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Axisymmetric numerical investigation of the heat transfer enhancement from a heated plate to an impinging turbulent axial jet via small vortex generators

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ABSTRACT

The consequences of installing one or two vortex generators on a flat plate under axisymmetric conditions are presented in this work in order to analyse if heat transfer from the plate can be enhanced. Two different configurations have been considered to optimise the radial location of the vortex generators which can improve the heat transfer in comparison with a flat plate without them. To that end, we have conducted several numerical simulations of a turbulent jet impinging against a plate with one or two small tabs and the heat transfer from the plate quantified in terms of the Nusselt number. A jet Reynolds number of 23,000 and a nozzle-to-plate distance of 2 nozzle diameters were used throughout the study. Thanks to a parametric study, with the tab positions as parameters, we obtain different response surfaces which will help us to identify the optimal tab configurations. After that optimization process, we shall show that, for certain radial locations of the tabs, the averaged heat transfer on the tabbed plate can be improved up to around 4.5% with just a 2% of more pumping power due to pressure losses on the tabs. Furthermore, it is even more remarkable the fact that the averaged heat transfer can even be enhanced with around 25% of less pumping power requirements than when the plate is completely flat. We shall show that this effect is due to the fact that the tabs reduce the friction losses on the tabbed plate and, consequently, the pumping power needs. On the contrary, the heat transfer at the stagnation point cannot be ever increased.

1. Introduction

Nowadays, heat transfer enhancement from a flat surface, by means of a jet impinging against it, is worth investigating because of its interest in many engineering applications, such as heat transfer of electronic cores [1], cooling material shaping processes [2], tempering of glass and metal sheets [3], furnace heating [5], heat transfer on windshields of vehicles [4] or heat transfer of blades in gas turbines [6]. Normally, the system under study is considered as a flat plate with a jet impinging normal against it. This problem called the attention of many researchers for decades. First studies about heat transfer from a flat surface to an impinging jet were reported by Baughn and Shimizu [7], where the Nusselt number profile along a plate was researched when a single circular turbulent air jet at ambient temperature impinged against it, and Cooper et al. [8], whose work established that the optimal distance from the plate to the jet $\widehat{H}$ to enhance heat transfer when $Re = 23,000$ was $\widehat{H} = 2\widehat{D}$, where $\widehat{D}$ was the jet diameter. In Lee and Lee [9], heat transfer was studied by using an elliptic cross sectional nozzle showing that stagnation heat transfer could be 15% higher than for circular exit section and also heat transfer enhancement was found everywhere. As well, heat transfer rate and uniformity can be enhanced by means of swirl generators with respect to circular nozzle, which is a very exploited arrangement (Ortega- Casanova and Granados-Ortiz [10], Ianiro et al. [11], and Huang and El-Genk [12]), or by using multichannel swirling jets, which allows the user to obtain a higher averaged heat transfer rate at all nozzle-to-plate distances studied, as shown in Ianiro and Cardone [13].

According to vortex generators, there is a huge number of researches looking for heat transfer enhancement when this kind of devices are used [see 14 for a huge review on the topic]. However, regarding the use of vortex generators on flat plates, a detailed review is included in what follows: Edwards and Alker [15], used cubes and delta-winglet vortex generators on a flat surface, getting important local heat transfer enhancement of 76%; in 1986, rectangular-winglet vortex generators on a flat plate where

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Nomenclature

Roman symbols

(r, z)	cylindrical-polar coordinates
ΔP	pressure drop
$\hat{-}$	dimensional variable
C_f	friction coefficient.
c_p	heat capacity
d_1	radial location of the first tab
d_2	radial location of the second tab
ds	representative grid size
GCI	Grid Convergence Index
K	thermal conductivity
L	height of the tab
N	total number of cells
Nu	Nusselt number
p_f	formal order of accuracy
p_o	observed order of accuracy
Pr	Prandtl number
Q	flow rate
q	heat flux
r	two grid sizes ratio
Re	Reynolds number
S	surface of the plate
y^+	turbulent wall distance
D	diameter of the impinging jet
e	internal energy per unit mass
G	generation of the indicated property due to mean velocity gradients
H	nozzle-to-plate distance
h	enthalpy
k	turbulent kinetic energy
P	pressure
R	radius of the impinged plate
T	temperature
U	jet mean velocity at the tube exit
V	velocity component
v'	velocity fluctuation component
Y	dissipation of the indicated property

Subscripts

0	Nusselt number at the stagnation point
A	area-weighted average property
eff	effective property
i, j, l	r, θ, z coordinates
p	pth grid
t	turbulent property

Greek symbols

δ	Dirac's delta
Γ	effective diffusivity
μ	viscosity
ν	kinematic viscosity
ρ	density
τ_w	wall shear stress
θ	azimuthal coordinate
ω	specific turbulent dissipation rate

Superscripts

$*$	tabbed to fin plate property ratio
fp	flat plate
tp	tabbed plate

studied by Turk and Junkhan [16]. They showed that by using different aspect ratios and angles of attack for the winglets, in general, the heat transfer can be improved with a favourable pressure gradient, achieving local spanwise-averaged heat transfer enhancements of 250%; both Jacobi and Shah [17], and Fiebig [18], found that longitudinal vortices showed better heat transfer characteristics and less pressure losses than transverse vortices. That is the reason why many surfaces are equipped with longitudinal vortex generators and, then, receiving more attention at this moment; in that sense, Lee et al. [19], simulated delta wing type longitudinal vortices, focusing on the effects on the boundary layer. They found that longitudinal vortices disturbed the turbulent and thermal boundary layer, which improved heat transfer due to anisotropy of turbulent intensity; in an air-cooled condenser, Du et al. [20], used four types of longitudinal vortex generators to enhance air-side heat transfer, and they found that the delta-winglet generators were the best of the five tested to enhance heat transfer; Sinha et al. [21], simulated the air flowing through fin-tube heat exchanger where rectangular-winglet where inserted to enhance heat transfer. By means of numerical simulations they found that the device performance improved with the increase of the winglet angle of attack up to a certain point and then it was going down; Wu and Tao [22], by means of experimental and numerical tests, for $Re \leqslant 2{,}000$, showed that the averaged Nusselt numbers on the plate increased with the increase of the attack angle of delta-winglet vortex generator in comparison with those of the flat plate; Tian et al. [23], carried out a numerical study on the laminar heat transfer from a flat-plate channel where both rectangular- and delta-winglets, with two different configurations, were used to increase the heat transferred from the channel and, by applying field synergy principle analysis, found that the rectangular performed better than the delta-winglets, being the highest increase of the Nusselt number around 45%; Min et al. [24], by means of numerical simulations, carried out a study on a combined longitudinal vortex generator, comprising two rectangular wings, one mounted vertically and the other horizontally at certain angles of attack, and found that by using the latter the Nusselt number increased around 20% in comparison with using only the vertical vortex generator; Caliskan [25], developed a new concept of both triangular and rectangular vortex generators, working the former better than the latter, and were tested in a rectangular channel for $3{,}288 \leqslant Re \leqslant 37{,}817$ being the increase in the Nusselt number around 50%; Skullong et al. [26], carried out an experimental investigation on the thermal performance enhancement in a solar air heater channel by combining wavy-groove and delta-wing vortex generators, and found that by adding the vortex generators, in comparison with the wavy-groove plate, the highest increase in the Nusselt number was around 45%.

Regarding the combined use of impinging jets and vortex generators, as in this work, at least to the authors knowledge, few previous works have been found. In that sense, it is worth mentioning the work done by Nakod et al. [27], where triangular-like vortex generators are located around the stagnation point of an impinging jet at $Re = 25{,}000$. Experimentally they studied the effect of the number of rows, radius of a row and number and inclination angle of vortex generators on the Nusselt number. In comparison with a flat plate, their better configuration gave an increase of 163% on the area-weighted average Nusselt number for a nozzle-to-plate distance of 2 nozzle diameters.

Other surface plate modifications have been also taken into account in order to enhance heat transfer. That is the case of, among others, Ortega-Casanova and Granados-Ortiz [10], and