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Review

Numerical simulation of the heat transfer from a heated plate with surface variations to an impinging jet

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ABSTRACT

The study of heat transfer between impinging jets and non-uniform heated plates is presented here to analyse if surface variations along the plates, (i.e. dimples, bumps, and bumps&dimples, as we study here), can improve the heat transfer phenomenon. To that end, numerical simulations of the impingement of two different types of axisymmetric turbulent jets on a non-flat plate, located at a known distance H from the jet exit, have been conducted. The cylindrical jet used, of diameter D, is created by a swirl generator nozzle that, depending on its configuration, can produce jets with high or low swirl intensity levels. Different values of non-dimensional nozzle-to-plate distance, H/D, have been studied, as well as different values of the Reynolds number, Re. To know whether or not surface variations along the plate improve the heat transfer between the impinging jet and the plate, our results are compared with those obtained when a flat plate is used.

Contents

1. Introduction

Jet impingement on heated surfaces is frequently used as a tool to enhance heat transfer between them, especially at the stagnation point. Heat transfer has also a major effect at the region where the jet impinges on the surface, due to the development of the boundary layer along the surface, where heat exchange processes take place. The interest of studying this heat transfer mechanism through impinging jets is owing to its many engineering applications, such as the heat transfer of blades in gas turbines [1], the cooling of electronic devices [2–6], the heat transfer on windshields of vehicles [7], or cooling in grinding processes [8], between others.

In all the industrial applications presented above, a jet impinges on a surface whose form depends on the particular application under study. Normally, the surface is considered as a flat plate with

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Nomenclature

c_p	fluid heat capacity
CFD	computational fluid dynamics
ds	differential surface element
D	diameter of the jet
e	specific internal energy
G	production of turbulence due to mean velocity gradients
GCI	grid convergence index
h	enthalpy
H	distance from the nozzle to plate
k	turbulent kinetic energy
K	thermal conductivity of the fluid
L	swirl parameter
LDA	laser doppler anemometry
n	nth computational grid
Nr	radial number of nodes
Nu	Nusselt number
$\overline{Nu}$	area-weighted average Nusselt number
Nz	axial number of nodes
p	pressure
PIV	particle image velocimetry
Pr	Prandtl number
q	heat flux
Q	flow rate
$r,\ \theta,\ z$	radial, azimuthal and axial coordinates
R	radius of the impinged surface
Re	Reynolds number
S	impinged surface
T	temperature
$u,\ v,\ w$	radial, azimuthal and axial velocities
UDF	user-defined function
v'	velocity fluctuations
$\vec{V}$	velocity vector
W_c	characteristic velocity
y^+	dimensionless wall distance
Y	turbulent dissipation

Symbols

$\mathcal{N}$	Nusselt coefficients ratio
$\overline{\mathcal{N}}$	area-weighted average Nusselt coefficients ratio
$\mathcal{R}$	nozzle #1
$\mathcal{S}2$	nozzle #2

Greek symbols

δ	Dirac's delta
Δ	representative mesh size
Δz_p	position of the first node from the plate
ϵ	turbulent kinetic energy dissipation
γ	grid refinement factor
Γ	effective diffusivity
μ	fluid viscosity
ν	fluid kinematic viscosity
ω	specific turbulent dissipation rate
ρ	fluid density
σ	standard deviation. Heat transfer uniformity
τ	computational time
ε	relative error
ϱ	observed order of accuracy

Subscript

0	magnitude evaluated at $r = 0$
a	approximate
coarse	coarse grid
e	Richardson extrapolation value
fine	fine grid
it	iterations
eff	effective
ext	extrapolate
$i,\ j$	coordinate direction in compact tensor notation
j	jet
p	plate
t	turbulent

Superscript

b	bumped plate
d	dimpled plate
db	dimpled&bumped plate
f	flat plate

the jet impinging perpendicular on it (see 9], for a review). However, less studies have been carried out on non-uniform surfaces. In Ekkad and Kontrovitz [10], can be found an experimentally study of the effect of dimple location in a plate and the effect of dimple depth, for different jets with different Reynold numbers. A similar study can be found in Kanokjaruvijit and Martinez–Botas [11], where various jets impinge on a staggered array of hemispherical dimples with the consideration of various parametric effects, such as Reynolds number, jet-to-plate distance, depth of the dimples, and curvature of the dimples for both impinging on dimples and impinging on flat separation portions, showing that the variations on the shape of the plate (concretely with shallow dimples) are able to enhance the heat transfer up to a 70% with respect to the plate one and showing that dimples are more effective when a strong crossflow is present.

Other interesting studies of the shape variation, specifically in terms of seeing how one single dimple/bump is relevant, could be the one by Imbriale et al. [12], where the heat transfer between a concave surface and a row of air jets impinging on it is studied by an experimental study by varying the inclination of the jets, pitch, impinging distance, Mach and Reynolds numbers. In Öztekin et al. [13], an experimental and numerical study is carried out to investigate the turbulent slot jet impingement cooling characteristics on concave plates (big dimple) by varying the surface curvature and the Reynolds number (around ten times lower Reynolds numbers than those used in the present paper). The more relevant outcomes of this research were that both the average and stagnation point Nusselt numbers decrease when the nozzle-to-surface distance increases, both the average and stagnation point Nusselt numbers increase when Reynolds number increases, and it is disclosed that the surface curvature increases the average Nusselt number from a depth value.

The analysis of a bump in a flat plate can be seen in Zhang et al. [14], combining both PIV and numerical simulation. In this paper, the single jet impinges on the protrusion and the local Nusselt number increases with its presence, obtaining relevant conclusions such as the local Nusselt number increases when the depth increases, and the average Nusselt number increases with bump relative depth and the jet Reynolds number.

Another interesting variation on plate, that also certifies how important the selection of its configuration is, in heat transfer terms, is the inclination. This particular variation is not going to be treated in the present research, but can be noticed in studies such as Beitelmal et al. [15], where an experimental analysis of