Effect of the impact distance on the thermal and dynamic behavior of a swirling jet impacting a flat plate

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Abstract

Impacts jets are widely used in industry whose purpose is the thermal transfer of industrial objects or thermal comfort of premises. This work is devoted to the numerical study of the influence of the variation of the impact distance on the thermal and dynamic behavior of a swirling jet impacting a plane plate. The variables treated are the reduced velocity Ur the reduced temperature Tr and the number of Nusselt Nu. In order to concretize our study, we made the numerical simulation based on the method of the finite volumes by means of the mathematical model with two equations of transport (k-ε) for the closure of the equations of NAVIER-STOCKES and this, by using the code of FLUENT calculation for the numerical resolution of such a flow. The results found clearly show the influence of this factor on the thermal and dynamic characteristics of the impact jet. The (k-ε) model gave acceptable and confrontational results with available experimental results.

Keywords: *Swirling impacting jet; impact height; flat plate; (k-ε) model.*

I. Introduction

The impacting jets are widely used today in the industry because they generate significant heat transfer. Applications include one or more jets such as drying of paper and textiles, cooling of electronic components or turbine blades, manufacture of glass to cool the glass sheet, in the metallurgical industry to cool the molten metal.

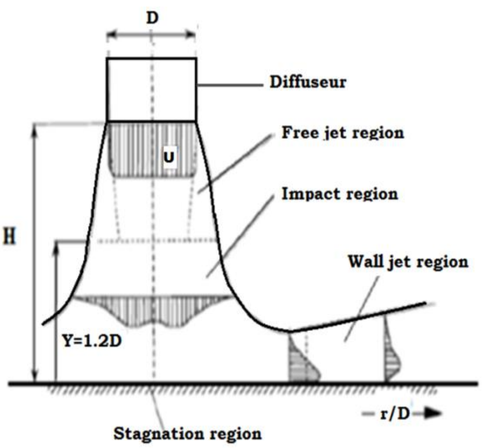

Figure1. Diagram of an impact jet [1].

The characteristics of a jet impact can be very different depending on the impact distance and therefore the area in which the impact is located. Three distinct regions are considered in the structure of an impact jet as shown in Figure 1.

II. EXPERIMENTAL DEVICE

The realized experimental device consists of a frame of the cubic shape (5) of metal; having at its upper part the hot air blowing device, directed from the top downwards and in its lower part a diffuser (1). A particular arrangement of rods supporting temperature probes (2); the temperature field is explored through a portable anemometer device VELOCICALC more (4). Rods easily guided vertically and horizontally, a horizontal plate (3) Formica material, the temperature, support the probes and velocity fields are measured in different stations in the axial and radial directions of flow. The ambient temperature Ta is obtained from the temperature T measures.

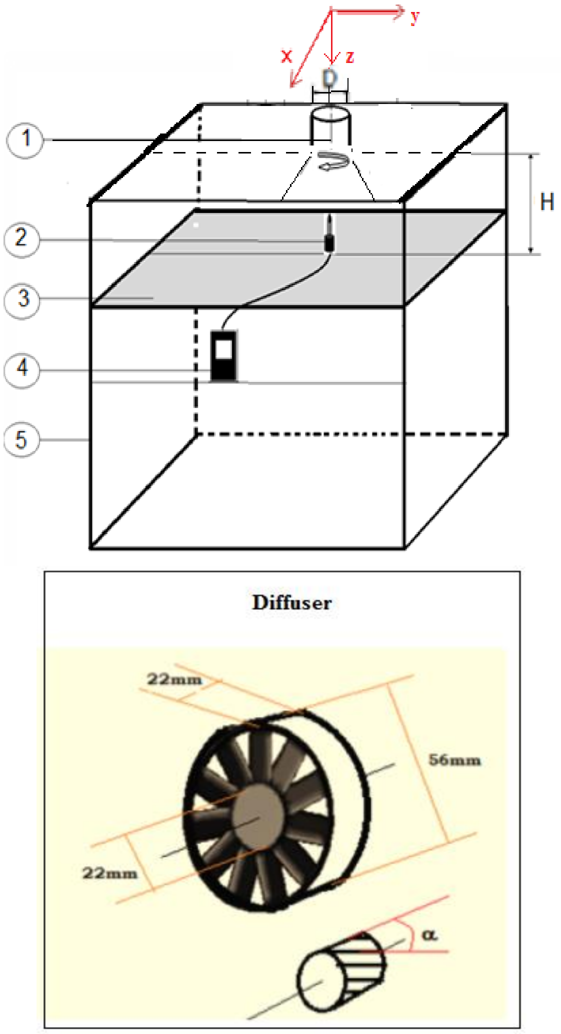

Figure 2.Experimental configuration and visualization of digital sensors

A. The number of swirl

A dimensionless number that defines a measure of the ratio between the angular momentum of the axial flow and axial momentum characterizes the swirl and is expressed as [2]:

$$S = \frac{\int_0^R r^2 UWdr}{R\int_0^R r\left(U^2 - \frac{W^2}{2}\right)dr} \qquad (1)$$

The swirl number can be evaluated at any position of the jet because the two quantities are calculated. Swirling helps promote and improve the process of mixing and transfer, as well as the jet has the advantage of quickly flourishing in free jets.
Another empirical formula is used for calculating the number of swirl according to the geometric parameters of the swirl generator. This number S can be written as [3] as follows:

$$S = \frac{2}{3}\left(\frac{1-\left(\frac{R_h}{R_n}\right)^3}{1-\left(\frac{R_h}{R_n}\right)^2}\right).tg\alpha \qquad (2)$$

B. Operating conditions

The experimental setup was placed in a local with the following dimensions:
Length = 40m width = 3.5m height = 3m. There must be a free flow and an insulation of the experiment, the initial temperature at the blowing opening is 90 °C for each jet.

C. Dimensionless variables

The reduced temperature (Tr) and reduced speed (Ur) are expressed as follows:

$$T_r = \frac{T_i - T_a}{T_{max} - T_a} \quad ; \quad U_r = \frac{U_i}{U_{max}} \qquad (4)$$

III. NUMERICAL PROCEDURE

A. The turbulence model (k-ε) standard

The turbulence model (k-ε) is a model of turbulent viscosity in which Reynolds stresses are assumed to be proportional to the gradient of the average velocity, with a proportionality constant representing the turbulent viscosity.
This hypothesis, known by the name the assumption of "Boussinesq" provides the following expression for the Reynolds stress tensor [6]:

$$\rho\overline{u_i' u_j'} = \rho\frac{2}{3}k\delta_{ij} - \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \frac{2}{3}\mu_t\frac{\partial u_i}{\partial x_i}\delta_{ij} \qquad (5)$$

Here it is the turbulent kinetic energy defined by

$$k = \frac{1}{2}\sum_i \overline{u_i'^2} \qquad (6)$$

Eddy viscosity is obtained by assuming that it is proportional to the product of the scale of the turbulent velocity and length scale. In (k-ε) model, these scales velocities and lengths are obtained from two parameters k and the kinetic energy dissipation rate ε. So can express by the following relation:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \qquad (7)$$

With: $C_\mu = 0.09$ (empirical constant).

k values and ε required in the equation are obtained by solving the following conservation equation:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho u_i k)=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\varepsilon+S_k \quad \frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho u_i\varepsilon)=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right)+G_{1\varepsilon}\frac{\varepsilon}{k}(G_k-C_{3\varepsilon}.G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \qquad (8)$$

with $C_{1\varepsilon}=1.44$ and $C_{2\varepsilon}=1.92$ are empirical constants, $\sigma_k=1.0$ and $\sigma_\varepsilon=1.3$ are Prandtl numbers for k and ε, respectively, S_k and S_ε are source terms for k and ε, respectively.

G_k: represents the generation of the turbulent kinetic energy due to the average velocities gradient.

$$G_k=\mu_t\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right)\frac{\partial u_j}{\partial x_i} \qquad (9)$$

G_b: coefficient generation of turbulence due to the entrainment.

$$G_b=-g_i\frac{\mu_t}{\rho\sigma_h}\frac{\partial\rho}{\partial x_i} \qquad (10)$$

The Nusselt number characterizes the heat transfer from the impinging jets. It is a dimensionless number that quantifies the heat transfer between a fluid and a wall of the baffle plate. It represents the ratio of convective exchanges on conductive exchanges [8].

$$Nu=\frac{h.L}{\lambda} \qquad (11)$$

Such as:

h: Local convective heat transfer coefficient [$W.m^{-2}.K^{-1}$]

λ: The thermal conductivity of air, taken at the reference temperature[$W.m^{-1}.k^{-1}$]

L: Length of the plate [m]

It is calculated by an empirical formula:

$$Nu=0.037.Re^{0.8}.(Pr)^{0.33} \qquad (12)$$

Re: Is the Reynolds number. It is defined by:

$$Re=\frac{\rho.U.L}{\mu} \qquad (13)$$

ρ : density of air [$kg.m^{-3}$]

U: average velocity [$m.s^{-1}$]

D: hydraulic diameter [m]

Pr: Prandtl number is a dimensionless number which represents the ratio of momentum diffusivity and thermal diffusivity

$$Pr=\frac{\mu.Cp}{\lambda} \qquad (14)$$

μ : Dynamic viscosity [N.s.m-2]

Cp: Specific heat [J.kg-1.K-1]

λ: Air thermal conductivity en [W.m-1.k-1].

IV. Results and discussion

A. Influence of impact distance

In the first graph of Figure 3, we can say that the lower the impact distance, the lower the temperature increased and stabilized.

The second graph of Figure 3 shows that the higher the impact distance, the faster the velocity increased and the lower the height the faster the speed stabilized and became almost uniform over the entire surface of the plate.

In the third graph of Figure 3, it is noted that the more the impact distance of the plate decreased, the more the number of Nusselt decreased and tended to stabilize.

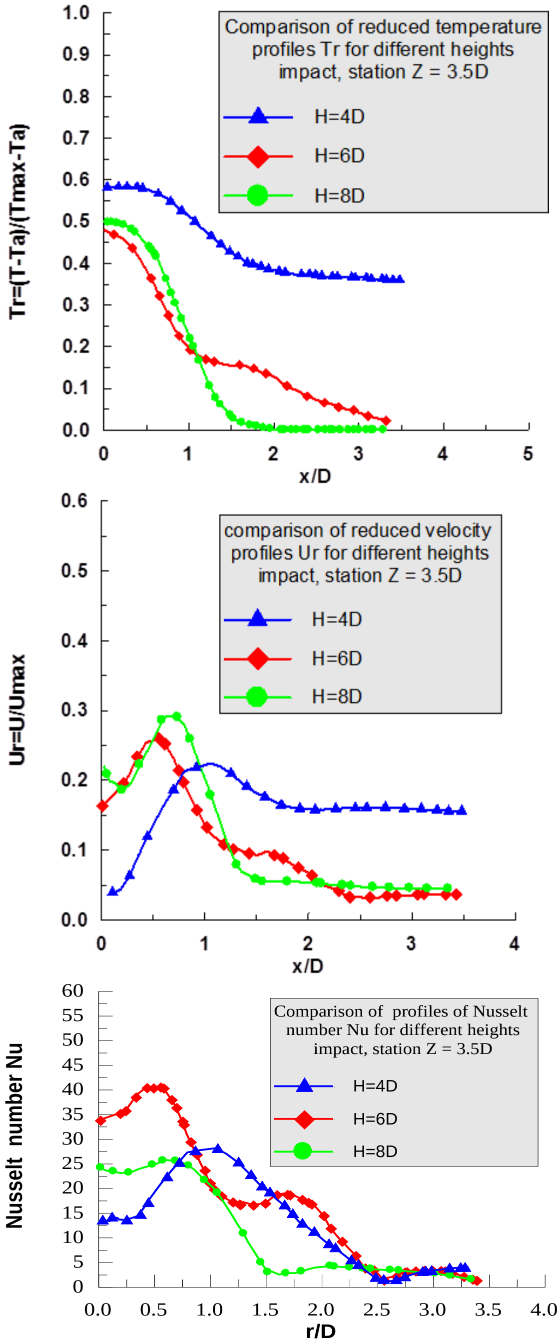

Figure 3. Comparison of the profiles of the reduced temperature Tr and the reduced velocity Ur for different distances of impact.

B. *Temperature field and velocity vectors*

Figure 4 provides the temperature fields and field vectors for a 4D Impact distance and inlet temperature T, calculated with (k- ε) model. It can be seen that the jet appeared at first as a free jet in the region of established flow from the injection port to the end of the potential cone and it is characterized by the weakening of the axis velocity and vitality hence the established flow area. Then the jet was deviated from its initial direction in the axial deflection region. Finally the velocity was mainly radial and where the boundary layer thickness increased in the radial direction was called the wall jet region.

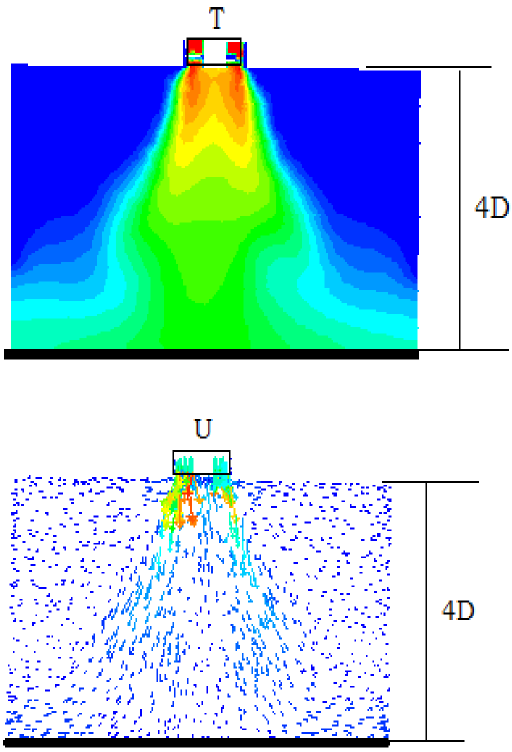

Figure 4. Temperature and velocity vector fields.

C. *Validation of results*

The quality of comparison between the numerical results and experimental values can be seen in Figures 5 and 6 on the inlet temperature Tr, at the reduced velocity *Ur* in the (y, z), respectively. The numerical results of the model with two transport equations (*k-ε*) used to simulate this case, are in good agreement with experimental results, despite however a smaller gap in the first stations, and without omitting the influence of uncertainties on the operated measurements. However the (*k-ε*) model still considers an isotropic turbulent viscosity and despite these shortcomings it gave acceptable results qualitatively and nevertheless, it is a relatively simple and inexpensive simulation tool.

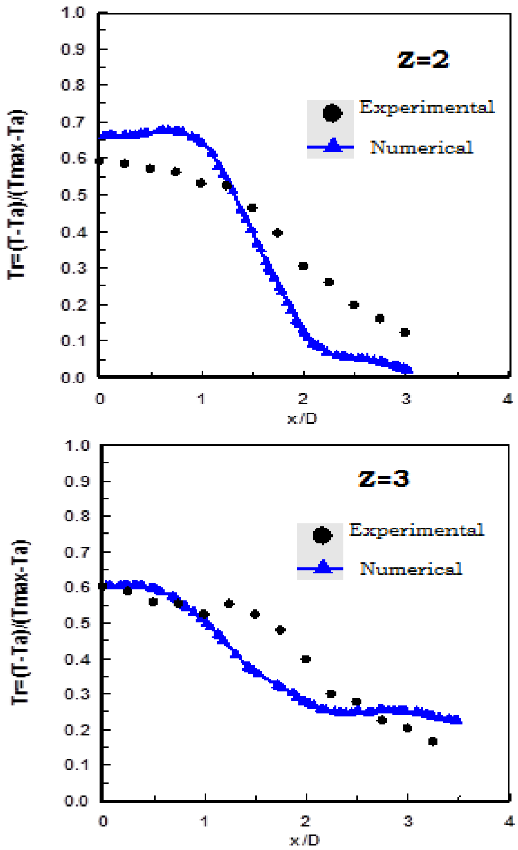

Figure 5: Comparison of numerical and experimental profiles of the reduced temperature *Tr* in the (r, z), with height of impact 4D

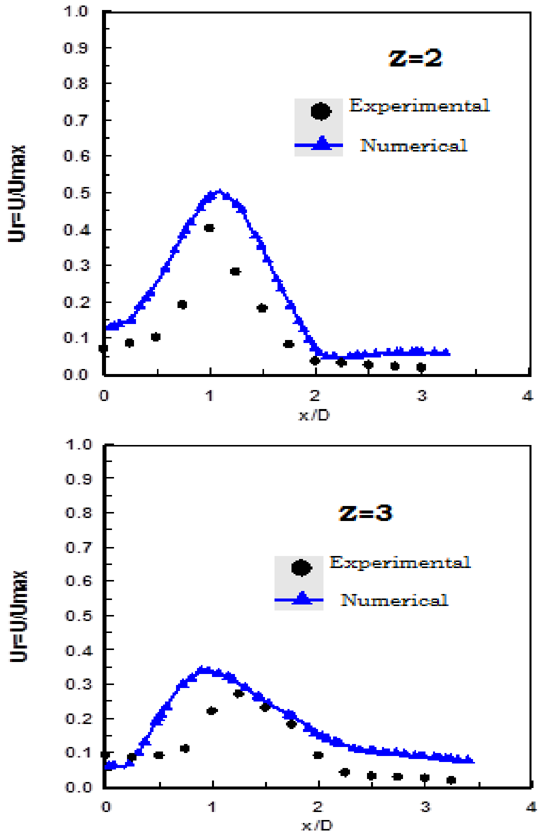

Figure 6. Comparison of numerical with experimental profiles of the reduced velocity Ur, in the (r, z), with distance of impact 4D

V. Conclusions

The swirling jet impacting a plane plate was simulated numerically by fluent software by means of the turbulence model (k-ε). The latter gave results of temperatures and velocities having profiles given to those of the experimental results. This study allowed us to find the same thermal characteristics:

• Swirling ensures thermal homogenization with large spreading. It slows the fluid particles and better promotes the development of the jet by ensuring a uniform temperature distribution along the plate.

• The presence of the plate reduces the temperature amplitudes of the jet, the temperature of the plate decreases downstream of the jet as we approach the plate.

• The magnitude of the axial temperature near the impact surface is greater when the distance of impact decreases, and we note that, the more the impact distance of the plate decreases, the more the number of Nusselt decreases and tends to stabilize.

In the comparison between the numerical results and the experimental results, we note that the model with two transport equations (k-ε) produces acceptable results, which coincide with the experimental results. Therefore, this model remains a relatively simple simulation tool that can yield decent and inexpensive results to use.

Nomenclature and units

D: diameter of the diffuser [m]
d: diameter of the valve diffuser support [m]
H: the impact height [m]
G_θ : Flux of angular momentum [$m^4.s^{-2}$]
G_x : Flux of Axial momentum [$m^4.s^{-2}$]
R: radius of the diffuser [m]
r, X: dimensional cylindrical coordinates [m]
Nu: Nusselt Number [-]
R_h : Radius of the valve diffuser support [m]
R_n : Radius of diffuser [m]
Re: Reynolds number [-]
S: swirl number [-]
T_a : Ambient temperature [°C]
T_i : Jet temperature at the point considered. [°C]
T_r : reduced temperature [-]
T_m : Maximum temperature at the outlet of the diffuser [°C]
U: dimensionless velocity in the axial direction [$m.s^{-1}$]
U_m : Maximum velocity at the exit of the diffuser [m.s-1]
U_r : Reduced dimensionless axial velocity. [-]
U_i : Jet velocity at the point considered [$m.s^{-1}$]
V: dimensionless velocity in the radial direction [$m.s^{-1}$]
W: Dimensionless velocity in the tangential direction [$m.s^{-1}$]
α: inclination angle of the vanes [°deg]

References:

[1] Popiel. C, Trass. O, Visualization of a free and impinging round jet. Thermal and Fluid Sciences. 2005; vol 4, p 253–264.

[2] Gupta, A.K, Lilley, D.G, Syred, N. Swirl flows, London: Abacus Press, 1984.

[3] Huang, Y, Yang, V. Dynamics and Stability of Lean-Premixed Swirl-Stabilized Combustion. Progress in Energy and Combustion Science. 35 2009, 4, pp. 293-364.

[4] H. Sato, M. Mori, T. Nakamura. Development of a dry ultra-low NOx double swirler staged gas turbine combustor. Energy Technology Research Institute, Tokyo -Gas Co, Ldt TOKYO, JAPAN, Journal of Engineering for Gas Turbine and Power. January 1998, Vol. 120.

[5] Braikia M., Loukarfi L., Khelil A., Improvement of thermal homogenization using multiple swirling jets. University Lille Nord de France. Thermal Science. 2012, Vol. 16, No1, pp. 239-250 239 Original scientific paper DOI: 10.2298/TSCI101026131B.

[6] Lunder B. E, Spalding. D.B. Mathematical models of turbulence, Dept. of Mechanical Engineering, Imperial Collogue of Science and Technology. LONDON. England 1972.

[7] Dinh VO. Ngoc. Numerical methods of local Integral on Finite Volumes. School of Engineering, University of Moncton, Canada.

[8] Wigley G, Clark J.A. Heat transport coefficients for constant energy flux models of broad leaves. Boundary Layer Meteorology.1974; 139-150, 1974.

[9] FLUENT User's Guide, 2006.