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A numerical method for the efficient design of free opening hoods in industrial and domestic applications

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ABSTRACT

In this paper, a numerical method for the design of free opening hoods in industrial and domestic applications is presented. The method is based on a CFD (Computational Fluid Dynamics) formulation for the capturing velocity assessment in capturing hoods which account for geometrical and viscous effects. Different hoods, which differ in shape (square and rectangular) and size, are created and their velocity field determined numerically. A comparison between the obtained numerical results and results obtained from empirical formula found in literature are presented and the discrepancy between them highlighted. Then, starting from the numerical results, a new equation, which takes into account viscous effects, is proposed, together with its range of applicability and its level of confidence. The suggested equation is simple in nature and it can be user friendly for the designer, in order to predict the air velocity in front of a capturing hood, and therefore to correctly and efficiently design the ventilation system.

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1. Introduction

In recent years, a renewed interest in the field of capturing hoods for industrial and civil application has grown. These systems, which can be found in many applications (such as chemical industry, food industry, industrial warehouses and buildings), are used to convey exhaust gases, polluted or contaminated air, humid air, etc. from the inside to the outside of the environment in which it is installed. Hood design must fulfill a number of requirements in order to ensure: (i) a correct fluid dynamic performance, (ii) space requirement which is as low as possible and (iii) the minimum energy consumption of the installed auxiliary devices, such as the extractor fans. In particular, energy consumption and savings in hood applications have recently gained attention in Europe. In a recent European Directive (2009/125/EC) [1], eco-design requirements for products that can have a significant environmental impact and, at the same time, can present significant potential for improvement through innovative design have been set. In particular, the European Directive preparatory studies show that the energy consumption of the hood must be reduced by improving the energy efficiency (stand-by/off-mode) and fluid dynamic efficiency (volume flow rate related to the electric power consumption of the extractor fan). Therefore, to improve the fluid dynamic efficiency, the study of the performance of hoods has to be carried out and studied in detail.

A number of papers in which the applications of capturing hoods are studied can be found in literature. In particular, some main types of capturing hoods are studied. *Local hoods for dust collection* are an important part of machine tools [2]. In this application, the hood is positioned very near to the source of effluents to be captured. For the other three kinds of applications, the hood can not be installed near the source of effluents to allow the operator movements. *Capturing hoods in food applications* are widespread both in industrial plant and in domestic application. Kitchen capturing hoods are used to achieve a comfortable environment by keeping the odors caused by cooking confined [3,4], thanks to a suitable arrangement of the openings. Capturing hoods located above hobs can also be used to accommodate extracting fans, which have to guarantee the correct flow rate and the sufficient head for filter pressure drop. Hoods are also used in industrial devices for food production and treatment. For instance, in bread rotary ovens external hoods are used to capture the hot vapors leaving the cooking chamber when the oven doors are opened. *Canopy hoods* are an important tool for operator protection when harmful or toxic substances are used [5, 6, 7]; in these cases the extraction capacity of the fan is to be linked to the degree of openness of the canopy hood. Other applications are cataloged in terms of fluid dynamic features, such as capturing hoods used within ducts in which there

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Nomenclature

a,b,c,d	model coefficient
B	blockage damping term
D	diameter
F	shape factor
g	coefficient of Garrison Equation
f_1	blockage coefficient
f_2	blockage damping coefficient
H	hood height
k	turbulent kinetic energy
L	hood length
N	refinement level
p	pressure
Q	volume flow rate
Re	Reynolds number
S	hood opening area
v	velocity
W	hood width
y	distance along the hood axis

Greek letters

α	coefficient of Fletcher Equation
β	coefficient of Fletcher Equation
δ	turbulence boundary layer
ε	dissipation of turbulent kinetic energy
μ	viscosity
ρ	density

Acronyms

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DVE	Dalla Valle Equation
FCBM	Fluid Cells in the Basic Mesh
FE	Fletcher Equation
FLLM	Fluid Cells in the Local Mesh
GE	Garrison Equation
PCBM	Partial Cells in the Basic Mesh
PCLM	Partial Cells in the Local Mesh
RMSE	Root Mean Square Error
SIMPLE	Semi-Implicit Method for Pressure Linked Equation

Subscripts and superscript

eq	equivalent (referred to opening hood area)
f	referred to the opening hood area
peak	maximum value (referred to velocity)
y	referred to the y-axis hood
t	total
0	referred to the hood opening area
1, 2	referred to the coefficient of Garrison Equation
*	normalized

is a transverse flow [8,9], for which the analysis of the interaction between the fluid velocity fields is crucial for a proper design.

In a hood design procedure, the general shape and dimension of the suction opening (rectangular, circular,…) and the location of the hood in accordance with the specific process must be established. Since the velocity decay away from the hood opening is remarkable, it is crucial to locate the capturing hood as close as possible to the contaminant source. Therefore, a key parameter for its optimal design is the knowledge of the velocity distribution in the vicinity of the hood opening. In fact, to ensure capturing performance, the hood capture velocity must be higher than the escape velocity at all points in the zone of contaminants/fume generation. For this reason, a number of empirical formulas which allow the calculation of the velocity distribution have been used in practice. These formulas relate the velocity along the hood axis to the distance from the hood opening. In this way, by knowing the law of velocity variation from an undisturbed environment up to the hood opening, the required capturing velocity, and, in turn, the volumetric exhaust flow rate for a given hood opening area can be inferred. In this manner, the fan which matches the correct volumetric flow rate can be chosen and, thus, the energy requirements of the hood can be minimized.

Capturing hoods with a free (not flanged) opening are a class of hoods in which the ingestion of the fluid to be captured can come from the entire perimeter of the hood opening. In this paper, this particular class of hoods is investigated. At this time, for the design of free opening hoods, empirical formulas are used. The formula which can be found in literature are based on non-viscous formulation, i.e. the velocity is calculated without taking into account the boundary layer near due to the hood walls and the viscous effects due to vortices and recirculation, and do not include hood geometry influence. However, viscous effects are always present in real applications and, if not taken into account, they can give origin to an incorrect velocity assessment, in particular near the hood opening. Moreover, the geometrical topology, such as the opening aspect ratio, can significantly alter the velocity distribution.

In this paper, a CFD-based formulation for the velocity field assessment in capturing hoods with free openings which account for geometrical and viscous effects is presented. Different hoods, which differ in shape (square and rectangular) and size are created and their velocity field determined numerically. The numerical model is firstly set up by a thorough grid-independent analysis. A comparison between the obtained numerical results and the results obtained by applying empirical formula found in literature are presented and the discrepancy between them highlighted and discussed. Furthermore, the velocity field in front of the hood and its dependence on the geometric shape of the hood have been studied. The dependence is expressed through dimensionless parameters. Starting from the numerical results, a new equation for the velocity field assessment of capturing hoods, which takes into account viscous effects, is proposed together with its range of applicability and its level of confidence. The validity of the new equation is also checked outside the limits indicated by allowing a wider confidence interval.

In synthesis, the main contributions of this paper are:

- The review of empirical formula currently used for the determination of the velocity in front of capturing hoods with free openings and the assessment of their limit of validity;
- The detection and the investigation of the viscous effects which affect the performance of capturing hoods;
- The formulation of a new equation, which includes viscous effects and geometrical parameters dependence, which describes the velocity distribution and its decay along the hood axis.

2. Model description

In order to perform the CFD calculations, a capturing hood model is used. The hood model geometry is a truncated pyramid of height $H = 0.4$ m with a rectangular base (hood opening) whose

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