ENC-2020-0082
NATURAL CONVECTIVE HEAT TRANSFER FROM TWO ISOTHERMAL FLAT PLATES WITH ONE IN HORIZONTAL AND THE OTHER INCLINED

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Abstract. A numerical study of the heat transfer process by natural convection in two flat isothermal plates with the same depth has been undertaken. In this study, the vertical distance between the two plates is relatively small, and as a result, there is an interaction between the flows over both plates, which affects their heat transfer rates. Furthermore, it is considered that one of the plates is kept in a horizontal position, while the other is inclined in relation to the horizontal plane. Both the case where the below plate is horizontal, and the above plate is inclined and the case where the below plate is inclined, and the above plate is horizontal have been considered. Through simulations, the effect of the dimensionless vertical spacing between the plates and the angle of inclination of the inclined plate on the mean heat transfer rates over the entire surface of each plate have been studied. The mean flow has been assumed to be steady and the conditions considered included those under which turbulent flow can develop. The standard $k - \varepsilon$ turbulence model with buoyancy force effects accounted was used to obtain the numerical solution. The numerical solutions were performed with the aid of the commercial CFD solver ANSYS FLUENT©. The heat transfer rates considered, expressed in terms of mean Nusselt numbers, depend on the Rayleigh number, the angle of inclination of the inclined plate, whether it is the above or below plate that is inclined and on the dimensionless vertical spacing between the plates. Results have only been obtained for a Prandtl number of 0.71, i.e., the value for air at ambient conditions.

Keywords: natural convective heat transfer, $k - \varepsilon$ turbulence model, isothermal plates, inclined plates

1. INTRODUCTION

A numerical investigation was conducted to study the heat transfer process by natural convection in two thin, isothermal, two-dimensional plates, which are vertically aligned and of the same depth. The configuration where one of the plates is horizontal and the other is inclined at a relatively small angle to the horizontal has been considered. Both cases where the below plate is horizontal, and the above plate is inclined and where the below plate is inclined, and the above plate is horizontal have been studied. The flow situations considered are shown in Fig. 1.

Figure 1 shows frontal views of the two situations considered and defines the width of the system, *L*, and the distance between the plates, *d*. Consideration has been given to the situation where the vertical distance between the two plates is relatively small. The surfaces of the plates are all assumed to be at the same temperature, being this temperature higher than that of the surrounding fluid. There is thus heat transfer from both the upper and lower surfaces of both plates. As previously mentioned, attention has been given to the case where the vertical distance between the plates, *d*, is relatively small compared to the width of the system, *L*. As a result, there is an interaction between the flows over the two plates, which affects their heat transfer rates. While results have been obtained for the values of the mean heat transfer rates of the upper and lower surfaces of each plate, attention here will only be given to the mean heat transfer rates over the entire surface of the above plate and over the entire surface of the below plate.

The results obtained here should give an indication of the factors that have a significant effect on heat transfer rates in such practical situations. Although there have been several studies on the process of heat transfer by natural convection on simple two-sided horizontal plates, relatively little attention has been given to natural convective heat transfer when there are two or more horizontal plates vertically aligned and reasonably close to each other.
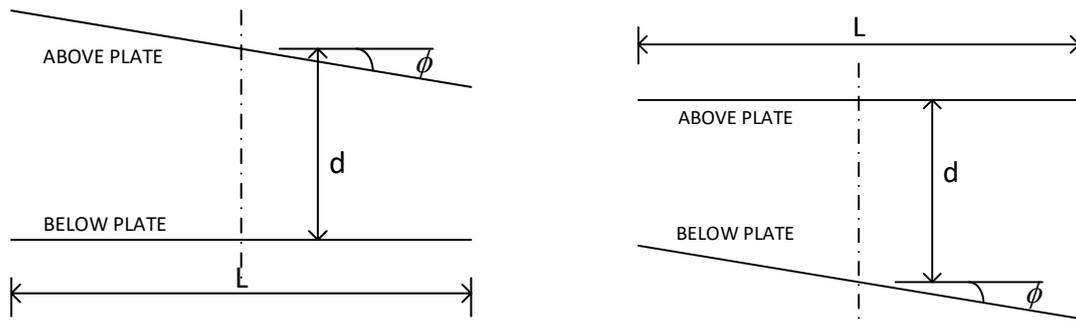
(a) The case where the above plate is inclined, and the below plate is horizontal.

(b) The case where the above plate is horizontal, and the below plate is inclined.

Figure 1. Types of flow situation considered.

Suriano and Yang (1968) conducted numerical analyzes to study the phenomena of natural convection in horizontal and vertical flat plates, considering a range of Rayleigh number up to 300 and Prandtl number from 0.72 to 10. In the work published by Chambers and Lee (1997), expressions capable of determining the mean Nusselt numbers associated with natural convection on the upper and lower surfaces of uniformly heated horizontal plates were defined using results obtained in numerical simulations performed for Rayleigh numbers between 86 and 1.9×10^8 while a similar study was published by Wei et al. (2003) for a range of Rayleigh numbers from 1.0×10^5 to 1.7×10^7. The relationship between the Prandtl number and the natural convective heat transfer in a thin horizontal isothermal plate was extensively researched by Fontana (2014). Recently, Oosthuizen and Kalendar (2016), conducted a study on the behavior of the natural convective heat transfer on both sides of an isothermal horizontal plate, with a circular shape, negligible thickness and with an adiabatic middle section.

The effects of the inclination of flat plates on their heat transfer rates by natural convection have been extensively studied by several authors. In the work published by Wei et al. (2002) the influence of the angle of inclination on the mean and local Nusselt numbers on both surfaces of a thin and uniformly heated plate was evaluated for a Rayleigh number range from 4.8×10^6 to 1.87×10^8. A more comprehensive research was performed by Corcione et al. (2011), who produced numerical simulations for inclination angles between 0° and 75°, Rayleigh numbers varying from 10 to 10^7 and Prandtl numbers varying between 0.7 and 140. Numerical simulations using computational fluid dynamics were performed by Guha et al. (2019) to define in detail the fluid-thermal dynamics related to the phenomena of natural convective heat transfer between inclined heated plates and a fluid.

Dooher and Mills (2000) coordinated an experimental study to investigate the phenomena of natural convective heat transfer between steady laminar water and both sides of heated and vertically stacked horizontal plates. The instability phenomena associated with natural convective heat transfer in square and parallel plates were investigated numerically by Fu et al. (2017). A numerical study of heat transfer from two vertically aligned horizontal circular plates with the same diameter was described in the work of Oosthuizen (2017) while a numerical study of heat transfer from two vertically aligned horizontal two-dimensional plates was presented in the work of Oosthuizen (2018). In this way, there does not appear to be much available information on the heat transfer rates that arise in situations in which there are two vertically separated heated plates for the case where one plate is horizontal and one is inclined at a small angle to the horizontal.

The present study is a complementation of these different works developed in the area of thermal engineering and aims to produce results that indicate the phenomena associated with heat transfer by natural convection in two isothermal, thin and vertically spaced flat plates, one being positioned horizontally and another inclined with a small angle to the horizontal. Due to the simplifying hypotheses adopted, the situation investigated in this research does not accurately represent a real physical system. However, it is expected that the results obtained provide an indication of the factors that have a significant effect on the natural convective heat transfer rates in devices with a configuration similar to that presented in this work, like solar collectors with integrated thermal storage and integrated circuits.

2. BOUNDARY CONDITIONS AND TURBULENCE MODEL

The two plates have been assumed to be thin, therefore, there is no heat transfer by conduction between their surfaces. In addition, to simplify the analysis of the system, the flow has been presumed to be steady and the radiation effects have been considered negligible. The surfaces of both plates were maintained at a uniform temperature equal of $T_w = 310$ K. The temperature of the undisturbed air, far away from both plates, is $T_f = 290$ K at atmospheric pressure.

The width of the system and the depth of both plates are unitary. The width of the horizontal plate is unitary while the width of the inclined plate varies to ensure the vertical alignment of both plates. The values of the dimensionless vertical distance that were used are 0.1, 0.3 and 0.5. Furthermore, the values of the angle of inclination used both for the case where the above plate is inclined and the case where the below plate is inclined are 2.5°, 5° and 7.5°.

Most air properties were considered constant and equivalent to those under ambient temperature and pressure conditions. The Boussinesq approach has been adopted in dealing with the buoyancy forces and with fluid density changes resulting from the temperature change in the flow field. The standard $k - \varepsilon$ turbulence model has been used with full account being taken of buoyancy force effects, and the numerical approach adopted here to determine when turbulence develops involves solving the Reynolds averaged governing equations together with the turbulence model for all conditions considered. Extensive grid-independence testing has been undertaken and the heat transfer results presented in this paper are to within approximately 1% independent of the mesh size. The numerical solution has been obtained using the commercial CFD solver ANSYS FLUENT©.

Similar numerical approaches have been used extensively by several authors in previous studies (Suriano and Yang, 1968; Schmidt and Patankar, 1991; Savill, 1993; Plumb and Kennedy, 1997; Zheng *et al*., 1998; Wei *et al*., 2002; Wei *et al*., 2003; Xamán *et al*., 2005; Albets-Chico *et al*., 2008; Oosthuizen and Nyalor, 2009; Oosthuizen and Kalendar, 2016; Oosthuizen, 2017; Oosthuizen, 2018). There does not appear to be experimental work about the case studied here available in the literature, therefore, it is not possible to compare the results obtained with the numerical model adopted here with experimental results that reflect the physical situation addressed in this research. Furthermore, the $k - \varepsilon$ turbulence models do not give good predictions of transition in all flow situations. Nevertheless, the results obtained in these previous studies indicate that the numerical model adopted here give results of acceptable accuracy for the type of flow situation being considered.

3. SOLUTION PROCEDURE

The mean heat transfer rates from both heated plates have been expressed in terms of mean Nusselt numbers based on the entire heat exchange surface of the above plate, $\overline{\mathrm{Nu}}_{d\,(\mathrm{above,total})}$, and on the entire heat exchange surface of the below plate, $\overline{\mathrm{Nu}}_{d\,(\mathrm{below,total})}$. Although heat transfer rates have been obtained independently for the top and bottom surfaces of each plate, consideration here has only been given to the mean Nusselt numbers over the entire surface of the above plate and over the entire surface of the below plate, in order to facilitate the understanding of the phenomena involved in this process and generalize the results obtained by the numerical simulations.

These mean Nusselt numbers are dependent on 4 different parameters, which include the Rayleigh number, Ra_d, the dimensionless vertical distance between both plates, which is defined as $D = d/L$, , the angle of inclination of the inclined plate, ϕ, and which of the plates is inclined, i.e.:

$$\overline{\mathrm{Nu}}_{d\,(\mathrm{above/below,total})} = \mathrm{function}(\mathrm{Ra}_d, D, \phi, \text{which plate inclined}) \tag{1}$$

being

$$\mathrm{Ra}_d = \frac{g\,\beta(T_w - T_f)d^3}{\nu\alpha} \tag{2}$$

where g is the gravitational acceleration, β is the bulk coefficient of thermal expansion, ν is the kinematic viscosity of the fluid and α is the thermal diffusivity of the fluid.

Mean Nusselt numbers can be obtained combining Eqs. (3) and (4), i.e.:

$$\overline{\mathrm{Nu}}_{d\,(\mathrm{above/below,total})} = \frac{\overline{h}_{d\,(\mathrm{above/below,total})}\,d}{k} \tag{3}$$

$$q_{(\mathrm{above/below,total})} = \overline{h}_{d\,(\mathrm{above/below,total})}A_{(\mathrm{above/below,total})}(T_w - T_f) \tag{4}$$

$$\overline{\mathrm{Nu}}_{d\,(\mathrm{above/below,total})} = \frac{q_{(\mathrm{above/below,total})}\,d}{A_{(\mathrm{above/below,total})}k(T_w - T_f)} \tag{5}$$

In Eq. (5), $q_{(above/below,total)}$ were obtained through numerical solutions with the aid of the commercial CFD solver ANSYS FLUENT$^{©}$ using the standard $k-\varepsilon$ turbulence model with buoyancy force effects accounted.

4. RESULTS AND DISCUSSION

Variations of the mean Nusselt numbers based on the mean heat transfer rates over the total surface area of the below plate and over the total surface area of the above plate, i.e., $\overline{\mathrm{Nu}}_{d\,(below,total)}$ and $\overline{\mathrm{Nu}}_{d\,(above,total)}$, with respect to the Rayleigh number for different values of the dimensionless vertical distance between the plates, D, and for different plate inclination angles, ϕ, were obtained for both cases where the above plate is inclined and the below plate is inclined, and numerical simulations were performed for Rayleigh numbers varying between 10^4 to 10^{14}.

Figures 2 to 13 show the variation of the mean total Nusselt number for the above and below plates with the Rayleigh number for various values of the dimensionless centerline plate spacing, D, for both cases where the above plate is inclined and where the below plate is inclined.
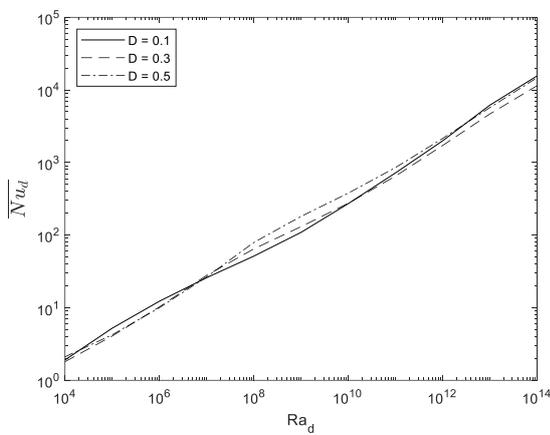
Figure 2. Variation of the mean total Nusselt number for the above plate with the Rayleigh number for the case where the above plate is inclined at an angle of 2.5°.
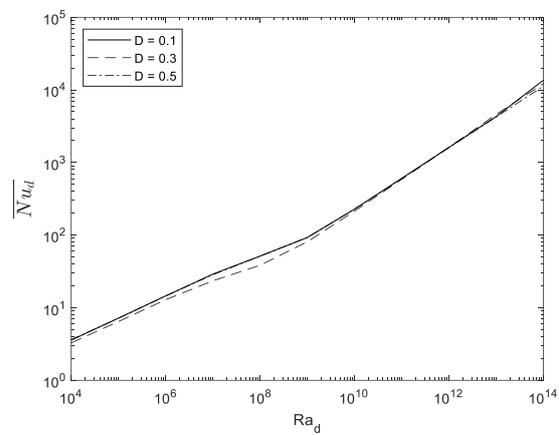

Figure 3. Variation of the mean total Nusselt number for the below plate with the Rayleigh number for the case where the above plate is inclined at an angle of 2.5°.
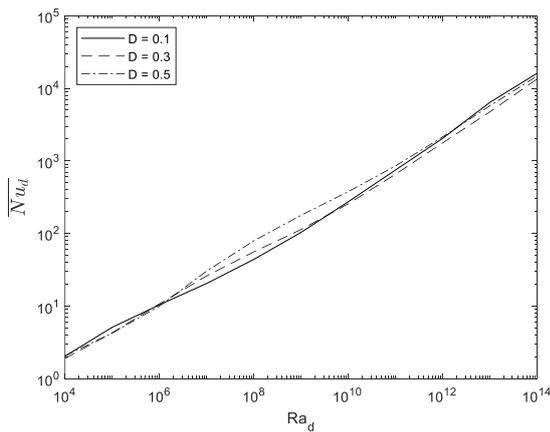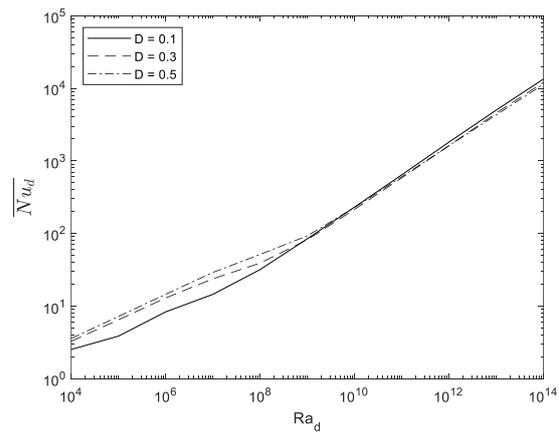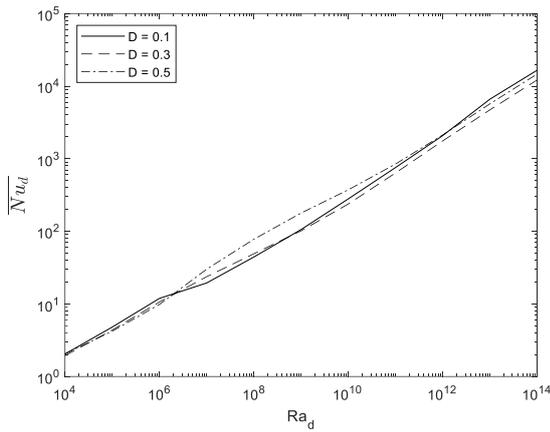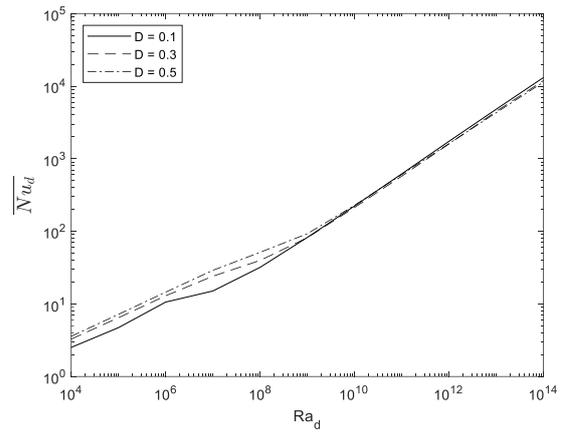

Figure 4. Variation of the mean total Nusselt number for the above plate with the Rayleigh number for the case where the above plate is inclined at an angle of 5°.

Figure 5. Variation of the mean total Nusselt number for the below plate with the Rayleigh number for the case where the above plate is inclined at an angle of 5°.
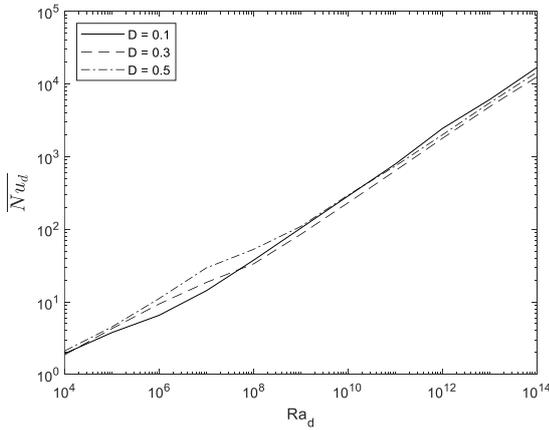
Figure 6. Variation of the mean total Nusselt number for the above plate with the Rayleigh number for the case where the above plate is inclined at an angle of 7.5°.

Figure 7. Variation of the mean total Nusselt number for the below plate with the Rayleigh number for the case where the above plate is inclined at an angle of 7.5°.

Figure 8. Variation of the mean total Nusselt number for the above plate with the Rayleigh number for the case where the below plate is inclined at an angle of 2.5°.
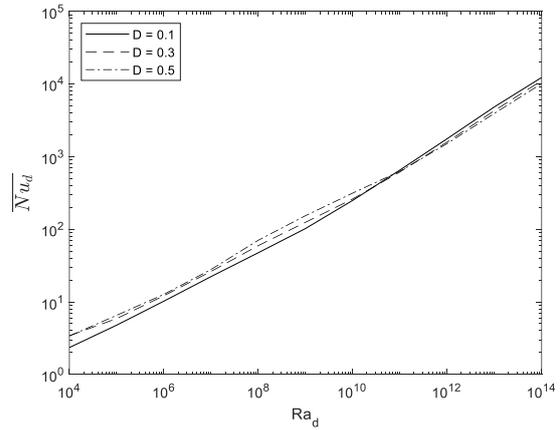

Figure 9. Variation of the mean total Nusselt number for the below plate with the Rayleigh number for the case where the below plate is inclined at an angle of 2.5°.
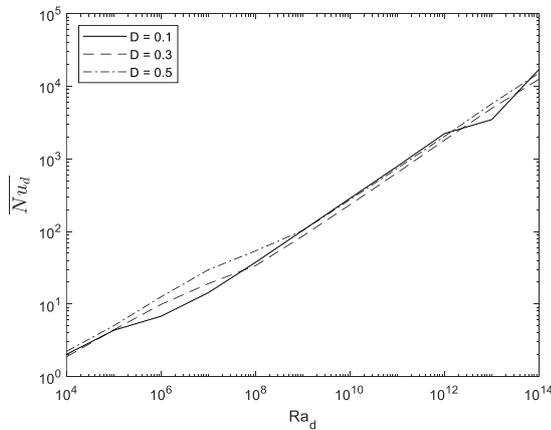

Figure 10. Variation of the mean total Nusselt number for the above plate with the Rayleigh number for the case where the below plate is inclined at an angle of 5°.
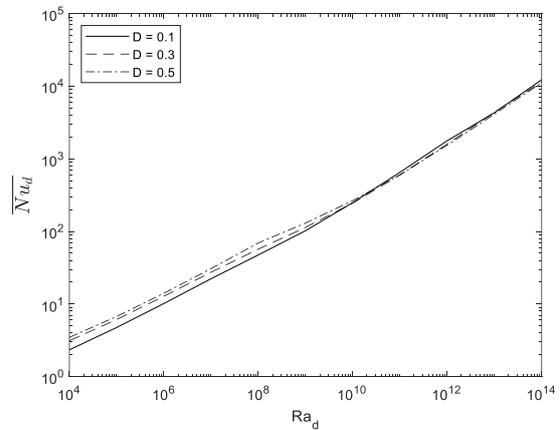

Figure 11. Variation of the mean total Nusselt number for the below plate with the Rayleigh number for the case where the below plate is inclined at an angle of 5°.

Figure 12. Variation of the mean total Nusselt number for the above plate with the Rayleigh number for the case where the below plate is inclined at an angle of 7.5°.

Figure 13. Variation of the mean total Nusselt number for the below plate with the Rayleigh number for the case where the below plate is inclined at an angle of 7.5°.
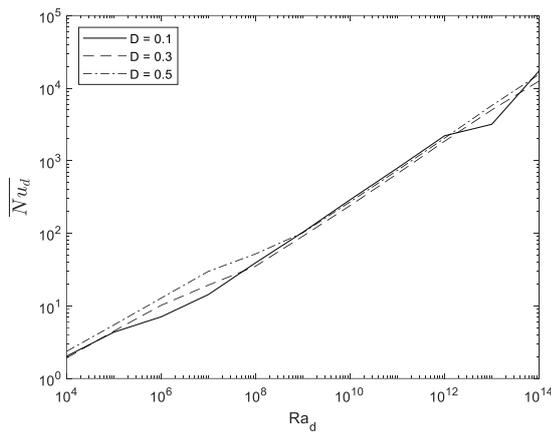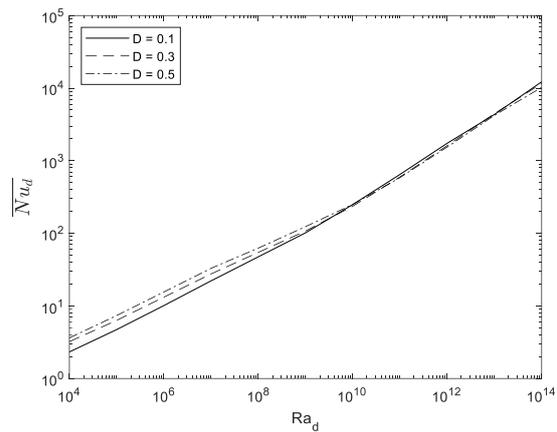
Considering the case where the above plate is inclined at an angle of 2.5° with respect to the horizontal and the below plate is positioned horizontally, Fig. 2 shows that for a range of Rayleigh numbers from 10^7 to 10^{10}, the increase in the dimensionless vertical distance between the plates causes an increase on the mean total Nusselt number for the above plate. The same result can be seen in Figs. 4 and 6, considering a range of Rayleigh numbers between 10^7 and 10^9, for the cases where the above plate is inclined at an angle of 5° and 7.5° respectively. For the other Rayleigh numbers evaluated in this study, the variation in the dimensionless vertical distance between the plates does not produce major changes on the mean total Nusselt number for the above plate, considering the cases where the above plate is inclined and the below plate is horizontal.

The results highlighted in Fig. 3 indicate that, for the case where the above plate is inclined at an angle of 2.5° and the below plate is horizontal, the mean total Nusselt number for the below plate does not undergo major changes with the increase in vertical distance between the plates for the Rayleigh number range considered in the simulations. Figures 5 and 7 demonstrate the variation in the mean total Nusselt number for the below plate in numerical simulations performed for the cases where the above plate is inclined at an angle of 5° and 7.5° respectively. The graphs indicate that in both cases, for a range of Rayleigh numbers between 10^4 and 10^9, the heat transfer rate on the below plate increases as the dimensionless vertical distance between the plates increases. For Rayleigh numbers greater than 10^9, the mean total Nusselt number does not change significantly with the change in the distance between the centers of the plates.

Figures 8, 10 and 12 show that for cases where the below plate is inclined and the above plate positioned horizontally, and considering Rayleigh numbers between 10^4 and 10^7, the mean Nusselt number based on the total heat transfer area of the above plate increases as the vertical distance between the plates rises. For Rayleigh numbers greater than 10^7, the heat transfer rate for the above plate does not vary significantly with the change in the vertical distance between the plates.

Considering also the cases where the below plate is inclined and the above plate is positioned horizontally, it is possible to notice in Fig. 9 that for an inclination angle of 2.5° and for a range of Rayleigh numbers between 10^4 and 10^{10}, the mean total Nusselt number for the below plate rises with the increase of the dimensionless vertical distance between the plates. The same phenomenon can be seen for a range of Rayleigh numbers from 10^4 to 10^9, considering inclination angles of 5° and 7.5°, as highlighted in Figs.11 and 13, respectively. For higher Rayleigh numbers, it is possible to observe that the heat transfer rate by natural convection in the below plate does not undergo major changes with the adjustment in the vertical distance between the plates.

The results obtained by the numerical simulations performed in this research, demonstrated that for both situations addressed, the mean Nusselt numbers for both the above and below plates are directly affected by the vertical distance between the plates when considering low and intermediate Rayleigh numbers, while for higher Rayleigh numbers, the heat transfer rates on both plates are less influenced by the different vertical distances considered in this study. These results may be related to the different fluid flow characteristics found for each range of Rayleigh numbers. For lower Rayleigh numbers, the interaction between the flows over the two plates is more influential on heat transfer rates due to the smoother movement performed by the fluid in laminar and transitional flow regimes, while the disordered movement of the fluid associated with the turbulent flow regime found in higher Rayleigh numbers, decreases the influence of the vertical distance between the plates on the mean total Nusselt numbers.

Figures 14 to 21 demonstrate the different variations for the mean total Nusselt numbers of both plates with respect to the angle of inclination, considering both cases where the above plate is inclined and where the below plate is inclined. These graphs were generated for different Rayleigh number values which generically represent the phenomena observed in the numerical simulations.
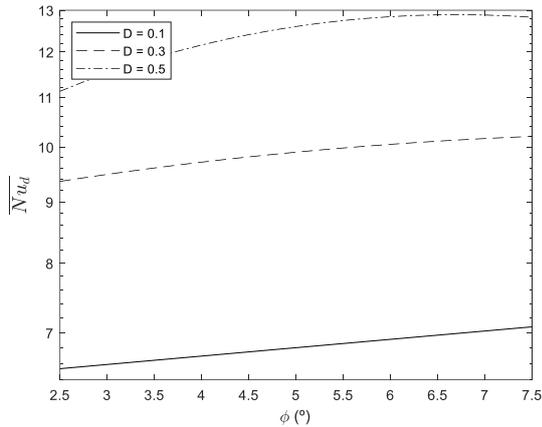
Figure 14. Variation of the mean total Nusselt number for the above plate with the angle of inclination of the below plate for Ra = 10^6.
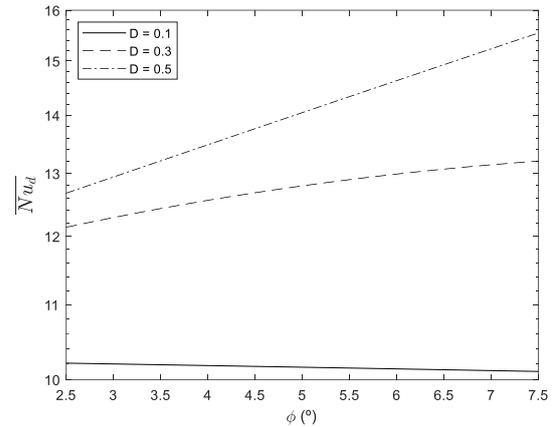

Figure 15. Variation of the mean total Nusselt number for the below plate with the angle of inclination of the below plate for Ra = 10^6.

Figure 16. Variation of the mean total Nusselt number for the above plate with the angle of inclination of the above plate for Ra = 10^8.

Figure 17. Variation of the mean total Nusselt number for the below plate with the angle of inclination of the above plate for Ra = 10^8.

Figure 18. Variation of the mean total Nusselt number for the above plate with the angle of inclination of the below plate for Ra = 10^{10}.

Figure 19. Variation of the mean total Nusselt number for the below plate with the angle of inclination of the below plate for Ra = 10^{10}.
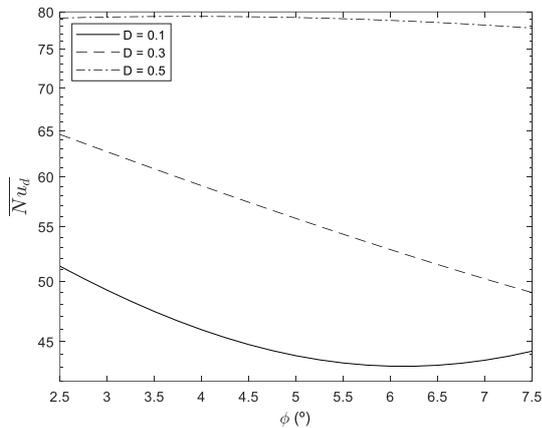
Figure 20. Variation of the mean total Nusselt number for the above plate with the angle of inclination of the above plate for Ra = 10^{10}.
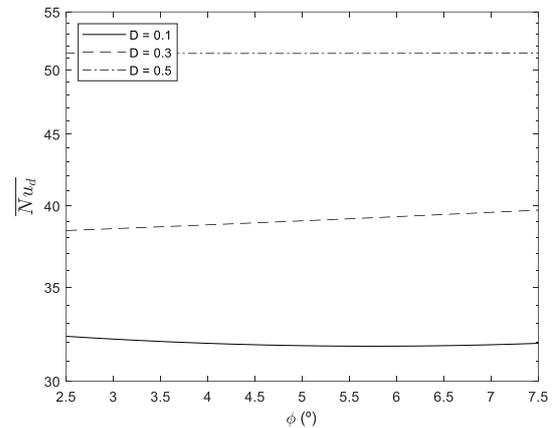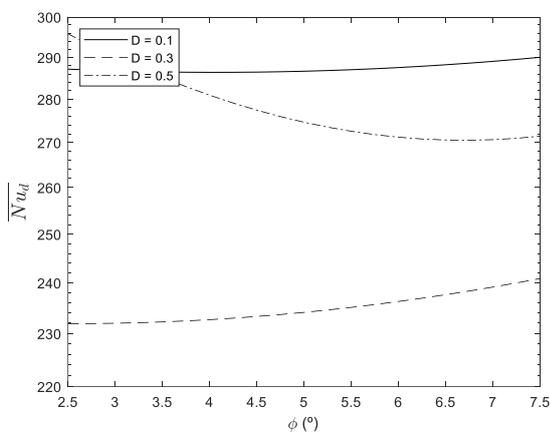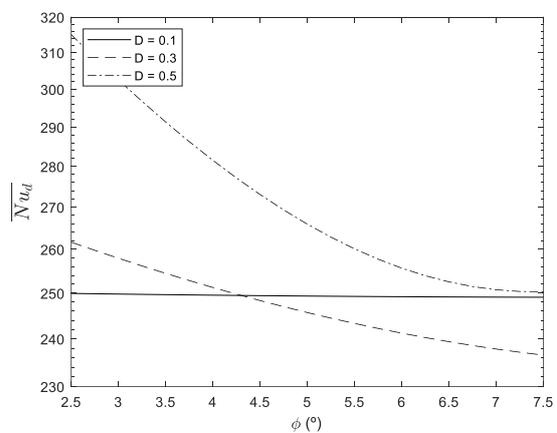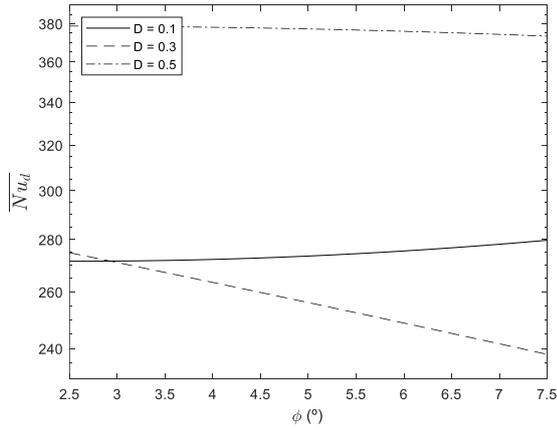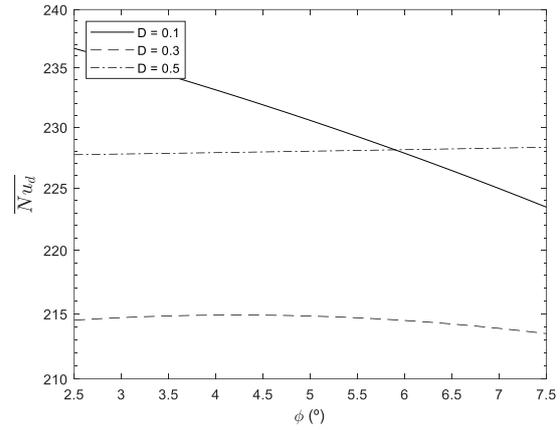

Figure 21. Variation of the mean total Nusselt number for the below plate with the angle of inclination of the above plate for Ra = 10^{10}.

Results shown on Figs. 14 to 17 demonstrate that for both situations where the below plate is inclined and the above plate is horizontal and where the above plate is inclined and the below plate is horizontal, the mean total Nusselt numbers for both plates increases as the vertical distance between them increases, when considering low Rayleigh numbers. Furthermore, as seen in these figures, the variation on the angle of inclination in both cases does not produce a significant variation in heat transfer rates for both plates. Similar results were observed for most cases involving low Rayleigh numbers.

Considering higher Rayleigh numbers, Figs. 18 to 21 show that the behavior of the mean total Nusselt numbers for both plates assumes a more sporadic behavior with the variation of the vertical distance between the plates and the angle of inclination of the inclined plate. This result was expected due to the more chaotic characteristic of the fluid movement in turbulent flow. However, due to the higher relative heat transfer rates involved in these cases, it can be noted that for higher Rayleigh numbers, the mean total Nusselt numbers for both plates does not change significantly with the variation in vertical distance between the plates and in angle of inclination. Similar results were observed for most cases involving high Rayleigh numbers.

As expected, the results demonstrate that the use of two plates spaced vertically at a short distance and with one plate inclined and the other one positioned horizontally produces higher heat transfer rates than those obtained by horizontal plates individually, however, when comparing the individual results produced for each plate with the typical Nusselt numbers produced by horizontal plates, it is noted that the mean Nusselt numbers obtained in this research for each plate are smaller than those obtained for the case where heat transfer by natural convection occurs on both surfaces of a horizontal plate.

As previously mentioned, the results shown in Figs. 2 to 21 are based on the mean total Nusselt numbers for the entire surface of the above plate and for the entire surface of the below plate, however, the numerical solutions performed with the aid of the commercial CFD solver ANSYS FLUENT© provided results in the form of heat transfer rates for the lower and upper surfaces of each plate. These results were employed in multiple linear regressions to fit different correlations between the mean Nusselt numbers of each surface for both plates with the Rayleigh number, Ra_d, the dimensionless vertical distance between both plates, D, and the angle of inclination of the inclined plate, ϕ.

In general, in natural convective heat transfer situations, correlations between the mean Nusselt number and other parameters of interest can be written with the aid of a power-law expression, i.e.:

$$\overline{\mathrm{Nu}}_d = C\mathrm{Ra}_d^{m}D^{n}\phi^{p} \tag{6}$$

where the constants C, m, n e p can be obtained using the least-square method.

For the case where the above plate is inclined and the below plate is positioned horizontally, Eqs. (7) to (10), show, respectively, correlations for the mean Nusselt numbers on the top surface of the above plate, $\overline{\mathrm{Nu}}_{d\,(above/top)}$, on the bottom surface of the above plate, $\overline{\mathrm{Nu}}_{d\,(above/bottom)}$, on the top surface of the below plate, $\overline{\mathrm{Nu}}_{d\,(below/top)}$, and on the bottom surface of the below plate, $\overline{\mathrm{Nu}}_{d\,(below/bottom)}$, i.e.:

$$\overline{\mathrm{Nu}}_{d\,(above/top)} = 0.07312\mathrm{Ra}_d^{0.39435}D^{0.8417}\phi^{0.00411} \tag{7}$$

$$\overline{\text{Nu}}_{d\text{ (above/bottom)}} = 0.05545\text{Ra}_d^{0.37725}D^{-0.27128}\phi^{-0.0291} \tag{8}$$

$$\overline{\text{Nu}}_{d\text{ (below/top)}} = 0.0233\text{Ra}_d^{0.41982}D^{0.20879}\phi^{0.00512} \tag{9}$$

$$\overline{\text{Nu}}_{d\text{ (below/bottom)}} = 0.17607\text{Ra}_d^{0.32034}D^{-0.03338}\phi^{0.01037} \tag{10}$$

Moreover, for the case where the below plate is inclined and the above plate is positioned horizontally, Eqs. (11) to (14), show, respectively, correlations for the mean Nusselt numbers on the top surface of the above plate, $\overline{\text{Nu}}_{d\text{ (above/top)}}$, on the bottom surface of the above plate, $\overline{\text{Nu}}_{d\text{ (above/bottom)}}$, on the top surface of the below plate, $\overline{\text{Nu}}_{d\text{ (below/top)}}$, and on the bottom surface of the below plate, $\overline{\text{Nu}}_{d\text{ (below/bottom)}}$, i.e.:

$$\overline{\text{Nu}}_{d\text{ (above/top)}} = 0.04791\text{Ra}_d^{0.38015}D^{-0.21778}\phi^{0.00081} \tag{11}$$

$$\overline{\text{Nu}}_{d\text{ (above/bottom)}} = 0.05225\text{Ra}_d^{0.40164}D^{0.79243}\phi^{0.0419} \tag{12}$$

$$\overline{\text{Nu}}_{d\text{ (below/top)}} = 0.20556\text{Ra}_d^{0.32306}D^{-0.00146}\phi^{-0.02933} \tag{13}$$

$$\overline{\text{Nu}}_{d\text{ (below/bottom)}} = 0.02679\text{Ra}_d^{0.41343}D^{0.19812}\phi^{0.00853} \tag{14}$$

The results obtained by using these correlations, when considering low and intermediate Rayleigh numbers, provide values for mean Nusselt numbers close to those retrieved through numerical simulations. However, the use of these equations for higher Rayleigh numbers does not provide sufficiently accurate results. Although these correlations provide somewhat accurate results for most of the Rayleigh numbers considered in this work, the error associated with their uses could be reduced by establishing specific equations for different Rayleigh number ranges. This procedure will be carried out in a future work.

5. CONCLUSIONS

A numerical study of the heat transfer process by natural convection in two flat isothermal plates, spaced vertically at a small distance, and with one plate inclined and the other one positioned horizontally has been undertaken. In both cases, the one where the above plate is inclined and the below plate is horizontal, and the one where the below plate is inclined and the above plate is horizontal, the results obtained by the numerical simulations show that for smaller Rayleigh numbers, the mean total Nusselt numbers for both plates increases as the dimensionless vertical distance between the plates increases, while for higher Rayleigh numbers, the changes on the vertical distance between the plates does not produce major variations in the heat transfer rates on both plates. Regarding the effects produced by the angle of inclination, the results showed that for both cases, the variation of the angle of inclination does not produce a significant variation in the heat transfer rates on both plates.

Furthermore, the results obtained demonstrate that the use of two plates spaced vertically at a short distance, with one inclined and the other positioned horizontally, produces higher heat transfer rates than those obtained with individual horizontal plates, however, due to the interaction between fluid flows over both plates produced by the small vertical distances considered in this study, the mean Nusselt numbers obtained for each plate are considerably smaller than those for horizontal heated plates.

The results obtained with these numerical simulations provide a good basis for understanding the phenomena involved in this process and indicate mean Nusselt numbers that may arise in such situations, however, the development of experiments in the future is fundamental to validate the numerical model employed in this work and the results here obtained. Additionally, a more in-depth study in the future may also include more simulations for other angles of inclination and for additional vertical distances between the plates. More accurate correlations to better determine the mean Nusselt numbers involved in this process can also be considered for future extensions of this work.

6. ACKNOWLEDGEMENTS

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