18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

ENC-2020-0309
STUDY OF THE INFLUENCE OF ONE AND TWO TRIANGULAR STEPS IN THE NATURAL CONVECTIVE HEAT TRANSFER RATE FROM A THIN HORIZONTAL SURFACE WITH ONE HEATED SIDE

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Abstract. *This article consists of a numerical analysis of the influence of one and two triangular steps in the natural convective heat transfer from a thin horizontal surface with one heated side. The main objective of this work is to calculate the natural convective heat transfer rate between the horizontal surface with triangular steps and the ambient air. Two situations were considered. A horizontal plate containing one triangular step with angles varying between 2º to 6º and a horizontal plate containing two triangular steps, being the first step similar to the previous one and the second step with angles varying between 3º to 7º. All results obtained with one and two triangular steps were compared with a situation of a thin horizontal plate with one heated side without triangular steps subject to natural convective heat transfer to the ambient air. Effects on the natural convective heat transfer were analyzed according to the inclination angle of both triangular steps and the Rayleigh number varying between 10^6 to 10^{12}. Results were obtained numerically using the standard $k-\varepsilon$ turbulence model including effects of buoyant forces with the aid of the commercial CFD solver ANSYS FLUENT©. Depending on the results obtained, geometric recommendations of the situation under analysis can be made that provide the greatest improvement in the natural convective heat transfer rate from the horizontal plate with one or two triangular steps.*

Keywords: *natural convective heat transfer, $k-\varepsilon$ turbulence model, isothermal plates, triangular steps, heat transfer enhancement*

1. INTRODUCTION

Heat transfer enhancement refers to the application of basic concepts of heat transfer processes to improve the rate of heat removal on a surface. There are several techniques that can improve the heat transfer rate from a surface. One of them is the engineering of new surfaces that causes increased local turbulence, which can be achieved using mechanical inserts in simple surfaces. For example, the enhancement of the heat transfer rate produced by using a wavy surface arises from the increase in the surface area exposed to the fluid to which the heat is being transferred and, in some cases, from the changes in the near surface flow produced by the presence of the surface waves. The total enhancement of the heat transfer rate will depend on the shape and relative size of the surface waves. Many wavy shapes have been considered in past studies, but the most common shapes considered remain rectangular, triangular and sinusoidal waves. There are several studies in the literature focusing wavy surfaces, e.g., (Oosthuizen, 2016a), (Oosthuizen, 2016b), (Prétot *et al*., 2000), (Prétot *et al*., 2003), (Siddiqa and Hossain, 2013), (Siddiqa *et al*., 2015), (Oliveira and Oosthuizen, 2018) and (Oliveira and Oosthuizen, 2019). Another way to increase the heat transfer is to increase the heat transfer area by including geometric steps on a surface. In this context, a numerical investigation of the influence of one and two triangular steps in the natural convective heat transfer rate from a thin horizontal surface with one heated side has been undertaken. There does not appear to be much available information on the heat transfer rate that arise in these situations.

The main objective of this work is to calculate the natural convective heat transfer rate between a horizontal surface containing triangular steps and the ambient air. Two situations were considered. A horizontal plate containing one triangular step with angles varying between 2º to 6º and a horizontal plate containing two triangular steps, being the first step similar to the previous one and the second step with angles varying between 3º to 7º. All results obtained with one and two triangular steps were compared with the situation of a thin horizontal plate with one heated side without triangular steps subject to natural convective heat transfer to the ambient air. Effects on the natural convective heat transfer were analyzed according to the inclination angle of both triangular steps and the Rayleigh number varying between 10^6 to 10^{12}. The main idea here is to investigate the influence of one and two triangular steps in the behavior of the natural flow and whether their uses causes heat transfer enhancement when compared to the situation without any triangular steps. The results were obtained in a numerical way, firstly including one triangular step with further comparison with results without any steps, and secondly including one more triangular step with further comparison with results without any steps and also with one triangular step.

2. PHYSICAL SITUATION

The physical situation considered in this work is shown in Fig. 1:

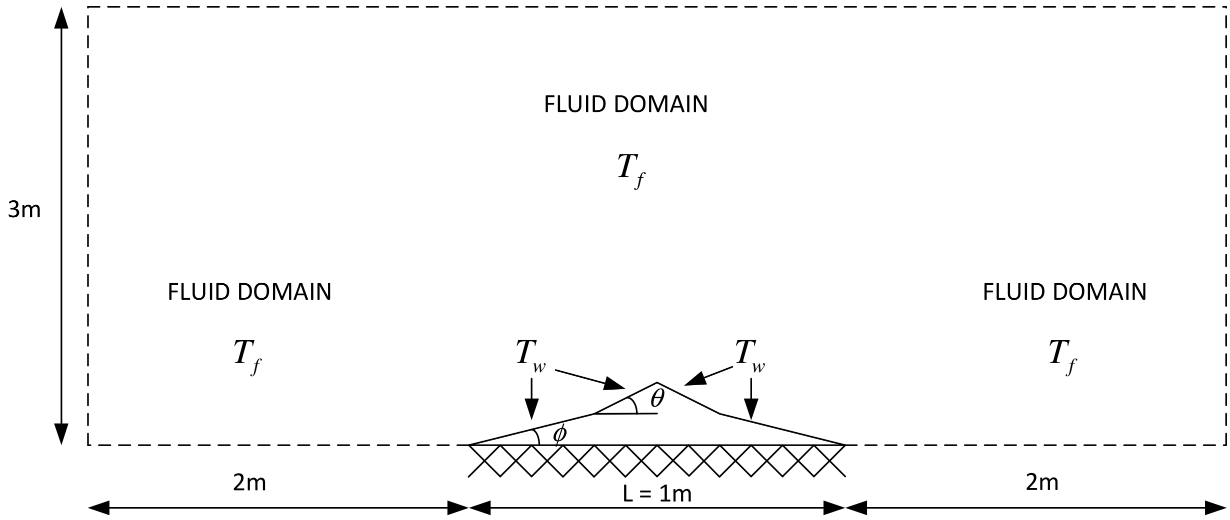

Figure 1. Thin horizontal surface with triangular steps.

The situation under analysis consists of a thin, one sided, two-dimensional horizontal surface having a uniform surface temperature T_w. The horizontal surface is in contact with a surrounding fluid at constant temperature T_f. The bottom side of the horizontal surface (with or without triangular steps) is thermally insulated. For a heated surface, $T_w > T_f$, the horizontal surface will exchange thermal energy with the surrounding fluid by natural convection. Radiation effects will be neglected. The horizontal heated surface has unit width *L* and unit depth *w*. The first triangular step has an inclination angle denoted by ϕ and the second triangular step has an inclination angle denoted por θ. The purpose of this study is to calculate the heat transfer rate by natural convection between the heated surface and the surrounding fluid. The mean Nusselt number related to the natural convective heat transfer can be calculated using the Newton law of cooling based on the width *L* of the horizontal surface and the definition of the mean Nusselt number based on the width *L* of the same horizontal surface, that is:

$$\overline{\mathrm{Nu}_L} = \frac{qL}{(wL)(T_w - T_f)k} \tag{1}$$

where $\overline{\mathrm{Nu}_L}$ is the mean Nusselt number based on *L* and on the mean heat transfer rate, q is the mean heat transfer rate and k is the thermal conductivity of the fluid.

3. SOLUTION PROCEDURE

In obtaining the numerical results discussed above the mean flow has been assumed to be steady. The Boussinesq approximation has been used, i.e., fluid properties have been assumed to be constant except for the density change with temperature in momentum equation. This gives rise to the buoyancy forces and the density change being assumed to be proportional to the temperature change. Radiant heat transfer effects have been neglected. Allowance has been made for the possibility that turbulent flow can occur in the system. In order to deal with this the basic $k-\varepsilon$ turbulence model with standard wall functions and with full account being taken of buoyancy force effects has been used. The mathematical model consists of an equation for the turbulent kinetic energy κ, Eq. (2), and a transport equation for the dissipation of turbulent kinetic energy ε, Eq. (3):

$$\frac{\partial(\rho\kappa)}{\partial t}+\text{div }(\rho\kappa\text{U})=\text{div }\left[\frac{\mu_t}{\sigma_\kappa}\text{ grad }\kappa\right]+2\mu_t S_{ij}\cdot S_{ij}-\rho\varepsilon \tag{2}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\text{div }(\rho\varepsilon\text{U})=\text{div }\left[\frac{\mu_t}{\sigma_\varepsilon}\text{ grad }\varepsilon\right]+C_{1\varepsilon}\frac{\varepsilon}{\kappa}2\mu_t S_{ij}\cdot S_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa} \tag{3}$$

Equations (2) and (3) contains five adjustable constants, e.g., C_μ, σ_k, σ_ε, $C_{1\varepsilon}$ and $C_{2\varepsilon}$. The basic $k-\varepsilon$ turbulence model uses values for these constants obtained through comprehensive curve adjustments for a wide range of turbulent flows, i.e., $C_\mu=0.09$, $\sigma_k=1.00$, $\sigma_\varepsilon=1.30$, $C_{1\varepsilon}=1.44$ and $C_{2\varepsilon}=1.92$. U is the velocity vector, μ_t is the turbulent viscosity and S_{ij} is the deformation rate. The horizontal surface has unit depth w and unit width L maintained at a uniform surface temperature $T_w=310$ K. Also, inclined surfaces of both triangular steps are maintained at a uniform surface temperature $T_w=310$ K. The surrounding fluid is air at a temperature $T_f=290$ K at atmospheric pressure in all cases. The bottom side of the horizontal surface is thermally insulated (with or without triangular steps).

The governing equations subject to the boundary conditions have been solved numerically using the commercial CFD solver ANSYS FLUENT©. The numerical approach used here in order to determine when turbulence develops involves solving the Reynolds averaged governing equations together with a turbulence model, in which the effects of buoyancy forces are taken into account, for all conditions considered and then monitoring the results obtained with increasing Rayleigh numbers to determine when significant turbulence effects develop. This approach has been used quite extensively in the study of forced convective flows, e.g., see (Schmidt and Patankar, 1991) and (Zheng *et al.*, 1998). The solutions presented in this work all basically have the following parameters:

1. The Rayleigh number, Ra_L, based on the reference length scale L of the heated surface and the difference between the temperature of the heated surface, T_w, and the temperature of the undisturbed fluid well away from the system, T_f, i.e.:

$$\text{Ra}_L=\frac{g\beta(T_w-T_f)L^3}{\nu\alpha} \tag{4}$$

2. The angle of inclination of both triangular steps, ϕ and θ;
3. The Prandtl number, Pr.

In Eq. (4), Ra_L is the Rayleigh number based on *L*, *g* is the gravitational acceleration, β is the bulk coefficient of thermal expansion, *L* is the width of the heated surface, ν is the kinematic viscosity of the fluid and α is the thermal diffusivity of the fluid. Results have only been obtained for a Prandtl number of 0.71, i.e., effectively the value for air at 300 K. Before obtaining numerical results, a mesh independence study was carried out using the highest Rayleigh number value, i.e., 10^{12}, for a case for a horizontal surface without any triangular step. All meshes were created with the aid of the GAMBIT© software. Results of the mesh independence test can be seen in Tab. 1:

Table 1. Mesh independence test

Number of elements	$\overline{\text{Nu}_L}$
200.000	1254.55
300.000	1210.89
400.000	1375.31
500.000	1386.45
600.000	1382.12

According to Tab. 1, for approximately 500.000 elements, the mean Nusselt number remained approximately constant. This number of elements was then used in all numerical simulations. In all simulations, the mean Nusselt number integrated over the surface was monitored to ensure convergence and to verify that the simulation reached the steady state. The complete computational domain is 5m width and 3m high. Due to symmetry, half of the computational domain was simulated. The configuration of the ANSYS FLUENT© solver was based on the work of Oliveira and Oosthuizen (2018), Oliveira and Oosthuizen (2019), Oosthuizen (2016a) and Oosthuizen (2016b), having already been extensively tested and validated with results of numerical and experimental works by these authors. The convergence criteria used for all variables in numerical simulations was 10^{-5}.

4. RESULTS AND DISCUSSION

Typical variations of the mean Nusselt number based on the mean heat transfer rate with Rayleigh number for various values of inclination angle of both triangular steps, ϕ and θ, were obtained numerically. Values of the first triangular step inclination angle that were used are 2°, 4° and 6°. Besides, values of the second triangular step inclination angle that were used are 3°, 5° and 7°. Numerical simulations were performed for Rayleigh numbers varying between 10^6 to 10^{12}. In all figures in this section, cases where $\phi = 0°$ and $\theta = 0°$ correspond to the case without any triangular steps, i.e., a flat horizontal surface. Typical results involving the first triangular step are shown in Figs. 2 to 4.

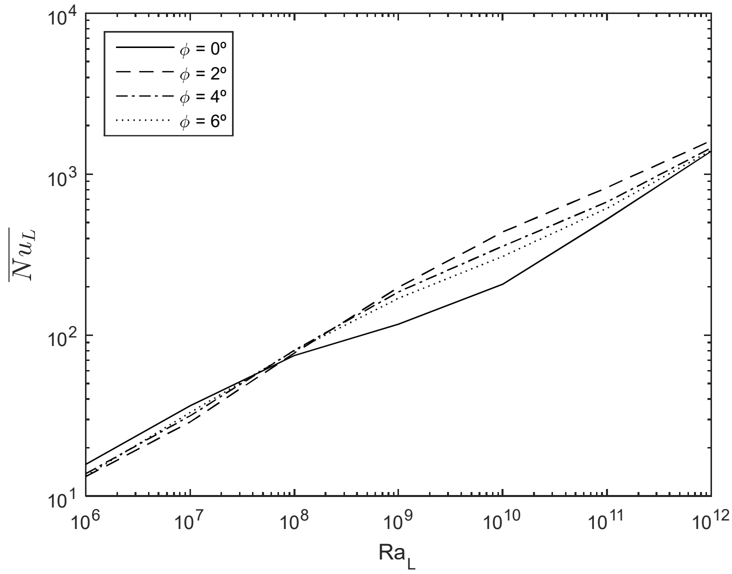

Figure 2. Variation of the mean Nusselt number with the Rayleigh number for $\theta = 0°$ in the case where the first triangular step inclination angle ϕ is equal to 2°, 4° and 6°.

Figure 2 shows the variation of the mean Nusselt number with the Rayleigh number for $\theta = 0°$ in the case where the first triangular step inclination angle ϕ varies between 2° to 6°. It can be noted that for Rayleigh numbers from 10^6 to 10^8, the insertion of one triangular step decreased the natural convective heat transfer rate, while for Rayleigh numbers from 10^8 to 10^{12}, the insertion of one triangular step increased the natural convective heat transfer rate. The major increase in the heat transfer rate occurred for $\phi = 2°$ while the minor increase in the heat transfer rate occurred for $\phi = 6°$.

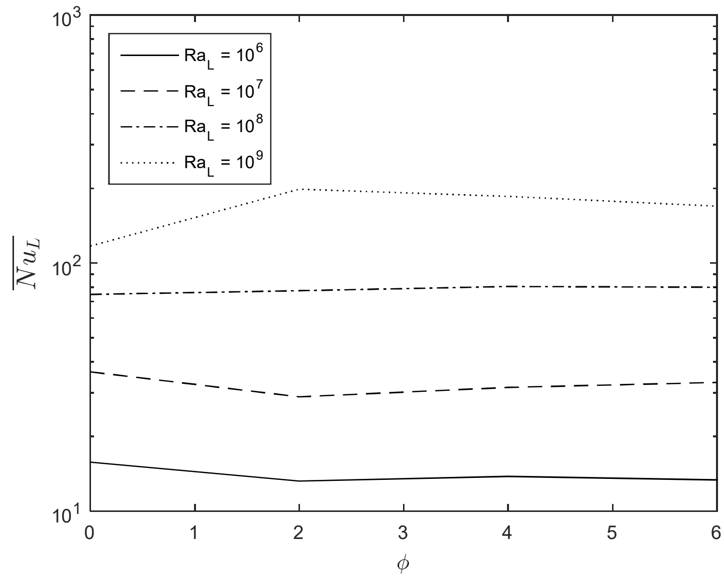

Figure 3. Variation of the mean Nusselt number with the first triangular step inclination angle for $\theta = 0°$ in the case where the Rayleigh numbers are equal to 10^6, 10^7, 10^8 and 10^9.

Figure 3 shows the variation of the mean Nusselt number with the first triangular step inclination angle for $\theta = 0^o$ in the case where the Rayleigh number are equal to 10^6, 10^7, 10^8 and 10^9. It can be noted that for Rayleigh number equal to 10^6 and 10^7, an increase in the angle ϕ causes a decrease in the mean Nusselt number. Besides, for a Rayleigh number equal to 10^8, the mean Nusselt number remains practically constant with the increase in the angle ϕ. Lastly, for a Rayleigh number equal to 10^9, it can be noted an increase in the mean Nusselt number for ϕ up to 2º and then a decrease in the mean Nusselt number with an increase of ϕ up to 6º.

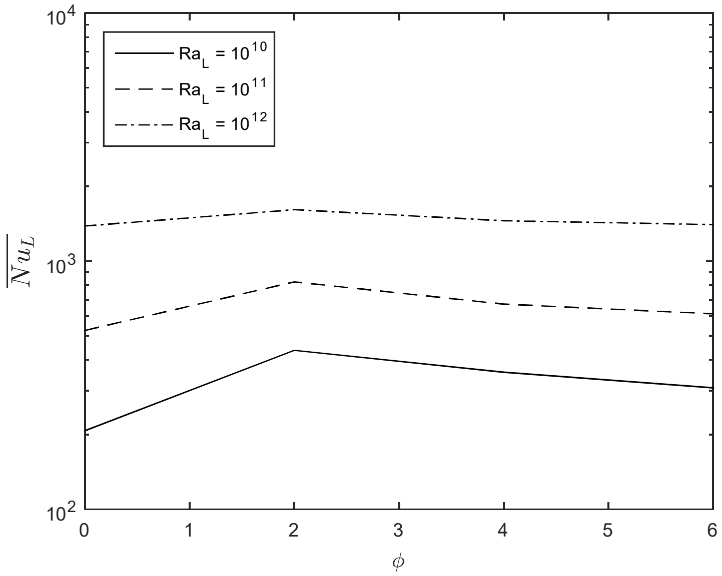

Figure 4. Variation of the mean Nusselt number with the first triangular step inclination angle for $\theta = 0^o$ in the case where the Rayleigh numbers are equal to 10^{10}, 10^{11} and 10^{12}.

Figure 4 shows the variation of the mean Nusselt numbers with the first triangular step inclination angle for $\theta = 0^o$ in the case where the Rayleigh numbers are equal to 10^{10}, 10^{11} and 10^{12}. It can be noted that for Rayleigh number equal to 10^{10} to 10^{12} an increase in the mean Nusselt number for ϕ up to 2° and then a decrease in the mean Nusselt number with an increase of ϕ up to 6°. For a more accurate comparison between the results, the percentage variation of the mean Nusselt number for Rayleigh numbers varying between 10^6 and 10^{12} are shown in Tab. 2:

Table 2. Percentage variation of the mean Nusselt number in comparison with $\phi = 0^o$ and $\theta = 0^o$ (flat horizontal surface) for Rayleigh number varying between 10^6 to 10^{12}.

Ra_L	$\phi = 2^o$ and $\theta = 0^o$	$\phi = 4^o$ and $\theta = 0^o$	$\phi = 6^o$ and $\theta = 0^o$
10^6	-16.03%	-12.41%	-15.24%
10^7	-20.67%	-13.42%	-9.32%
10^8	3.49%	7.62%	6.89%
10^9	69.56%	58.58%	44.84%
10^{10}	110.96%	72.28%	48.93%
10^{11}	57.05%	27.68%	16.67%
10^{12}	16.37%	5.02%	1.31%

From the results shown in Tab. 2, it was found that the use of one triangular step proved to be efficient in terms of increasing the natural convective heat transfer when compared to the case of a horizontal flat surface for almost all cases. This is most evident for Rayleigh numbers varying between 10^8 to 10^{12}. Besides, the major improvement in the natural convective heat transfer rate was observed for $\phi = 2^o$ $(\theta = 0^o)$. Typical results involving the second triangular step are shown in Figs. 5 to 13.

Figure 5 shows the variation of the mean Nusselt number with the Rayleigh number for $\phi = 2^o$ in the case where the second triangular step inclination angle θ varies between 3º to 7º. It can be noted that for Rayleigh numbers from 10^6 to 10^8, the insertion of two triangular steps decreased the natural convective heat transfer rate, while for Rayleigh numbers from 10^8 to 10^{12}, the insertion of two triangular steps increased the natural convective heat transfer rate. The major increase in the heat transfer rate occurred for $\phi = 2^{\circ}$ and $\theta = 3^{\circ}$ while the minor increase in the heat transfer rate occurred for $\phi = 2^{\circ}$ and $\theta = 7^{\circ}$.

Figure 6 shows the variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 2^{\circ}$ in the case where the Rayleigh numbers are equal to 10^6, 10^7, 10^8 and 10^9. It can be noted that for Rayleigh numbers equal to 10^6, 10^7 and 10^8 an increase of θ causes an increase in the mean Nusselt number. Moreover, for a Rayleigh number equal to 10^9 it can be noted a decrease in the mean Nusselt number with an increase of θ.

Figure 7 shows the variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 2^{\circ}$ in the case where the Rayleigh numbers are equal to 10^{10}, 10^{11} and 10^{12}. It can be noted that for Rayleigh numbers equal to 10^{10} to 10^{12} a decrease in the mean Nusselt number occurs with an increase of θ.

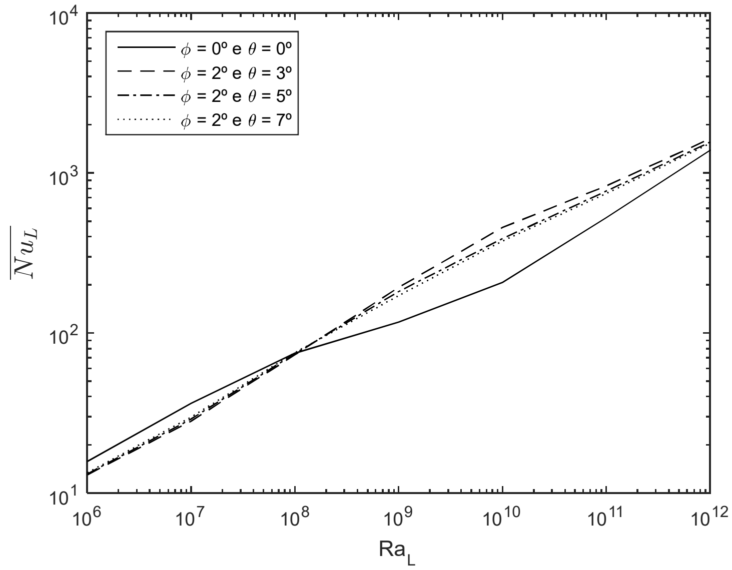

Figure 5. Variation of the mean Nusselt number with the Rayleigh number for $\phi = 2^{\circ}$ in the case where the second triangular step inclination angle θ is equal to 3º, 5º and 7º.

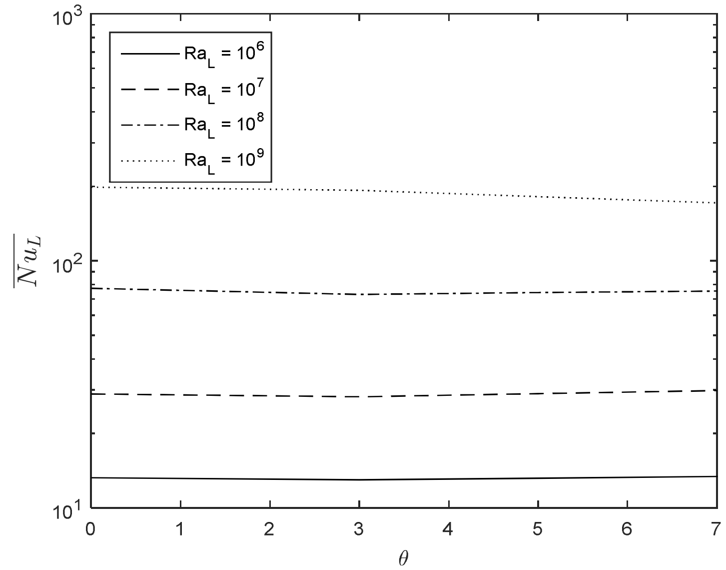

Figure 6. Variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 2^{\circ}$ in the case where the Rayleigh numbers are equal to 10^6, 10^7, 10^8 and 10^9.

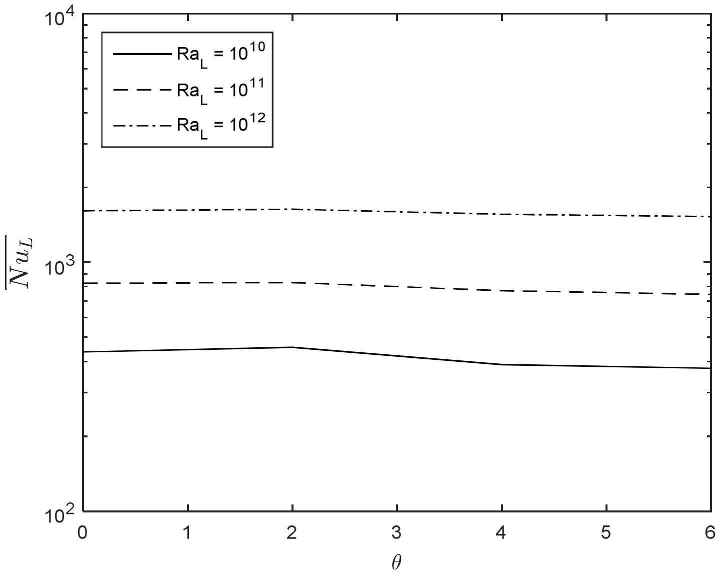

Figure 7. Variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 2^{\circ}$ in the case where the Rayleigh numbers are equal to 10^{10}, 10^{11} and 10^{12}.

Again, for a more accurate comparison between the results, the percentage variation of the mean Nusselt number for Rayleigh numbers varying between 10^6 and 10^{12} are shown in Tab. 3 comparing the results for a flat horizontal surface and two triangular steps $(\phi = 2^{\circ})$ and in Tab. 4 comparing the results for one and two triangular steps $(\phi = 2^{\circ})$:

Table 3. Percentage variation of the mean Nusselt number in comparison with $\phi = 0^{\circ}$ and $\theta = 0^{\circ}$ (flat horizontal surface) for Rayleigh numbers varying between 10^6 to 10^{12}.

Ra_L	$\phi = 2^{\circ}$ and $\theta = 3^{\circ}$	$\phi = 2^{\circ}$ and $\theta = 5^{\circ}$	$\phi = 2^{\circ}$ and $\theta = 7^{\circ}$
10^6	-17.70%	-16.40%	-15.07%
10^7	-22.75%	-20.43%	-18.15%
10^8	-2.29%	-0.55%	0.84%
10^9	64.69%	55.17%	46.45%
10^{10}	120.40%	87.66%	81.30%
10^{11}	58.01%	46.56%	41.57%
10^{12}	18.04%	12.67%	10.30%

Table 4. Percentage variation of the mean Nusselt number in comparison with $\phi = 2^{\circ}$ and $\theta = 0^{\circ}$ (one triangular step) for Rayleigh numbers varying between 10^6 to 10^{12}.

Ra_L	$\phi = 2^{\circ}$ and $\theta = 3^{\circ}$	$\phi = 2^{\circ}$ and $\theta = 5^{\circ}$	$\phi = 2^{\circ}$ and $\theta = 7^{\circ}$
10^6	1.98%	0.43%	-1.15%
10^7	2.62%	-0.31%	-3.17%
10^8	5.59%	3.91%	2.57%
10^9	2.87%	8.49%	13.63%
10^{10}	-4.47%	11.05%	14.06%
10^{11}	-0.61%	6.68%	9.86%
10^{12}	-1.44%	3.18%	5.22%

From the results shown in Tabs. 3 and 4, it was found that the use of two triangular steps proved to be efficient in terms of increasing the natural convective heat transfer when compared to the case of a horizontal flat surface for almost all cases. Besides, the percentage increase in the heat rate is greater with two triangular steps than for one triangular step, especially for Rayleigh numbers varying between 10^8 to 10^{12}. However, the percentage increase in the heat rate with two triangular steps when compared with one triangular step is not to apparent.

Figure 8 shows the variation of the mean Nusselt number with the Rayleigh number for $\phi = 4^{\circ}$ in the case where the second triangular step inclination angle θ varies between 3º to 7º. It can be noted that for Rayleigh numbers from 10^6 to 10^8, the insertion of two triangular steps decreased the natural convective heat transfer rate, while for Rayleigh numbers from 10^8 to 10^{12}, the insertion of two triangular steps increased the natural convective heat transfer rate. The major increase in the heat transfer rate occurred for $\phi = 4^{\circ}$ and $\theta = 3^{\circ}$ while the minor increase in the heat transfer rate occurred for $\phi = 4^{\circ}$ and $\theta = 7^{\circ}$.

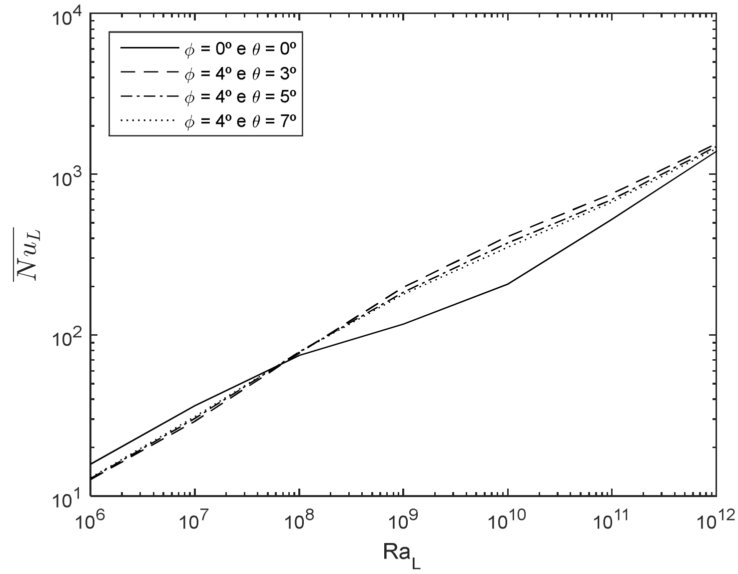

Figure 8. Variation of the mean Nusselt number with the Rayleigh number for $\phi = 4^{\circ}$ in the case where the second triangular step inclination angle θ is equal to 3º, 5º and 7º.

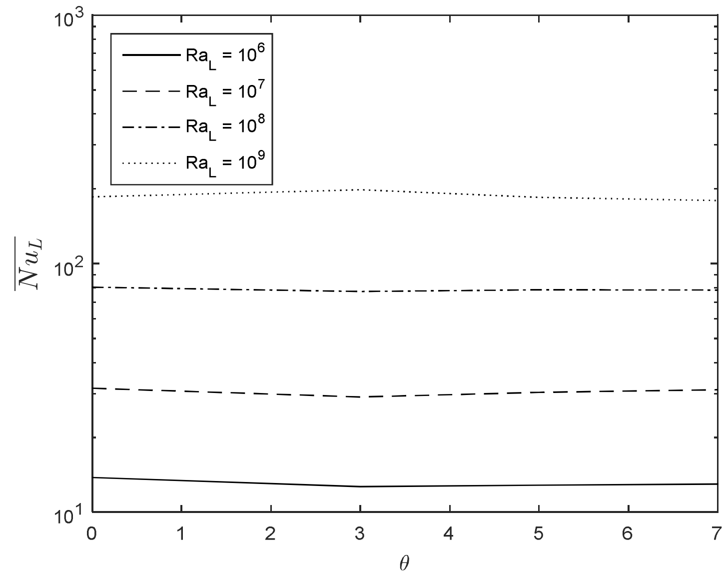

Figure 9. Variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 4^{\circ}$ in the case where the Rayleigh numbers are equal to 10^6, 10^7, 10^8 and 10^9.

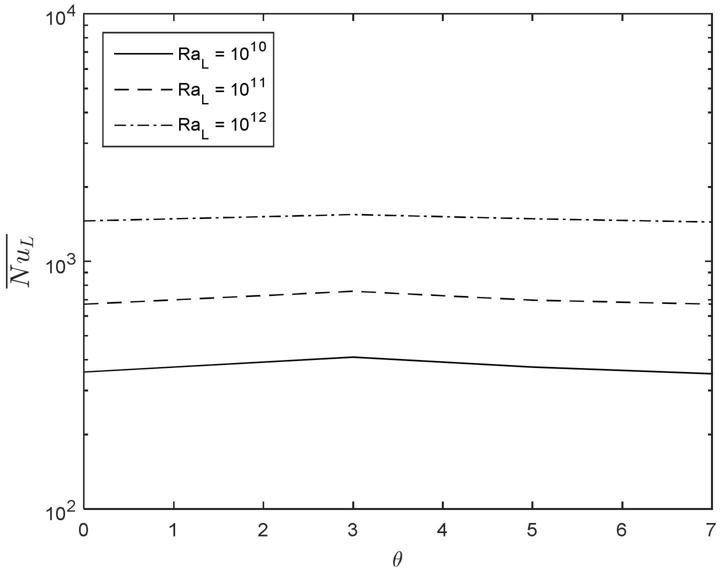

Figure 10. Variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 4^o$ in the case where the Rayleigh numbers are equal to 10^{10}, 10^{11} and 10^{12}.

Figure 9 shows the mean Nusselt numbers with the second triangular step inclination angle for $\phi = 4^o$ in the case where the Rayleigh numbers are equal to 10^6, 10^7, 10^8 and 10^9. It can be noted that for a Rayleigh number equal to 10^6, 10^7, 10^8 and 10^9 the mean Nusselt number remains practically constant with the increase of θ.

Figure 10 shows the mean Nusselt numbers with the second triangular step inclination angle for $\phi = 4^o$ in the case where the Rayleigh numbers are equal to 10^{10}, 10^{11} and 10^{12}. It can be noted that for Rayleigh numbers equal to 10^{10} to 10^{12} an increase of the mean Nusselt number for θ up to 3° and then a decrease of the mean Nusselt number with an increase of θ up to 7°.

For a more accurate comparison between the results, the percentage variation in the mean Nusselt number for Rayleigh numbers varying between 10^6 and 10^{12} are shown in Tab. 5 comparing the results for a flat horizontal surface and two triangular steps $(\phi = 4^o)$ and in Tab. 6 comparing the results for one and two triangular steps $(\phi = 4^o)$:

Table 5. Percentage variation of the mean Nusselt number in comparison with $\phi = 0^o$ and $\theta = 0^o$ (flat horizontal surface) for Rayleigh numbers varying between 10^6 to 10^{12}.

Ra_L	$\phi = 4^o$ and $\theta = 3^o$	$\phi = 4^o$ and $\theta = 5^o$	$\phi = 4^o$ and $\theta = 7^o$
10^6	-19.54%	-18.48%	-17.60%
10^7	-20.13%	-16.65%	-14.59%
10^8	3.38%	5.04%	4.78%
10^9	69.44%	57.93%	53.31%
10^{10}	97.99%	80.52%	69.61%
10^{11}	43.96%	32.52%	27.70%
10^{12}	11.44%	7.14%	3.97%

Table 6. Percentage variation of the mean Nusselt number in comparison with $\phi = 4^o$ and $\theta = 0^o$ (one triangular step) for Rayleigh numbers varying between 10^6 to 10^{12}.

Ra_L	$\phi = 4^o$ and $\theta = 3^o$	$\phi = 4^o$ and $\theta = 5^o$	$\phi = 4^o$ and $\theta = 7^o$
10^6	8.14%	6.93%	5.92%
10^7	7.74%	3.73%	1.35%
10^8	3.94%	2.40%	2.64%
10^9	-6.84%	0.41%	3.32%
10^{10}	-14.92%	-4.78%	1.55%
10^{11}	-12.75%	-3.79%	-0.02%
10^{12}	-6.11%	-2.02%	1.00%

Again, from the results shown in Tabs. 5 and 6, in general, it was found that the use of two triangular steps proved to be efficient in terms of increasing the natural convective heat transfer when compared to the case of a horizontal flat surface for almost all cases. However, the percentage of increase in the heat rate is greater with two triangular steps than for one triangular step, especially for Rayleigh numbers varying between 10^9 to 10^{12}.

Figure 11 shows the variation of the mean Nusselt number with the Rayleigh number for $\phi = 6^\circ$ in the case where the second triangular step inclination angle θ varies between 3° to 7°. It can be noted that for Rayleigh numbers from 10^6 to 10^8 the insertion of two triangular steps decreased the natural convective heat transfer rate, while for Rayleigh numbers from 10^8 to 10^{12}, the insertion of two triangular steps increased the natural convective heat transfer rate. The major increase in the heat transfer rate occurred for $\phi = 6^\circ$ and $\theta = 3^\circ$ while the minor increase in the heat transfer rate occurred for $\phi = 6^\circ$ and $\theta = 7^\circ$.

Figure 12 shows the variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 6^\circ$ in the case where the Rayleigh numbers are equal to 10^6, 10^7, 10^8 and 10^9. It can be noted that for a Rayleigh numbers equal to 10^6, 10^7, 10^8 and 10^9 the mean Nusselt number remains practically constant with the increase of θ.

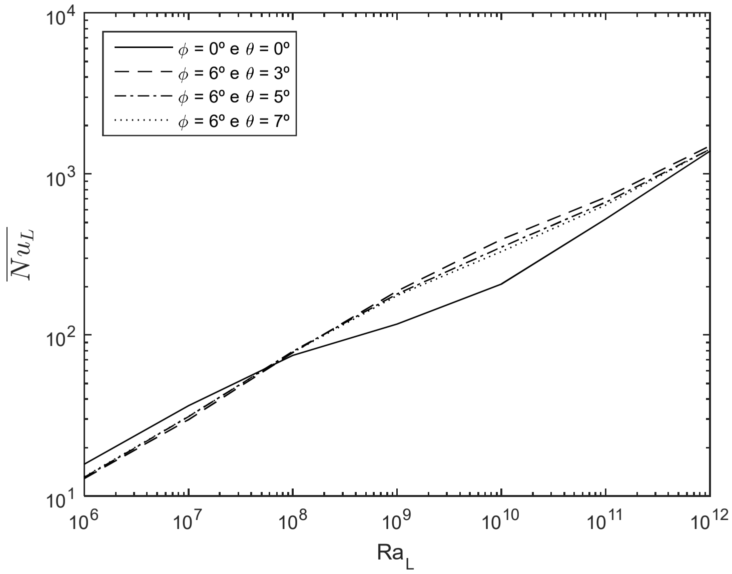

Figure 11. Variation of the mean Nusselt number with the Rayleigh number for $\phi = 6^\circ$ in the case where the second triangular step inclination angle θ are equal to 3°, 5° and 7°.

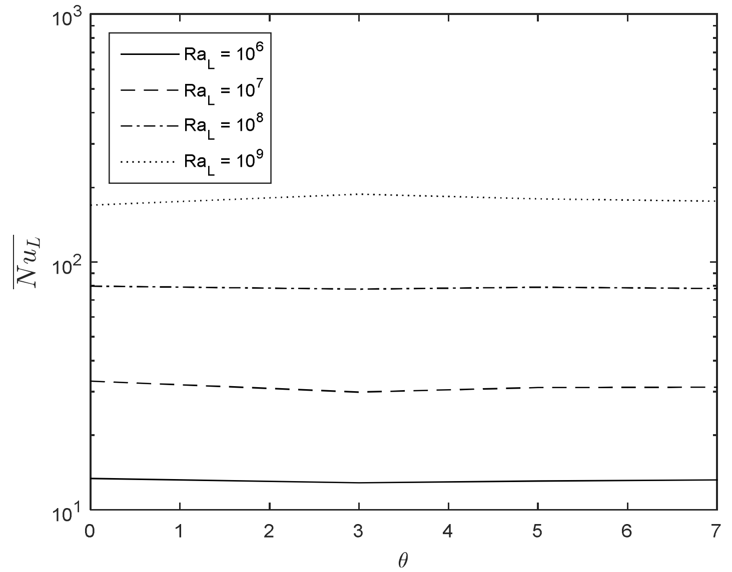

Figure 12. Variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 6^\circ$ in the case where the Rayleigh numbers are equal to 10^6, 10^7, 10^8 and 10^9.

Figure 13 shows the variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 6^\circ$ in the case where the Rayleigh numbers are equal to 10^{10}, 10^{11} and 10^{12}. It can be noted that for Rayleigh numbers varying from 10^{10} to 10^{12} an increase of the mean Nusselt number occurs for θ up to 3° and then a decrease of the mean Nusselt number with an increase of θ up to 7°.

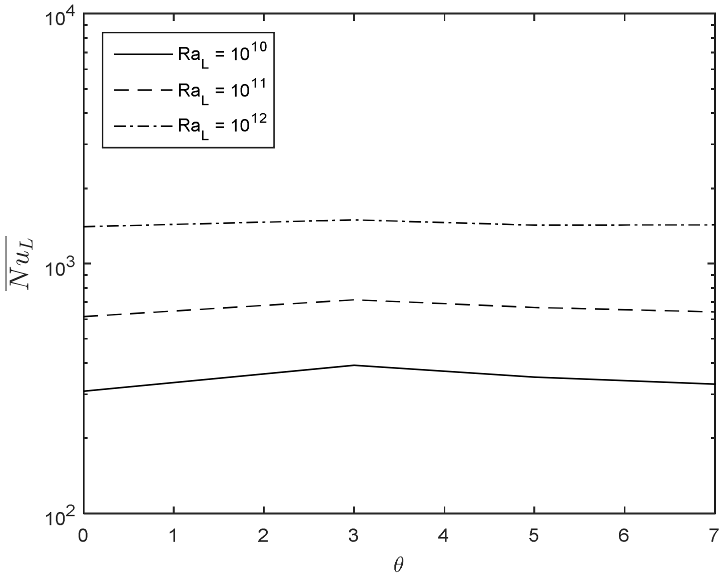

Figure 13. Variation of the mean Nusselt number with the second triangular step inclination angle for $\phi = 6^\circ$ in the case where the Rayleigh numbers are equal to 10^{10}, 10^{11} and 10^{12}.

Finally, for a more accurate comparison between the results, the percentage variation in the mean Nusselt number for Rayleigh numbers varying between 10^6 and 10^{12} are shown in Tab. 7 comparing the results for a flat horizontal surface and two triangular steps $(\phi = 6^\circ)$ and in Tab. 8 comparing the results for one and two triangular steps $(\phi = 6^\circ)$:

Table 7. Percentage variation of the mean Nusselt number in comparison with $\phi = 0^\circ$ and $\theta = 0^\circ$ (flat horizontal surface) for Rayleigh numbers varying between 10^6 to 10^{12}.

Ra_L	$\phi = 6^\circ$ and $\theta = 3^\circ$	$\phi = 6^\circ$ and $\theta = 5^\circ$	$\phi = 6^\circ$ and $\theta = 7^\circ$
10^6	-18.56%	-17.25%	-16.36%
10^7	-18.09%	-14.59%	-14.27%
10^8	3.93%	5.81%	4.55%
10^9	60.44%	53.61%	50.32%
10^{10}	89.22%	69.73%	59.16%
10^{11}	36.27%	26.94%	21.86%
10^{12}	7.87%	2.73%	3.02%

Table 8. Percentage variation of the mean Nusselt number in comparison with $\phi = 6^\circ$ and $\theta = 0^\circ$ (one triangular step) for Rayleigh numbers varying between 10^6 to 10^{12}.

Ra_L	$\phi = 6^\circ$ and $\theta = 3^\circ$	$\phi = 6^\circ$ and $\theta = 5^\circ$	$\phi = 6^\circ$ and $\theta = 7^\circ$
10^6	3.92%	2.37%	1.33%
10^7	9.68%	5.81%	5.46%
10^8	2.77%	1.01%	2.19%
10^9	-10.78%	-6.06%	-3.78%
10^{10}	-27.05%	-13.97%	-6.87%
10^{11}	-16.79%	-8.80%	-4.44%
10^{12}	-6.47%	-1.40%	-1.69%

From the results shown in Tabs. 7 and 8, in general, it was found that the use of two triangular steps proved to be efficient in terms of increasing the natural convective heat transfer when compared to the case of a horizontal flat surface for almost all cases. In this manner, it is recommended the insertion of two triangular steps for the angles used in this work.

5. CONCLUSIONS

A numerical study of natural convective heat transfer from a thin, one-sided, two-dimensional horizontal surface having a uniform surface temperature has been undertaken. The surface shape contains one or two triangular steps and the main objective of this work was to calculate the natural convective heat transfer rate between the surface with triangular steps and the ambient air. The main conclusion of this work is that the use of two triangular steps proved to be more efficient than one triangular step in terms of increasing the natural convective heat transfer when compared to the case of a horizontal flat surface for almost all cases. However, it has its limitation due to the angles used in the numerical simulations. As a future extension, other angles should be simulated and an experiment must be carried out to validate the numerical results obtained in this work.

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