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Turbulent Heat Transfer from a Flat Plate Placed Downstream of a Fence

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ABSTRACT
This paper presents an experimental study of the heat transfer and flow friction for turbulent flows of air over a heated flat plate mounted downstream of a fence. A rectangular brass plate is attached to a heating unit and fixed inside the test section of a subsonic wind tunnel. A number of non-metallic fences with different heights are used separately to promote turbulence over the plate. A series of experiments are conducted to examine the following parameters: fence height to plate length ratio (H/L), the distance between the fence and plate relative to plate length (S/L) and the Reynolds number, which is calculated based on the stream wise length of the plate ($1.5\times10^5 \leq Re_L \leq 4.5\times10^5$). The first set of the results, which is obtained for the case of the flat plate without a fence, satisfied with other published results. The results in the cases of the plate placed downstream of a fence revealed that the Nusselt number and friction factor are critically dependent on the fence height and the distance between the fence and the plate. A maximum Nusselt number enhancement ratio of 1.7 was achieved corresponding to a friction factor ratio of 2.5. New correlation was obtained for the thermal efficiency (η) based on the Nusselt number enhancement ratio and friction factor ratio at different arrangements of the considered parameters.
Keywords**:** Fence, flat plate, friction factor, heat transfer enhancement, Nusselt number, subsonic wind tunnel

I. INTRODUCTION

Heat transfer due to the passage of air over a flat plate has been studied widely. This type of flows occurs in many engineering and industrial applications such as cooling of electronic components, the flow through plate heat exchangers and cooling of gas turbine blades. Different techniques can be utilized to enhance and control the heat transfer process; for example, the use of obstacles [1], vortex generators [2], surface roughness [3], extended surfaces [4], facing steps [5], dimples [6], baffles [7] and fences [8]. The physical effects of using such techniques are: to form separated flows, to increase the disturbance and generate vortices, which are leading to promote turbulent flows and consequently, increasing the efficiency of the heat transfer process. So far, various experimental and numerical investigations have been made to study heat transfer in turbulent flows. Following is a summary of the key papers in this field.

An experimental study of turbulent effects on the heat transfer and the reattachment length downstream of a fence under various free stream condition of air was carried out in [9]. Another set of experimental results of heat transfer in the turbulent boundary layer flows was presented in [10]. The latter study showed the influence of using surface protruding fences on heat transfer and the behavior of the flow in the regions behind the fence.

An active control of the turbulent flow in the regions upstream and downstream a straight fence was investigated experimentally in [11]. These experiments were extended to include a swept fence with a sweep angle of 20^o in [12]. Further experimental investigations of the turbulent reverse flow downstream of a fence using span-wise vortices were carried out in [13].

Abdel-Moneim et al [14] performed a series of experiments to investigate the flow characteristics and the heat transfer from an electronic module fixed on a virtual printed circuit panel, which is mounted downstream of a straight fence. The study involved a range of Reynolds number of 8000 to 40000. Another experimental study for the augmentation of the heat transfer from a heat source mounted behind a guide fence was carried out in [15]. In the latter study the Reynolds number ranged from 5000 to 30000.

A particle image velocimetry (PIV) was utilized to measure velocity fields behind two-dimensional porous fence models in a wind tunnel simulation in [16]. The turbulence fields were analyzed using these measurements.

Numerically, Orellano and Wengle [17] demonstrated numerical results of turbulent flows over a surface-mounted fence. Both the direct numerical simulation (DNS) and the large eddy simulation (LES) methods were used to solve the Navier-Stokes equations. The obtained numerical results were validated against experimental data.

The heat transfer and flow characteristics of turbulent flow with one and two obstacles were predicted numerically in [18]. The governing equations were solved using finite difference scheme with unstructured staggered grid. The *k-ε* turbulent model was used with the associated wall function to express the turbulence configuration.

A computational study of transitional separating-reattaching flow on a square surface mounted obstacle and a forward facing step was presented in [19]. The results were obtained using large eddy simulations and validated against other published experimental and DNS data.

A numerical investigation of the heat transfer over a plate with backward facing step with and without fence was carried out in [20]. The geometry and grid generation were constructed using ANSYS ICEM software and the computations were performed using ANSYS FLUENT software.

In the present work, the influence of fence height and the distance between the fence and the heated plate on the heat transfer and pressure drop are investigated experimentally. The study also aims to provide new correlations for the thermal performance of heated plates mounted downstream of a fence, within a specified range of the Reynolds number.

The manuscript is organized as follows: A brief description of the experimental setup including experimental procedures and data reduction is provided in the next section. This is followed by the experimental results, discussion and conclusions.

II. EXPERIMENTAL SETUP

The present experimental setup is designed to investigate the heat transfer and flow characteristics on a flat plate placed downstream of a fence for a wide range of the Reynolds number. The experiments are conducted in flows of air over a heated flat plate located downstream of a fence in a subsonic wind tunnel. The Reynolds number, based on the length of the heating plate (L), ranged from 1.5×10^5 to 4.5×10^5. A photograph of the general experimental setup is displayed in Fig. (1) and a full detail of the experimental apparatus is illustrated schematically in Fig. (2).

Figure 1: The general experimental setup.

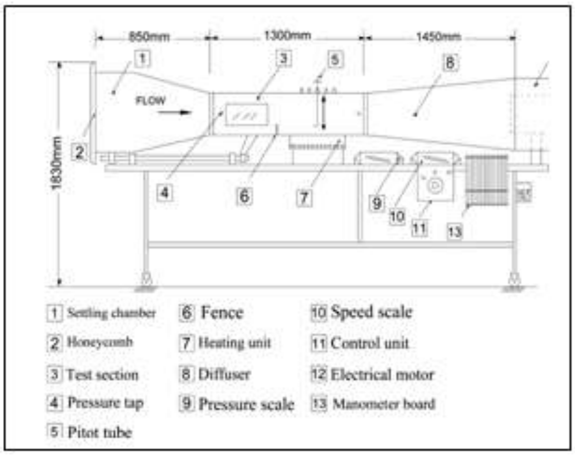


Figure 2: Schematic diagram of the experimental apparatus.

The wind tunnel consists of an inlet section, test section and a diffuser. The inlet section comprises a fiberglass contraction, which is clamped to two slider bars. A honey comb is attached to the inlet section for straightening the air flow at the entrance of the contraction cone. The diffuser section is equipped with a fan, which is driven by a3HP electric motor fixed at the diffuser outlet. The original test section was replaced by a new one, which is made of steel. The modified test section has an octagonal shape of 305 mm a side with an equivalent hydraulic diameter of 318 mm and stream wise length of 1300 mm. The test section contains a glass window and equipped by a heating unit as shown in Fig (1). The heating unit consists of a rectangular brass flat plate of 320 mm length (L), 120 mm width (W) and 4 mm thickness, 13 thermocouples (type k), main heater, asbestos insulation and wooden frame to prevent the heat loss from the backside of the main heater and finally a guard heater to create thermal equilibrium in the asbestos insulation layer, which is placed between the main and guard heaters.

Three different fences with different heights (H) are used separately in each run. The fence is a vertical plate made from a PVC sheet of 120 mm width, 5 mm thickness and a sharp upper edge with a backward chamfer of 45°. A maximum fence height of 15% of the test section height is considered and the H/L ratios of 0.0625, 0.09375and 0.14375 are applied. Different spacing (S) between the fence and the leading edge of the plate, with a maximum spacing of 7 times of the maximum fence height, are investigated in such a manner that the ratio S/L= 0.007, 0.1875, 0.3125, 0.375, 0.45, 0.6875, 0.81 and 1. A schematic diagram of the arrangement of a fence and the plate inside the octagonal test section is illustrated in Fig. (3).

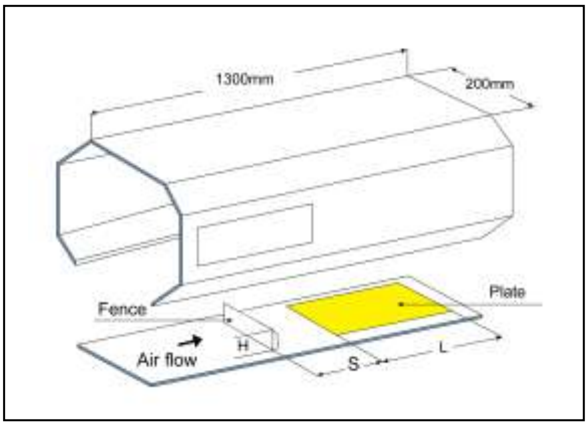


Figure 3: Configuration of the test section

A complete set of measuring instruments is utilized including digital voltmeters for measuring the voltage drop on the main and guard electric heaters; digital multimeters for measuring the resistance of the two heaters; two transformers for controlling the input power to the heating plate via supplying both the main and guard heaters by a variable voltage and a digital thermometer with the accuracy of ±1oC for reading thermocouples output. The inlet air velocity is measured via a calibrated manometer board. A standard pitot – static tube in conjunction with an inclined manometer is used for measuring the mean flow velocity in the hydro-dynamically fully developed flow region. The pressure drop of the flow at the inlet of the test section is measured using the manometer board and the pressure drop across the test section is measured using inclined manometers. The inlet temperature of the air flow is recorded by a standard thermometer. Heat loss by conduction from the edges of the heating plate is determined by the recording of the readings of four thermocouples, which are embedded in the asbestos surrounding the edges.

In each typical data run, firstly, the appropriate fence is set upstream of the flat plate at a specific distance between them in the test section. Secondly, all observable joints are sealed to prevent air from leaking. Then the air flow and the power to the heating unit are switched on and adjusted to predetermined values. The plate is heated over the whole area and the input power is adjusted to maintain the plate heat flux constant. Finally, after about 30 minutes, when the heated plate reaches steady state, the different variables are recorded. These variables are: inlet air temperature, plate surface temperature, pressure drop across the test section, voltage and resistance of the main electric heater. The heat transfer coefficient is determined from the heat flux density and the difference between the wall and fluid temperatures. The heat transfer surface is simulated by a 0.0002 m thick metal foil with thermocouples welded to its internal surface.

The average convective heat transfer coefficient (h) is evaluated from

$$h = \frac{q''_{net}}{T_s - T_\infty} \tag{1}$$

where (T_s) and (T_∞) are the plate surface temperature and the air mean film temperature respectively. (q''_{net}) is the heat flux, which is corrected for conduction and radiation losses as in [21].

The average Nusselt and Reynolds numbers are calculated based on the characteristic length of the heating plate as follows:

$$Nu = \frac{hL}{k_a} \quad \text{and} \quad Re = \frac{u\,L}{\nu}$$

where (k_a) is the thermal conductivity of the air, (L) is the characteristic length of the plate, (u) is the free stream velocity and (ν) is the kinematic viscosity of the air at the mean film temperature.

The friction factor (f) is calculated in terms of the frictional pressure drop along the test section of the wind tunnel as follows:

$$f = \left(\frac{\Delta P}{\frac{1}{2}\rho u^2}\right)\frac{D}{L_{ts}} \tag{2}$$

where ΔP is the pressure drop across the test section, ρ is the air density, D is the hydraulic diameter of the test section and L_{ts} is the length of the test section.

To evaluate the deviation inherent in the current measurements, an uncertainty analysis is carried out. Percentages of errors in the measurements of electrical voltage and resistance are 0.3% and 0.2% respectively. The uncertainty percentages of the plate surface area, plate surface temperature and mean film temperature measurements are 0.5%, 0.33%and 0.66% respectively. Percentages of uncertainties in the measurements of the air flow velocity and pressure drop are 0.5% and 2.0% respectively. Consequently, the percentage of error of the Nusselt number is estimated at 2%, the Reynolds number is 1.8% and the Fanning friction factor is 5.5%.

III. RESULTS AND DISCUSSION

The current experimental setup is allowed to investigate the heat transfer and flow characteristics on a flat plate placed downstream of a fence for a wide range of the Reynolds number. The obtained results are presented and discussed in this section.

To validate the current measurements, a number of experiments were conducted for flows over a plate without a fence, which covered a range of the Reynolds number from 1.3×10^5 to 4.45×10^5. A comparison between the present result of the average Nusselt number and the correlations obtained in [22] and [23] suggests that there is very good agreement as shown in Fig. (4). The result of the friction factor is presented in Fig. (5), associated with the correlation achieved in [22]. Good agreement is noticed between the current result and the reference data. The very good compatibility of the results guarantees that the current measurements and present experimental data are correct. Based on this the following correlations are obtained for the average Nusselt number and average friction factor in the case of air flow over a heated plate without a fence:

$$Nu_O = 0.017(Re_L)^{0.8546}$$

and

$$f_O = 0.2179(Re_L)^{-0.168} .$$

These correlations are valid with a small deviation of 4% for the Nusselt number and a reasonable deviation of 8% for the friction factor, within the considered range of the Reynolds number.

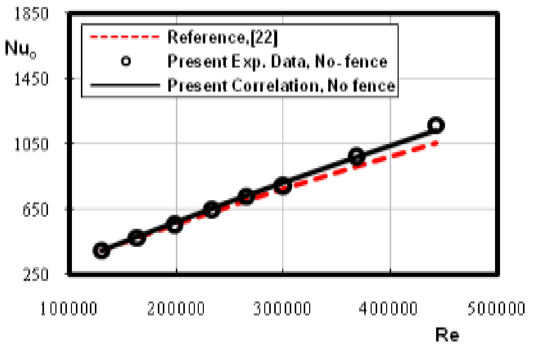


Figure 4: Validation of the current experimental results of the average Nusselt number.

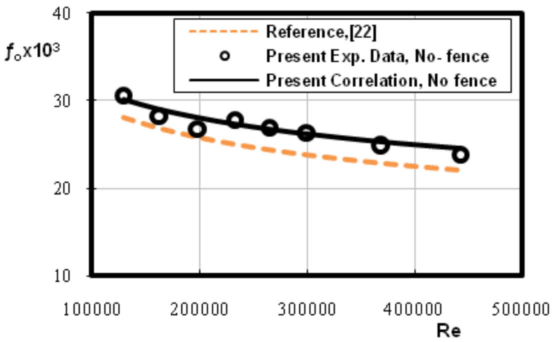


Figure 5: Validation of the current experimental results of the friction factor.

After the positive validation procedures, further studies were made, for the cases where a fence was set upstream of the hot plate. As stated earlier three different fence heights (H) at eight different spacing (S) were investigated within the range of the Reynolds number between 1.5×10^5 and 4.5×10^5. Figure (6) shows the average Nusselt number as a function of the Reynolds number for the different (H/L) and (S/L) configurations.

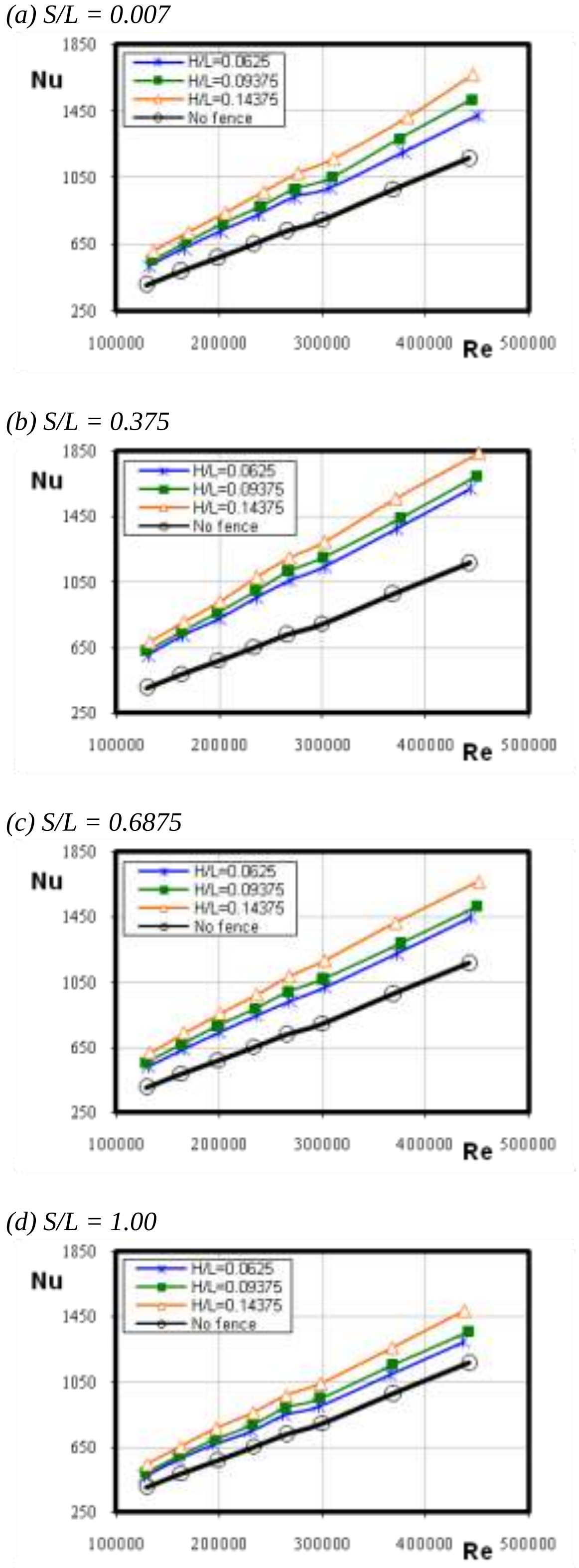


Figure 6: Variation of the average Nusselt number as a function of the Reynolds number of different flow arrangements.

It is clear that the values of the Nusselt number of the cases of flow in presence of a fence are higher than the values in the cases of flow without a fence, which confirm that the enhancement in the heat transfer is achieved. It can be seen that the enhancement in the heat transfer is significant at relatively low ratios of (S/L). This enhancement reduces with the increase in the spacing due to the decay in the vortex strength. The fence configuration, which has the highest ratio of (H/L) produces the maximum enhancement in heat transfer among the other configurations that are tested in this work. Also, the enhancement in the average Nusselt number increases with the increase in the Reynolds number as shown in Fig. (6). The main reason for the heat transfer enhancement owes to promote the turbulence of the airflow via induces the recirculation flow with secondary vortices behind the fence and the occurrence of flow separation-reattachment phenomena. The shear layer separates upstream of the leading face of the fence and reattaches downstream of the trailing face at reattachment length depends on both Reynolds number and the fence height. To discuss this point further, the stream-wise flow velocity component (u) along the mid plane of the test plate is measured at five different test positions (x/L) starting from the upstream edge of the plate. The velocity profiles are then plotted for two different H/L ratios at different S/L ratios as shown in Fig. (7). The velocity profiles indicate that a separation-reattachment flow pattern exists downstream of the fence. Also, the figures reveal that the reattachment length depends on both the free stream velocity and (H/L) ratio.

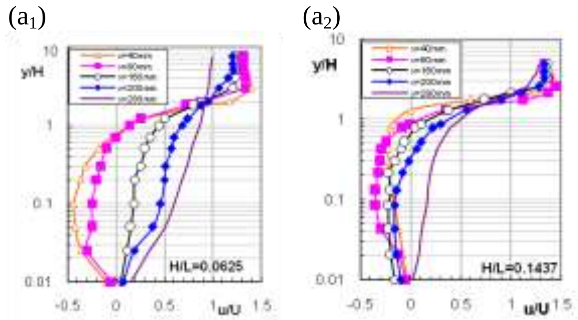
The ratio of reattachment length to the fence height (Lr/H) is correlated in terms of the Reynolds number and (H/L) ratio for the different fence configurations as follows:

$$(Lr/H)_{corr} = 1.0652\ (Re_L)^{0.1449} (H/L)^{0.0357}$$

This correlation is valid, with a maximum deviation of 11%, within the range of the Reynolds number from 1.3×10^5 to 4.5×10^5 and for the range of (H/L) from 0.0625 to 0.1437.

The average Nusselt number for the plate downstream of a fence is correlated as a function of Reynolds number, H/L and S/L ratios and the following correlation is obtained:

$$Nu_{corr} = 0.0554\ (Re_L)^{0.8156} (H/L)^{0.1542} (S/L)^{-0.0014}$$



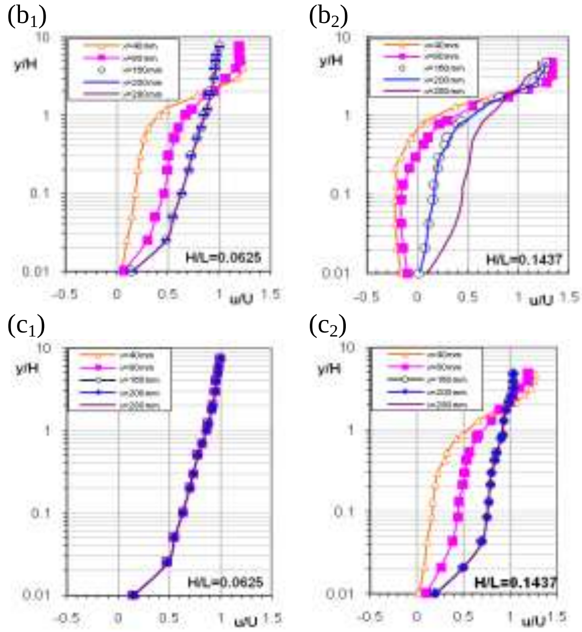


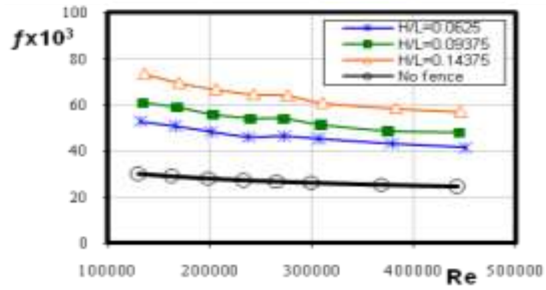
Figure 7: Velocity profiles at different positions along the mid plane of the test plate at various S/L ratios of *0.007 (a_1 & a_2), 0.375 (b_1 & b_2) and 1.0 (c_1 & c_2).*

Figure (8) shows the current results for the Fanning friction factor in the cases of air flow in the presence of a fence upstream of the plate. It is obvious that the friction factor is dependent on the Reynolds number, fence height and the distance between the fence and the plate. However, at the high (S/L) ratio the effect of the fence height on the friction factor is diminished. The present data of Fanning friction factor are correlated with the Reynolds number, H/L and S/L as follows:

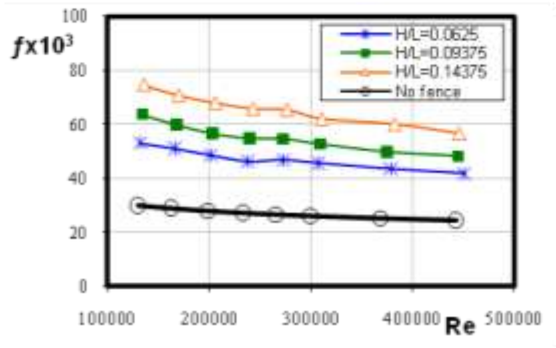
$$f_{corr} = 1.768\ (Re_L)^{-0.2041} (H/L)^{0.3926} (S/L)^{0.0041}$$

Both correlations of Nusselt number and Fanning friction factor are valid for Reynolds number ranging from 1.3×10^5 to 4.5×10^5, (H/L) ratio from 0.0625 to 0.1437 and (S/L) from 0.007 to 1.0. The correlated and the experimental data for both the average Nusselt number and Fanning friction factor within the investigated ranges of the different parameters are shown in Fig. (9). Maximum deviations of ± 12% and ± 8% for the Nusselt number and friction factor respectively.

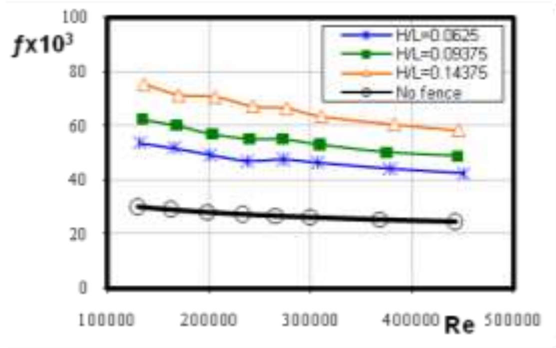
(a) S/L = 0.007



(b) S/L = 0.375



(c) S/L = 0.6875



(d) S/L = 1.00

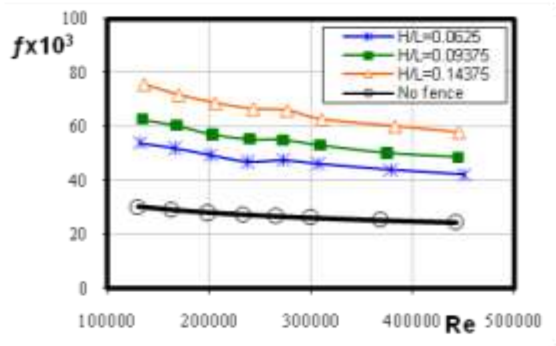
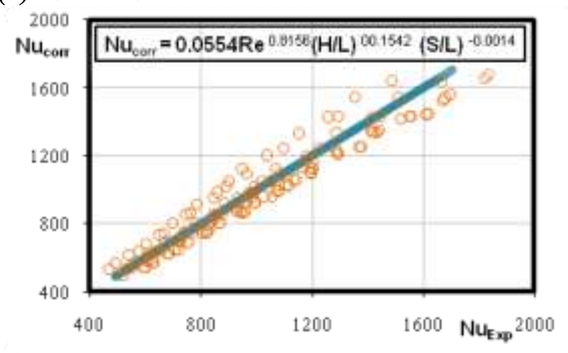


Figure 8: Variation of the Fanning friction factor as a function of the Reynolds number of different flow arrangements.

Finally, the thermal performance benefit of using a fence upstream of the plate is evaluated. The evaluation procedures are based on the condition of the equal mass flow rate of the free air stream. First, the ratios (Nu/Nu_o) and (f/f_o) at the different investigated parameters were determined. Here the subscript (o) in the Nusselt number and friction factor denotes to the case of flow without a fence. In this context, a maximum Nusselt number enhancement ratio (Nu/Nu_o) of 1.7 is achieved corresponding to a friction factor ratio (f/f_o) of 2.5. Then the thermal efficiency ratio [$\eta = (Nu/Nu_o) / (f/f_o)$] was plotted versus the Reynolds number as presented in Fig. (10). In general, it can be seen that the thermal efficiency ratio reduces with the increase in H/L or S/L ratios. Additionally, the fence with H/L = 0.0625 presents the best thermal performance; however, it provides the lowest Nusselt number. This owes to the low flow friction that is related to this fence arrangement.

(a) Nusselt number correlation



(b) Friction factor correlation

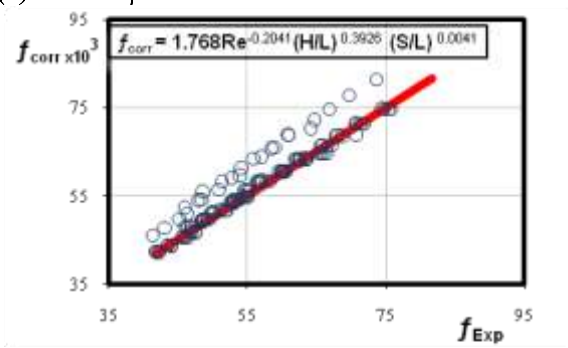
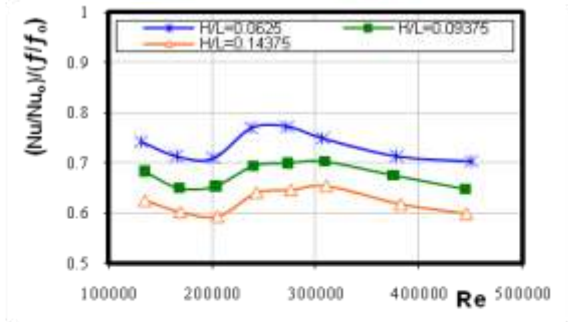
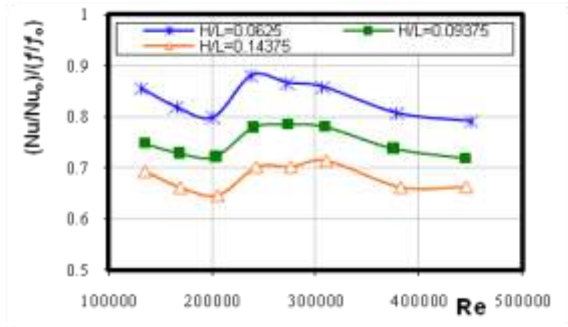


Figure 9: Correlations of the present experimental data.

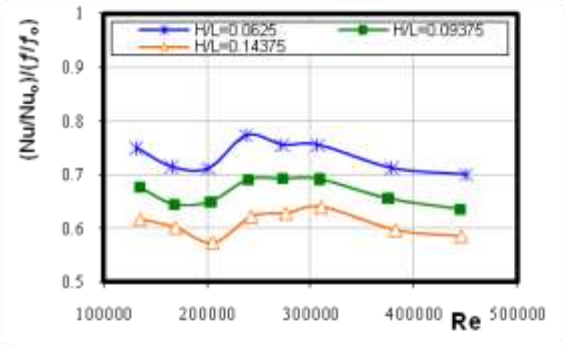
(a) S/L = 0.007



(b) S/L = 0.375



(c) S/L = 0.6875



(d) S/L = 1.00

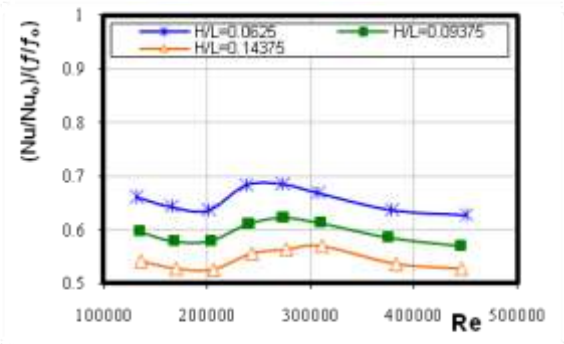


Figure 10: The thermal performance under the condition of equal mass flow rate of the air stream for different configurations.

IV. CONCLUSIONS

Experimental investigations of the heat transfer and flow friction for turbulent air flow over a hot plate that is placed downstream a fence are conducted successfully. The experiments covered a wide range of the Reynolds number from 1.3×10^5 to 4.5×10^5 and different geometric parameters including fence height and the distance between the fence and the plate. The conclusions of the study are summarized as follows:

- The results of the flows without fence show very good agreements with other published correlations for both the Nusselt number and the friction factor.
- There is a significant enhancement in the heat transfer associated with the increase in the friction factor in the cases of the presence of a fence in front of the hot plate. This enhancement in the heat transfer increases with the increase in the Reynolds number.
- The highest H/L ratio used in this work provides the largest heat transfer enhancement. The enhancement in heat transfer decreases as the distance between the fence and plate increases, in general.
- New correlations for the Nusselt number and friction factor are obtained, which is valid within the investigated range of the considered parameters.
- A maximum enhancement in the average Nusselt number of 70% is achieved at the condition ($Re=1.3\times10^5$, H/L = 0.1437 and S/L = 0.375). Whereas, this thermal enhancement is associated with an increase in the friction factor by 150%.
- Based on the equal mass flow rate condition, the fence with H/L = 0.0625 produces the best thermal performance.

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