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Numerical simulation of the optimal spacing for a radial finned tube cooled by a rectangular jet. I – Average thermal results

Ivano Petracci, Luca Manni, Fabio Gori[*]

Department of Industrial Engineering, University of Rome "Tor Vergata", Rome, Italy

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ABSTRACT

The present work investigates the average heat transfer on a finned cylinder cooled by a rectangular jet of height H. The diameter of the external cylinder, without fins, is D and the cylinder to slot ratio D/H is equal to 1. Numerical simulations are carried on with two turbulent models, RNG $k-\varepsilon$ and SST $k-\omega$. The jet flow can be characterized by the Reynolds number, defined with the diameter of the external cylinder without fins, D, or with the hydraulic diameter of the rectangular slot, $D_{\mathrm{hydr}} \approx 2H$. Two turbulent flows are investigated at $Re_D = 7100$, or $Re_{D\mathrm{hydr}} = 13{,}200$, and at $Re_D = 19{,}700$, or $Re_{D\mathrm{hydr}} = 36{,}700$. The main goal of the paper is to evaluate the optimal spacing, s, between the fins, and the optimal slot-to-cylinder distance, S/H, which maximize the average heat transfer on the finned cylinder. The optimization process is performed for a pitch of 3 mm and at a given value of the fin volume. The numerical simulations show that an optimal configuration is obtained when the ratio s/l of the spacing, s, to fin height, l, is maximum, and the cylinder is set at the slot-to-cylinder distance, $S/H = 3$.

1. Introduction

Enhancement of heat transfer is very important because many industrial processes are requesting an increasing amount of energy. The techniques of enhancement are classified as passive if they do not require power, or active if they need additional external energy [1].

Fourteen different enhancement techniques are described in Refs. [2,3], and, among the convective heat transfer ones, the impinging jet is considered very efficient because of the flow concentration and the limited expenses required to move the relatively small amount of fluid. On the other hand, if the focus is upon the target to be cooled, or heated, by the impinging fluid, an extended surface is considered as a passive technique, which is able to augment the convection heat transfer. In conclusion, the use of an impinging jet upon an extended surface, such as a finned cylinder, is a convenient way to realize an enhancement compound technique.

Heat transfer between finned cylinders and cross-flow of air has been extensively studied to improve the cooling of airplane engines and fin-and-tube heat exchangers. A trade-off is requested between the increase in the surfaces and the demand of smaller systems. Most of the articles of the literature, e.g. Refs. [4–6], have dealt with an air flow with larger dimension than the finned cylinder to be cooled. This flow condition is mentioned in this paper as "full flow" and is quite different from the case where the ratio between the cylinder diameter, D, and the jet height, H, i.e. D/H is greater or equal to 1, called "jet flow". Heat transfer on flat surfaces, impinged perpendicularly by a circular air jet [7] has been investigated with modified arrays of fin-type extensions.

On the other hand, literature presents few articles dealing with a slot jet impinging convex geometries with extended surfaces. A detailed overview of theoretical, experimental and numerical works is carried on in the next section, with the aim of investigating the optimization of the finned surface on a cylinder in order to maximize the heat transfer. Two subsections illustrate the state of art of the literature concerning the optimization of a finned cylinder impinged by a "full flow" and by a "jet flow".

2. Literature overview and aim of the work

2.1. Optimization of annular fins with rectangular profile, impinged by a "full flow"

In the following survey only a single fin or an assembly of radial fins with rectangular profile are examined. The main geometrical dimensions of the extended surface are reported in Fig. 1.

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[*] Corresponding author.
E-mail address: gori@uniroma2.it (F. Gori).

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Nomenclature

Latin

A	generic surface, m^2
Bi	Biot number
c	specific heat transfer, J kg^{-1} K^{-1}
D	diameter of cylinder, m
h	convective heat transfer coefficient, W m^{-2} K^{-1}
H	slot height, m
k	turbulence kinetic energy
l	fin height, m
L	length of cylinder or slot width, m
n	tests number
Nu	Nusselt number
p	fin pitch, m
PR	performance ratio
$\dot{Q}$	heat transfer, W
r	radius, m
Re	Reynolds number
s	distance between two fins, m
S	distance of cylinder from slot exit, m
t	fin thickness, m
t	time, s
T	temperature, K
u	velocity, m s^{-1}
V	generic volume, m^3
$\dot{V}$	volume flow rate, m^3 s^{-1}
x	coordinate, m
y	coordinate, m
z	coordinate, m

Greek

ε	fin effectiveness, turbulence energy dissipation rate
η	fin efficiency
κ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, kg m^{-1} s^{-1}
ν	kinematics viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
ω	dissipation per unit turbulence kinetic energy

Subscripts

a	air
b	base
e	external
fc	forced convection
hydr	hydraulic diameter
i	internal, generic position
j	generic position
lat	lateral
opt	optimum
t	tube
tot	total

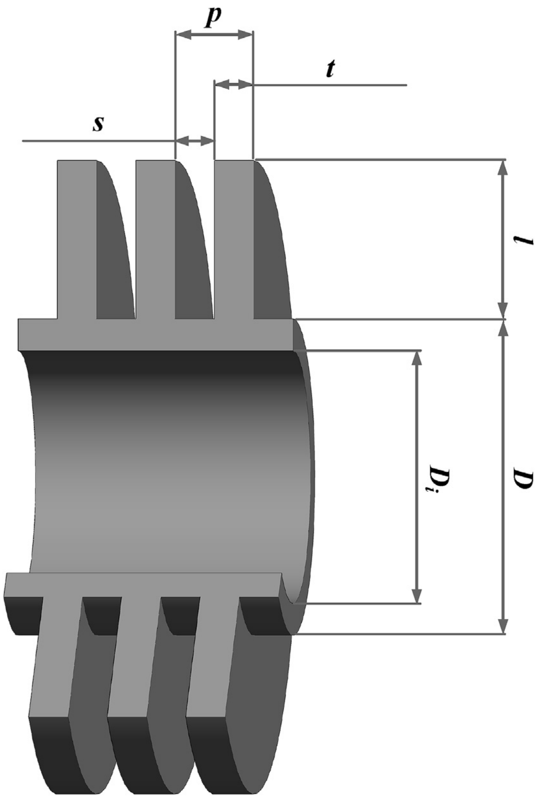

Fig. 1. Finned cylinder.

Kraus et al. [8] quoted the work of Harper and Brown [9] as the first significant attempt to provide a mathematical analysis of the fin efficiency for a circumferential fin with uniform thickness. Later on, Schmidt [10] considered the same profile of Ref. [9], stating that the minimum material is required if the fin temperature gradient (from base to tip) is linear, showing how the fin thickness of each type of fin needs to vary in order to obtain this result. The predicted shapes were not practical to be manufactured and he showed the optimum dimensions for longitudinal and radial fins of constant thickness (rectangular profile).

Brown [11] obtained the optimum dimensions of an individual radial fin with rectangular profile, providing a graphical representation in a practical working range. The expression of the heat, dissipated by the radial fin, versus its thickness was investigated for constant fin volume. The final equation relates the optimum width, and length of a uniform annular fin, with parameters as thermal conductivity, bore radius, heat-transfer coefficient between fin and coolant, and temperature difference between fin bore and coolant.

The analysis of Brown [11] employed the assumptions proposed by Murray [12] and Gardner [13] referred to as the Murray–Gardner assumptions, which are:

1. The heat flow in the fin and its temperature remain constant with time.
2. The fin material is homogeneous, its thermal conductivity is isotropic and constant.
3. The convective heat transfer coefficient on the fin is constant and uniform over the entire surface of the fin.
4. The temperature of the medium, surrounding the fin, is uniform.
5. The fin thickness is small compared to its height and length, so that temperature gradients across the fin thickness and heat transfer from the edges of the fin can be neglected.