtained for Ra number ranging from 10^3 to 10^5.

$$\langle Nu \rangle = 1.9763 Ra^{0.0433} \quad (1)$$

In this work, the case of a heat source with a flux varying periodically with time has been studied. For that purpose, various periods (P_c) have been considered. For example, temperature fields are shown in Fig.7 for constant and variable heat flux with a Rayleigh number equal to 10^4.

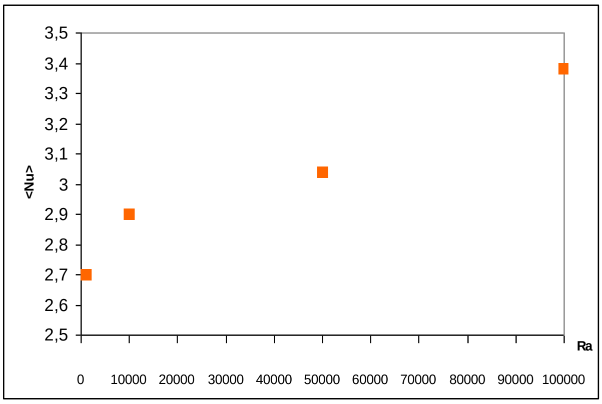
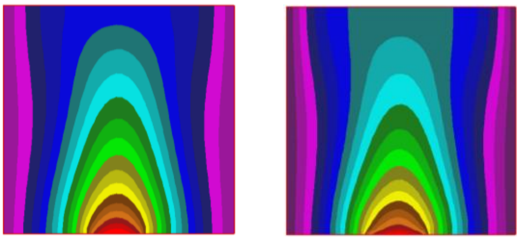


Figure 6. Average Nusselt number as a function of Rayleigh number.

The local Nusselt number (Nu_{local}) as a function of (x) is shown in figure 8 for Ra = 10^4 and various periods (P_c) of the source heat flux. The Nusselt numbers have been calculated along the source which is located at the center of the cavity lower plate. It can be noticed that for all periods (P_c), the local Nusselt number reaches minimum values at the center of the heat source and it is at maximum values for the source boundaries. The minimum and maximum values increase as the period of the flux is increased.



(a) **(b)**

Figure 7. Temperature fields for constant or variable heat flux. Ra = 10^4. (a): constant flux, (b): periodic flux with P_c = 2 s.

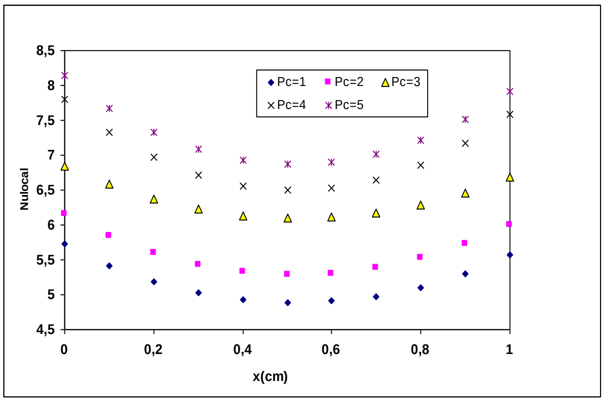


Figure 8. Local Nusselt number as a function of (x) for various periods (P_c) of the heat flux. Ra = 10^4.

In figure 9, the average Nusselt number as a function of the flux period is displayed for Ra equal respectively to 10^3 and 10^4. The average Nusselt increases with the flux period and for a same value of (P_c), <Nu> increases with (Ra). From the curves of figure 9, correlations between the average Nusselt number and the flux period have been obtained:

$$\text{for } Ra = 10^3: \langle Nu \rangle = 0.5203 P_c + 3.4646 \quad (2)$$

$$\text{for } Ra = 10^4: \langle Nu \rangle = 0.5656 P_c + 4.5903 \quad (3)$$

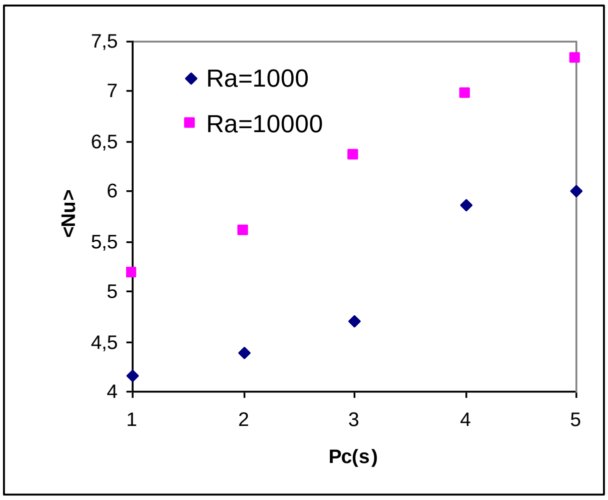


Figure 9. Average Nusselt number as a function of the flux period for two values of the Rayleigh number.

3.2. Case 2: Two heat sources.

For this case, the lower horizontal plate is heated locally by two sources, The first one is at constant heat flux (q_c)(left source in Fig.10)), the second source has either a constant heat flux (q_c) or a periodically variable flux (q_p) (right source in Fig. 10). The lengths of the two sources are the same (s = 1 cm) and the distance between them is (d).

The temperature fields obtained for Ra = 10^3 for various values of the distance separating the two sources (d) are shown in Fig. 11. The position of the left source being kept constant and it is at 1 cm.

The average Nusselt number as a function of the distance (d) is shown in Fig.12 for Ra = 10^3. It is obvious that the Nusselt number increases with the distance (d). From the curve of Fig.12, the correlation equation (4) between the average Nusselt number and the distance (d), is obtained.

$$\langle Nu \rangle = 1.2149\,(d) + 2.974 \quad (4)$$

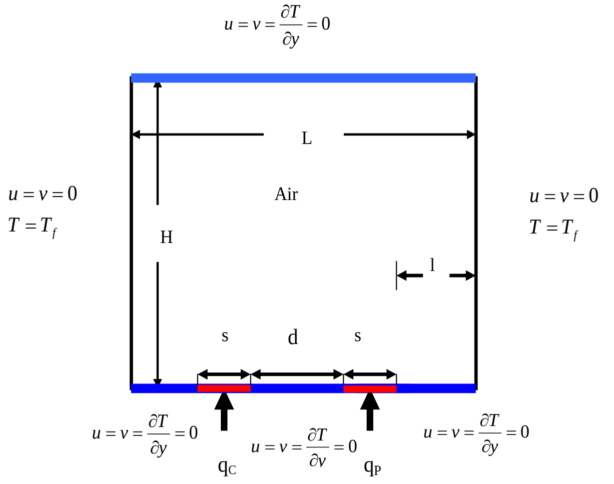


Figure 10. Geometry of the simulated case 2 with boundary conditions.

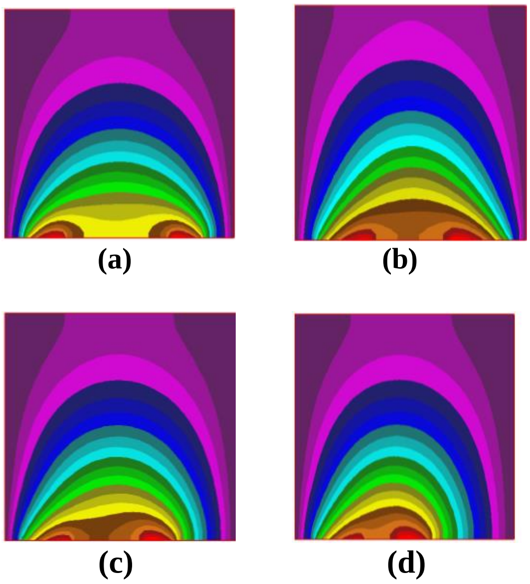


Figure 11. Temperature fields for various distances (d) separating the two heat sources. (a) : d = 2 cm, (b): d = 1.5 cm, (c): d = 1cm, (d): d = 0.5 cm.

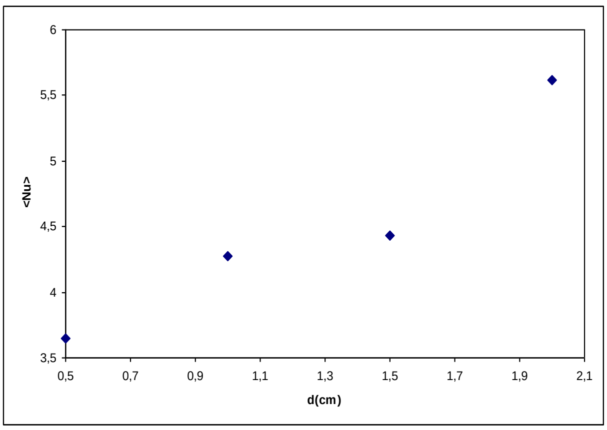


Figure 12. Average Nusselt number as a function of the distance (d) separating the two heat sources. Ra = 10^3.

In Figure 13, Temperature fields obtained for Ra = 10^3, are displayed for various periods (P_c) of the right source heat flux. The other source heat flux being kept constant. The distance between the two sources is d = 1 cm. Consequently, the positions of the source centers are respectively, x_{d1} = 1 cm and x_{d2} = 3 cm.

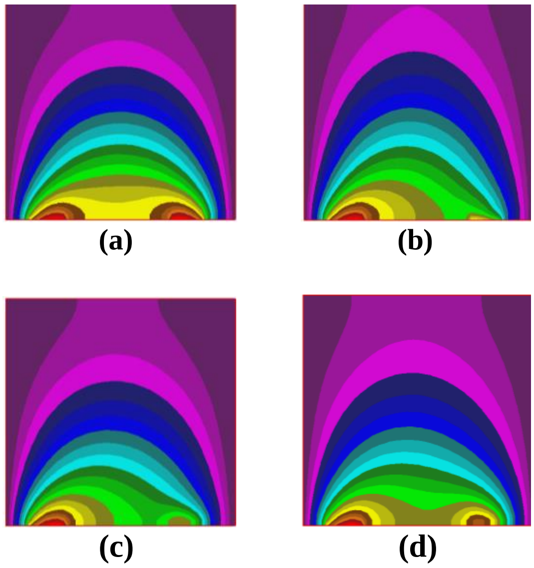


Figure 13. Temperature fields for various heat flux periods (P_c). Ra = 10^3. (a): constant flux, (b): P_c = 1s, (c): P_c = 4s , (d): P_c = 10s.

In Fig. 14, Temperature, at the center of the right source, as a function of time, is shown for three values of the heat flux period.

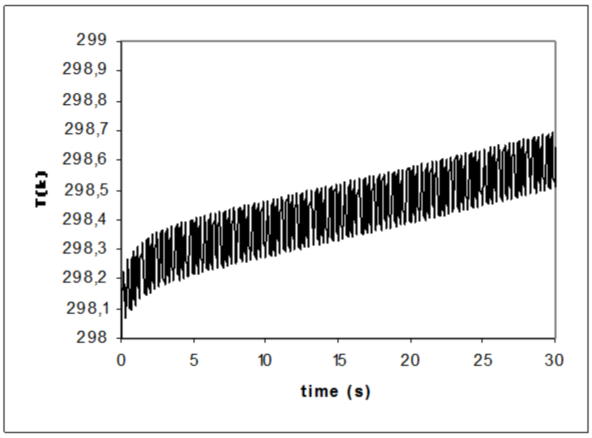
The average Nusselt number is drawn as a function of the flux period in Figure 15 for Ra equal to 10^3. From the curve in this figure, the correlation equation (5), between <Nu> and the period (P_c) of the right source heat flux, is obtained.

$$\langle Nu \rangle = 0.424(P_c) + 5.0203 \quad (5)$$

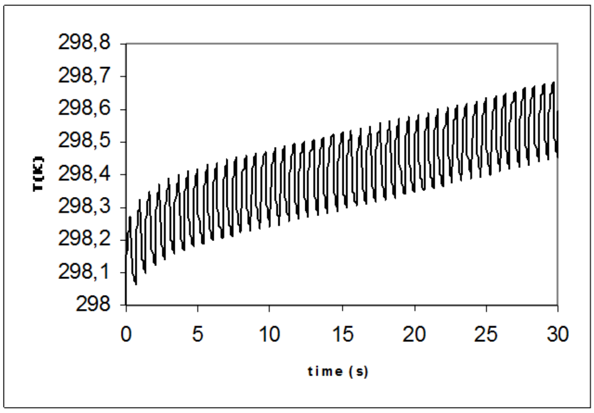
4. Conclusions

In this work, a numerical study of natural convection, in a cavity filled with air and which is locally heated from below by one or two sources, was carried out. Temperature and velocity fields were obtained. Local and average Nusselt numbers were also calculated. Our procedure of simulation was validated by comparing our results with those of other authors. The influence of various parameters (Rayleigh number, positions of the sources) was considered. Both cases of heat sources with constant or periodically variable fluxes were considered. Correlations between the Nusselt number and the various parameters (Rayleigh number, distance between sources, and period of the heat flux) were also obtained.

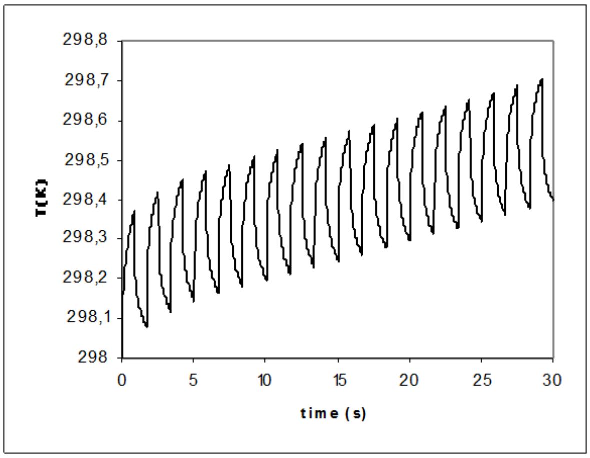
We hope that the obtained results will be useful for an optimum design of the electronic devices that allows maximum heat dissipation in order to avoid overheating of electronic components.



(a)



(b)



(c)

Figure 14. Temperature at the center of the right source, as a function of time, for three values of the heat flux period. Ra = 10^3, (a): P_c = 1 s., (b): P_c = 2 s., (c): P_c = 4s.

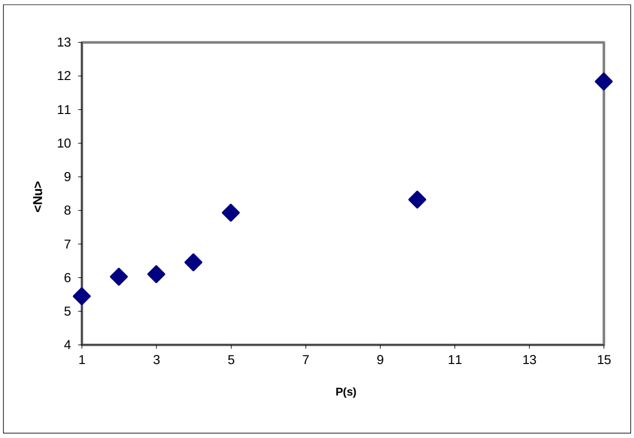


Figure 15. Average Nusselt number as a function of the heat flux period of the right source. Ra = 10^3.

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