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Effect of the grid geometry on the convective heat transfer of impinging jets

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ABSTRACT

Passive methods are recognized as one of the most efficient means to achieve high heat and mass transfer in impinging jets. In a recent study, Cafiero et al. (2014) demonstrated the effectiveness of square fractal grids (SFGs, obtained repeating the same square pattern at increasingly smaller scales) in terms of heat transfer enhancement when locating the grid in correspondence of the nozzle exit section. Indeed, the capability of producing turbulence at multiple scales and the possibility of tuning the peak in the turbulence intensity profile as a function of the grid geometric parameters are both extremely appealing for heat transfer enhancement purposes. In this study, the effect of the grid geometry on the convective heat transfer rate of impinging jets is assessed and discussed. Three main effects are taken into account: the grid thickness ratio (obtained by varying the thickness of the first iteration of the SFG), the effect of the secondary grid iterations and the choice of the initial pattern. It is demonstrated how a larger thickness ratio, which in the present case corresponds to an anticipated location of the peak in the turbulence intensity profile, is beneficial to get a spotted high convective heat transfer rate at short nozzle to plate distances. Either the use of a single square grid, or the choice of a different initial pattern (for example a circular fractal grid) is instead indicated when it is desirable a uniform distribution of the convective heat transfer rate.

1. Introduction

The versatility and capability to achieve high heat and mass transfer are the main peculiar properties that make impinging jets extremely appealing in countless application as glass tempering [2], cooling of electronic devices [3], food processing [4], turbine blades cooling [5] and many others; they are generally used where the necessity to achieve a high convective heat transfer joins the need of a uniform scalar transfer. However, especially with the growth of the electronic market, the demand for a high spotted heat transfer continuously increases. In this case the uniformity in the heat transfer rate is not required, thus opening the path to numerous solutions that aim to a localized enhancement of the convective heat transfer rate.

Many efforts have been spent over the years to address the main agents that play a key-role in the convective heat transfer of impinging jets [6–10]. In particular it results to be a complex combination of several fluid dynamics and geometric parameters: the jet Reynolds number (Re), the Prandtl number (Pr), the upstream turbulence level (Tu), the nozzle geometry (length L, diameter d), the impingement angle between the nozzle axis and the impinging plate and the nozzle exit section to plate distance (Y/d). In the case of a jet issuing through a straight long pipe, Hoogendorn [11] proposed a correlation for the stagnation point Nusselt number Nu_0, being $Nu = hd/k$ with h convective heat transfer coefficient and k the fluid thermal conductivity coefficient, as a function of the Reynolds number based on the pipe diameter and of the turbulence intensity level:

$$\frac{Nu_0}{Re^{1/2}} = 0.65 + 2.03\left(\frac{TuRe^{1/2}}{100}\right) - 2.46\left(\frac{TuRe^{1/2}}{100}\right)^2 \tag{1}$$

Two possible leads can be then followed to enhance the local convective heat transfer rate: tampering either with the mainstream turbulence or with the jet entrainment rate and its vortical structures (increasing the flow rate and as a consequence the effective Reynolds number). The use of swirling jets [12], chevron [13] or tabbed nozzles [14], lobed [15] or elliptic [16] nozzle exit sections are only few of the adopted solutions to achieve a higher

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Nomenclature

Roman letters

Y	axial coordinate, m
$\dot{m}$	mass flow rate, kg/s
$\dot{q}_j$	joule heating heat flux, W/m^2
$\dot{q}_r$	radiative heat flux, W/m^2
$\dot{q}_{nc}$	natural convection heat flux, W/m^2
$\dot{q}_{tc}$	tangential conduction heat flux, W/m^2
$\overline{Nu}$	average Nusselt number over a target area, dimensionless
Bi	$= hs/k_f$ Biot number, dimensionless
d	short pipe nozzle diameter, m
h	convective heat transfer coefficient, W/m^2/K
I	current intensity, A
k	fluid thermal conductivity, W/m/K
k_f	foil thermal conductivity, W/m/K
L	short pipe nozzle length, m
L_0	length of the first grid iteration side, m
L_N	length of the Nth iteration, m
L_r	$= L_0/L_N$ length ratio between the first and Nth iteration, dimensionless
N	number of grid iterations, dimensionless
Nu	$= hd/k$ Nusselt number, dimensionless
Nu_0	Nusselt number evaluated at $r/d = 0$, dimensionless
Pr	$= \nu/\alpha$ Prandtl number, dimensionless
r	radial coordinate, m
R_L^j	jth iteration length ratio, dimensionless
R_t^j	jth iteration thickness ratio, dimensionless
Re	$= V_j d/\nu$ Reynolds number, dimensionless
s	foil thickness, m
t_0	thickness of the first grid iteration, m
t_N	thickness of the Nth iteration, m
t_r	$= t_0/t_N$ thickness ratio between the first and Nth iteration, dimensionless
T_w	wall temperature, K
T_{amb}	ambient temperature, K
T_{aw}	adiabatic wall temperature, K
Tu	turbulence intensity level, dimensionless
V	voltage, V
V_j	fluid velocity, m/s
x^*	wake interaction lengthscale, m
x_{peak}	streamwise location of the peak in the turbulence intensity profile, m

Greek letters

α	fluid thermal diffusivity, m^2/s
Δp_0	head loss, Pa
ϵ	foil emissivity coefficient, dimensionless
ν	fluid kinematic viscosity, m^2/s
ρ	fluid density, kg/m^3
σ	Stefan–Boltzmann constant, W/m^2/K^4
σ_{Nu}	spatial variance of the average Nusselt number over a target area, dimensionless
θ	azimuthal coordinate, °

Acronyms

CFG	circular fractal grid
EDM	electrical discharge machining
FG	fractal grid
IR	infrared
JWT	jet without turbulator
SFG	square fractal grid
SG	square grid

entrainment of the ambient fluid towards the jet axis, which is directly related to the scalar transfer [17].

The use of grids or plates is instead a typical mean to enhance the turbulence intensity level of impinging jets. Gori and Petracci [18] assessed the effect of the turbulence intensity level on the convective heat transfer rate of a slot jet impinging on a cylinder. They found that when locating the grid between the slot jet exit section and the cylinder, owing to the grid generated turbulence, a sensitive increment in the turbulence intensity level at the impingement surface can be perceived. However, at a streamwise location beyond 10 slot widths the effect of the turbulence generated by the grid is completely dissipated.

Zhou and Lee [19], investigating the heat transfer of an impinging sharp edged orifice, proposed the use of a mesh screen located between the impinging plate and the orifice. They found a small increment of the convective heat transfer rate (about 3–4%), especially at short nozzle to plate distances. Zhou et al. [20] measured a more consistent increment of the stagnation point heat transfer rate when locating a grid right ahead of the orifice exit section (about 27% at $Y/d = 2$).

In a recent work, Cafiero et al. [1] proposed the use of fractal grids in circular impinging jets to enhance the convective heat transfer rate. They compared the performances of such devices with those obtained with a regular grid (with the same blockage ratio) and with the jet without turbulence promoter (JWT). The comparison was carried out under the same power input, thus with the same product of the volumetric flow rate times the pressure drop across the grid. Especially at short nozzle to plate distances, the increment that can be achieved using the fractal stirrers with respect to a regular grid is extremely significant (more than 40% in correspondence of the stagnation point and a nozzle to plate distance equal to 2). Cafiero et al. [21,22] investigating the flow field features of submerged jets equipped with fractal grids (FGs), addressed the strong increment of the convective heat transfer rate to their significantly larger entrainment rate. Indeed, the introduction of the grid is responsible for the production of streamwise vorticity. Its effect is twofold: first, since the streamwise vortices arise as a direct consequence of the presence of the grid, they lead to an immediate increment of the entrainment rate; moreover, these structures are dissipated at larger streamwise location (more than six nozzle diameters) with respect to the ring vortices that characterize the JWT case. Another element that plays a key-role in the convective heat transfer enhancement process of fractal jets must be addressed to their peculiar turbulence intensity profile. Indeed, striking differences can be spotted comparing the turbulence intensity profiles along the grid centreline in the case of regular or fractal grids. In the former case, a peak can be retrieved right beyond the grid, thus with a very short production region; beyond that point, the turbulence intensity level rapidly decays. Fractal grids produce turbulence at multiple scales thus leading to a more elongated production region, whose extent is a function of the grid geometry [23], a peak and a decay region, which can be modelled as exponential [24]. Mazellier and Vassilicos [24] found that an important scaling parameter for the FGs is the wake interaction lengthscale $x^* = L_0^2/t_0$. They demonstrated that in the case of wind tunnel experiments, the location of the peak in the turbulence intensity profile scales as $x_{peak} \approx 0.45 \cdot x^*$. Gomes-Fernandes et al. [25] proposed a correction of this scaling law accounting for the upstream turbulence level. Cafiero et al. [21] demonstrated that in the case of free fractal jets (i.e. without the impinging plate),