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Influence of screen solidity ratio on heat transfer upon a cylinder impinged by a rectangular jet

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ABSTRACT

The present work studies the enhancement of heat transfer on a cylinder impinged by a rectangular jet in presence of a metallic grid on the slot exit. The experiments are carried out to cool a smooth cylinder, electrically heated, with a rectangular jet of air, at three Reynolds numbers in turbulent flow, i.e. Re = 5100, 10,600 and 15,300, where the Reynolds number is defined with the cylinder diameter. Three metallic grids, identified by the French classification as NF06-10-20, are employed with the solidity ratio ranging from 24.3% to 67.7%, and the same diameter of the mesh filament (0.6 mm). Fluid dynamic measurements, performed with a hot film anemometer, are done to justify the thermal results. Heat transfer measurements are presented as local and mean Nusselt numbers. The comparison with the case without grid, indicated as NF00, is done at the same mass flow rate of the jet and the same power consumption of the wind tunnel to move the jet. The main goal of the paper is to evaluate how the solidity ratio of the metallic grids influences the heat transfer.

1. Introduction

Impinging jets are used to cool, heat or dry surfaces because they provide an efficient mean of heat and mass transfer [1]. Impinged flat surfaces have been the subject of many researches and the literature on this kind of surfaces is too vast to be mentioned. The peculiarities of the jet impingement on convex surfaces as cylinders are different because the surface curvature produces the well-known Coanda effect, and the present paper reviews only the impingement upon cylindrical surfaces. Since the impingement upon a cylinder relates to velocity and turbulence evolution of rectangular or two-dimensional jets, the paper reviews only rectangular jets impinging cylinders.

The flow of a rectangular jet has been investigated with the aim of understanding the evolution of velocity and turbulence. In the works [2–6] the jet interacts with the stagnant fluid just after the exit, and two zones are defined in comparison to the potential core, where the velocity on the centerline maintains equal to the exit one. The first one, before the end of the potential core, is the zone of flow establishment and the second one, after the end of the potential core, is the zone of established flow or fully developed region. Moreover, two regions of flow are present in the zone of flow establishment: the region of mixing fluid at the border with the stagnant fluid, and the potential core in the inner part of the jet flow.

The previous flow evolution has been updated with experiments showing that is possible to distinguish three types of flow in the region from the slot exit to the end of the potential core [7–12]. The first one is the flow with negligible disturbances, previously named undisturbed region of flow in [7–11], where the instant and the average height of the jet remain constant [12]. The second one is the flow with small disturbances, where the height of the jet increases or decreases slightly without formation of vortices [12]. The third one is the flow with large disturbances, where the coherent vortices are present. After the potential core the disturbances are very large and they determine the vortices breakdown. Some preliminary numerical simulations started the comparison with the experiments to capture the first type of flow [13], which depends on the Reynolds number, while independent numerical simulations were carried out in a round jet [14]. The main conclusion is that velocity and turbulence evolutions in a free jet flow depend on the exit values but also on the distance of the impinged object.

Objectives of the research on heat transfer upon a cylinder, impinged by a rectangular jet, are the optimal distance that maximizes the heat transfer [15–18], the ratio between jet height and cylinder diameter, and the dependence from the angle of impingement [19–24]. Heat transfer characteristics on a cylinder, impinged by a rectangular jet, are improved by introducing two, three or

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Nomenclature

Latin

A	generic surface, m^2
d	diameter of mesh filament, m
D	diameter of cylinder, m
h	convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
H	slot height, m
I	electrical current, A
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
L	length of cylinder or slot width, m
M	grid mesh size, m
n	number of thermocouples
N	tests number
NF	French classification of grids
Nu	Nusselt number
$\dot{Q}$	thermal power, W
R	electrical resistance, Ω
Re	Reynolds number
s	standard deviation of velocity, $m\,s^{-1}$
S	distance of cylinder from slot exit, m
S	grid fill factor
SR	solidity ratio
t	time, s
T	temperature, K
Tu	absolute turbulence intensity
u	velocity, $m\,s^{-1}$
$\dot{V}$	volume flow rate, $m^3\,s^{-1}$
x	coordinate, m
y	coordinate, m

Greek

Δ	difference
ε	emissivity
θ	angular position, °
ν	kinematics viscosity, $m^2\,s^{-1}$
σ	Stefan–Boltzmann constant, $W\,m^{-2}\,K^{-4}$

Subscripts

a	air
av	average, based on the velocity at the slot exit
abs	absolute
cyl	cylinder
fc	forced convection
i	generic position
k	conduction
loc	local
m	mean
nc	natural convection
r	radiation
ref	reference value
rel	relative value

more cylinders to be cooled [25–28], pulsating the impinging jet [29], and introducing fins around the cylinder [30–33].

The enhancement of heat transfer can be obtained by exciting or altering turbulence [34–35], acoustic excitation [36], application of swirl [37–38], introduction of streamwise vortices generators [39] and perforated plates between the nozzle and the target plate [40], or by installing mesh screens within the nozzle [41–42]. Turbulence promoters can modify the flow characteristics and represent a passive technique, according to [43], where the techniques to enhance heat transfer are classified as passive if they do not require external power.

Turbulence can be increased by screens, grids and perforated plates, with a consequent downstream decrease, according to the degeneration law, [44–46].

The main conclusion on the heat transfer of a rectangular jet of air impinging a cylinder is the close connection with the turbulence level in the jet, as reported in [47]. The turbulence of a free jet increases with the distance from the jet exit because of the jet evolution, and local-to-average Nusselt number increases as well, both reaching the maximum at a distance of about $S/H = 8$. In presence of the grid on the slot exit, local Nusselt number has the maximum just after the grid, then decreases to a minimum at $S/H = 4–5$, in agreement to the degeneration law of turbulence and then increases again up to $S/H = 10$. In [48] the mainstream turbulence of impinging jets has been enhanced using square fractal grids, i.e. a grid with a square pattern repeated at increasingly smaller scales.

The aim of the present work is to evaluate the influence of the solidity ratio on the heat transfer upon a cylinder impinged by a slot jet in presence of different grids, positioned on the exit of the slot. The distance between the impinged cylinder and the slot exit is variable in order to find the maximum local or average Nusselt numbers. The previous experimental apparatus has been modified to reduce the turbulence intensity on the flow at the slot exit.

2. Experimental apparatus

The jet flow is generated by a small wind tunnel with the fan driven by an inverter in order to control the mass flow rate. The radial fan has an electric power of 1.45 kW and a maximum volume flow rate of 0.15 $m^3\,s^{-1}$. A smooth diverging duct is located after the fan and before the settling chamber (square section of 135 by 135 mm).

The settling chamber employed in the experiments [47] was composed of three parts, with an overall length of 480 mm, connected one to each other by flanges. In the present experiments the first part of the settling chamber, just after the diverging duct, 150 mm long, has been modified dividing the duct in two elements, coupled by a new flange, in order to reduce the turbulence of the jet on the slot exit. Then, the calm duct is now composed of four parts and new metallic grids have been inserted along the entire settling chamber, in the three joints among the four parts, to decrease the turbulence. An ensemble of honeycombs is located in the first section of the calm duct, at the exit of the divergent. Fig. 1 presents the sketch of the wind tunnel employed in [47] and the details of the new settling chamber employed in the present work.

Three metallic grids have been chosen and arranged according to a cascade, taking into account that the turbulence damping ability of a screen increases with decreasing the mesh size for a given solidity and that subcritical screens give a large turbulence reduction, although their penalty in terms of pressure drop. The elements of the three grids are summarized in Table 1, according to the French classification. The distances between a grid and the following one have been checked to assure a dimensionless length $(x/M) > 20$ or $(x/d) > 500$, where M is the mesh size and d the grid diameter. The turbulence intensity at the wind tunnel exit is now smaller than 0.5%. The converging duct, which follows the last section of the settling chamber, has a contraction ratio of 13.5:1, an angle of 30° and a rectangular final area of 135 mm by 10 mm.