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NUMERICAL PREDICTION OF A SWIRLING JET SYSTEM IMPACTING BY THE RSM MODEL

NUMERIČKO PREDVIĐANJE UTICAJA SISTEMA VRTLOŽNOG MLAZA RSM MODELOM

Originalni naučni rad / Original scientific paper
UDK /UDC:
Rad primljen / Paper received: 20.11.2021

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Keywords
- turbulent swirling jet
- impinging a plaque
- thermal homogenization
- ventilation
- (k-ε) model

Ključne reči
- turbulentni vrtložni mlaz
- razbijanje naslaga
- termička homogenizacija
- ventilacija
- (k-ε) model

Abstract

This study deals with the numerical simulation of a system of vortex turbulent jets impacting a plate by two numerical models of closure of Navier-Stokes equations. The objective is to give a numerical forecast on the jets impacting by the RSTM model and to show the performance of this model. The experimental test bench comprises a diffuser of diameter D, impacting the perpendicular plate, varying the inlet temperature conditions in three configurations (T, T, T), (T/2, T, T/2), (T, T/2, T), such that impact height H = 4D. The swirling is obtained by a generator (vortex) of compound 12 fins arranged at 60° with respect to the vertical placed just at the outlet of the diffuser. The temperature of the swirling jets blowing on the plate is measured with a portable thermo anemometer device VELOCICALC PLUS, in different stations. The system has been digitally simulated by Fluent© /11/, using a turbulence model (k-ε). Note that the diffuser having balanced inlet temperatures (T, T, T), gives a better uniform distribution of temperature and speed over the surface of the plate compared to those of other configurations. This homogenization of temperatures derives from better thermal transfer of the plate. The model (k, ε) gives acceptable results that coincide with the experiment.

Izvod

Ova studija se bavi numeričkom simulacijom sistema vrtložnih turbulentnih mlazova koji deluju na ploču, pomoću dva numerička modela Navije-Stoksovih jednačina zatvorenog oblika. Cilj je da se da numerički model mlaza RSTM modelom i da se pokažu performanse ovog modela. Eksperimentalni sto za ispitivanje sastoji se od difuzora prečnika D, koji je usmeren na vertikalnu ploču, sa promenljivim uslovima ulazne temperature u tri konfiguracije (T, T, T), (T/2, T, T/2), (T, T/2, T), tako da je udarna visina H = 4D. Vrtloženje se dobija pomoću generatora vrtloga sastavljenog iz 12 lopatica raspoređenih pod uglom od 60° u odnosu na vertikalu, neposredno na izlazu iz difuzora. Merenje temperature vrtložnog mlaza na ploču obavlja se prenosivim termo anemometrom VELOCICALC PLUS, u različitim položajima. Sistem je digitalno simuliran programom Fluent© /11/, primenom modela turbulencije (k-ε). Primećuje se da difuzor sa uravnoteženim ulaznim temperaturama (T, T, T) daje bolju ravnomernu raspodelu temperature i brzine po površini ploče u poređenju sa drugim konfiguracijama. Ova homogenizacija temperatura proizilazi iz poboljšanog prenosa toplote ploče. Model (k, ε) pruža prihvatljive rezultate koji se poklapaju sa eksperimentalnim rezultatima.

INTRODUCTION

Several research works have dealt with convective transfer of free jets, confined, and impacting flat surfaces or complex geometries, the aim of which is to characterize the parameters involved in the flow, in order to improve the transfer of heat or localised mass in a part of the system. For this, it is necessary to know the structure of the impacting jet and the parameters which influence this behaviour. Many articles deal with this case, as the principle cited by Incropera and DeWitt /1/. Usually, the flow field of an impacting jet can be decomposed into different regions (Fig. 1). A cone potential region, a free jet area, an impact or deflection region, also called a stagnation region or 'impact region' and a radial jet zone parallel to the wall ('wall jet region'). Thus the main geometric parameters which intervene in the case of a fluid jet impacting a flat plate are:

1. The distance H, which separates the nozzle or the slot from the plate.
2. The diameter D of the nozzle or the width of the slot B.
3. The distance C between the centres of the jets in the case of several jets.

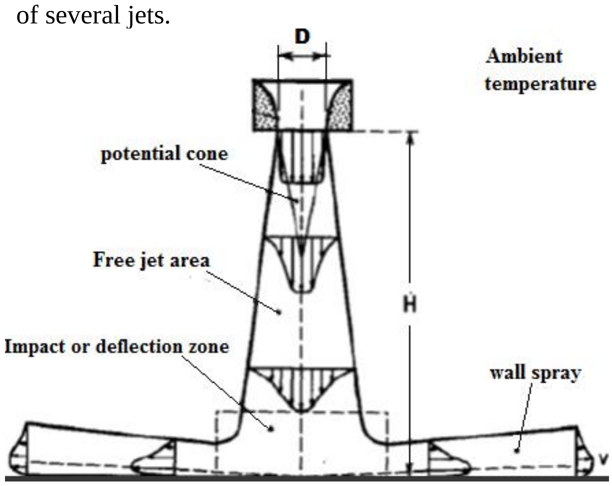


Figure 1. Diagram of a jet impacting a flat plate, /1/.

The nature of the flow is defined by the Reynolds number of the jet and therefore by the speed at the inlet, the type of fluid used, and the temperature of the jet at the inlet.

EXPERIMENTAL DEVICE

The experimental device produced is composed of a cubic-shaped frame (5), Fig. 2, made of metal; having at its upper part the hot air blower, directed from top to bottom and at its lower part, a diffuser (1), according to the configuration studied. This device makes it possible to sweep the maximal space provided by a particular arrangement of rods supporting the temperature probes (2); the temperature field is measured using a portable VELOCICALC PLUS thermo anemometer device (4). The probes are supported by rods easy to guide vertically and horizontally to sweep maximum space, a horizontal plate (3). The temperature and speed fields are measured at different stations in axial and radial directions.

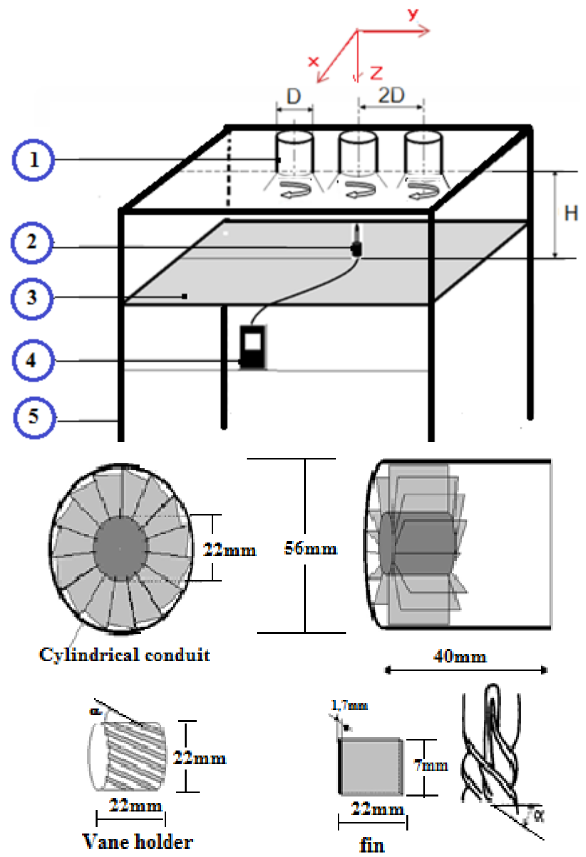


Figure 2. Experimental configuration and swirl generator, /2/.

The number of swirls

The swirl is characterized by a dimensionless number that defines a measure of the ratio between angular momentum of the axial flow G_θ and axial momentum G_X, /3/.

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

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 to quickly flow in free jets.

Another empirical formula is used for calculating the number of swirls defined according to the geometric parameters of the swirl generator. This number S can be written as follows, /4/:

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

such that: α is the angle of fins built swirl generator; R_h is the radius of vane diffuser support; R_n is radius of diffuser.

Note that in the case of a swirler hub without radius (R_h = 0), the expression becomes, /5/:

$$S=\frac{2}{3}\tan\alpha \cdot \qquad (3)$$

In this study, the axial and tangential velocities W and U, respectively, are measured at the outlet of a diffuser with swirling jet hot wire anemometer triple probes (DISA55M01). Four values of the swirl number can be used: S = 0 to α = 0°; S = 0.4 to α = 30°; S = 0.7 to α = 45°; and S = 1.3 to α = 60°, respectively. According to ref. /6/, the swirl number is used, which corresponds to α = 60°.

Operating conditions

The experimental setup is placed in a confinement of following dimensions: length 4 m; width 3.5 m; and height 3 m. There must be a free flow of the isolation and testing. Initial temperature at the blowing port is 90 °C for each jet.

The measured temperature

The reduced temperature (T_r) of measurement is obtained by reference to the average maximal temperature at the outlet of the blowing orifice and at ambient temperature:

$$T_r=\frac{T_i-T_a}{T_{\max}-T_a} \cdot \qquad (4)$$

The reduced dimensionless axial velocity is obtained with respect to maximal speed at outlet of blow opening $U_{\max}$:

$$U_r=\frac{U_i}{U_{\max}} \cdot \qquad (5)$$

Similarly, the radial and axial distances are given by reference to the diameter of the dimensionless form blow port *r/R* and *x/D*.

NUMERICAL PROCEDURE

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 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 Reynolds stress tensor, /7/:

$$-\rho\overline{u_i'.u_j'}=\rho\frac{2}{3}k\delta_{ij}-\mu_t\left(\frac{\partial u_i}{\partial X_i}+\frac{\partial u_j}{\partial X_i}\right)+\frac{2}{3}\mu_t\frac{\partial u_i}{\partial X_i}\delta_{ij} \cdot \qquad (6)$$

Here, the turbulent kinetic energy is defined by:

$$k=\frac{1}{2}\sum_i\overline{u_i'^2} \cdot \qquad (7)$$

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

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}, \tag{8}$$

where: $C_\mu = 0.09$ (empirical constant). The k values and ε required in the equation are obtained by solving the following conservation equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial X_j}(\rho u_i k) = \frac{\partial}{\partial X_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial X_j}\right) + G_k + G_b - \rho\varepsilon + S_k$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial X_j}(\rho u_i \varepsilon) = \frac{\partial}{\partial X_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial X_j}\right) +$$

$$+ C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon, \tag{9}$$

where: $C_{1\varepsilon} = 1.44$ 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, in respect; S_k and S_ε are terms for sources k and ε, respectively; G_k represents the generation of turbulent kinetic energy due to the average velocities' gradient,

$$G_k = \mu_t\left(\frac{\partial u_j}{\partial X_i} + \frac{\partial u_i}{\partial X_j}\right)\frac{\partial u_j}{\partial X_i}, \tag{10}$$

and G_b is coefficient of generation of turbulence,

$$G_b = -g_i \frac{\mu_t}{\rho\sigma_h}\frac{\partial \rho}{\partial X_i}. \tag{11}$$

The turbulence (RSM) model

The advantage of the Reynolds stress model (RSM), Gibson and Launder 1989 /8/, over the k-ε model is that each element of the Reynolds stress tensor $\overline{u_i' u_j'}$ is calculated from its own transport equation. This model, therefore, allows the study of flows characterised by anisotropic turbulence and in particular, the determination of the intensity of fluctuation in each direction. Thus, it is possible to write transport equations for double correlations $\overline{u_i' u_j'}$ with k as the summation index. However, three-order correlations appear which must again be modelled,

$$\underbrace{\frac{\partial \rho}{\partial t}(\overline{u_i' u_j'}) + \frac{\partial}{\partial x_k}(\rho u_k \overline{u_i' u_j'})}_{\text{convective transport}} =$$

$$= \underbrace{\frac{\partial}{\partial x_k}(\overline{u_i' u_j' u_k'}) + \overline{p(\delta_{kj}u_i' + \delta_{ik}u_j')} - \nu\frac{\partial}{\partial x_k}(\overline{u_i' u_j'})}_{\text{diffusive transport}} -$$

$$\underbrace{-\rho\left(\overline{u_i' u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial x_k}\right)}_{P_{ij}=\text{product}} + \underbrace{P\left(\overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_j'}{\partial x_i}}\right)}_{\varphi_{ij}=\text{pressure}} - \underbrace{2\mu\left(\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}}\right)}_{\varepsilon_{ij}=\text{dissipation}} -$$

$$\underbrace{-2\rho\left[\overline{u_j' u_m'}\varepsilon_{ikm} + \overline{u_i' u_m'}\varepsilon_{jkm}\right]}_{\text{rotational term}} + S_{ij} + D_{ij}. \tag{12}$$

Several terms of the equation must be modelled in order to close the system of equations.

The diffusive transport term is described as follows using a scalar coefficient for the diffusive transport,

$$D_{ij} = \frac{\partial}{\partial x}\left(\frac{\mu_t}{\sigma_k} + \frac{\partial \overline{u_i' u_j'}}{\partial x_k}\right), \tag{13}$$

where: coefficient $\sigma_k = 0.82$.

The pressure term is described as follows:

$$\Phi_{ij} = C_1\frac{\varepsilon}{k}(\overline{u_i' u_j'} - 2\delta_{ij}k) - C_2\left(P_{ij} - \frac{2}{3}\delta_{ij}P - \delta_{ij}\right) + \Phi_{ij}^w, \tag{14}$$

where: $\Phi_{ij}{}^w$ is wall reflection term, it tends to damp the normal stress perpendicular to the wall; $C_1 = 1.8$, $C_2 = 0.6$ are empirical constants, and

$$P = \frac{1}{2}P_{ij}. \tag{15}$$

Finally the dissipation term is described by the following formula, assuming that the dissipation is isotropic,

$$\varepsilon_{ij} = \frac{2}{3}\delta_{ij}\varepsilon. \tag{16}$$

The RSM model is considered to be the most suitable, within the framework of the Reynolds means approach, because it provides the quantities of the fluxes by solving the complete transport equations, which can be derived from Navier-Stokes equations.

Domain calculation and mesh

The computational domain is divided into a number of volumes called superposed control volume such that each volume surrounds each point of the mesh, Fig. 4.

The differential equation is integrated for each control volume and the result of this integration gives the discrete equation expressed using the values of function ϕ (scalar quantity) for a set of grid points. The obtained discrete equation expresses the principle of conservation for ϕ on the volume control in the same manner as the differential equation expressed for an infinitesimal volume control, /9/.

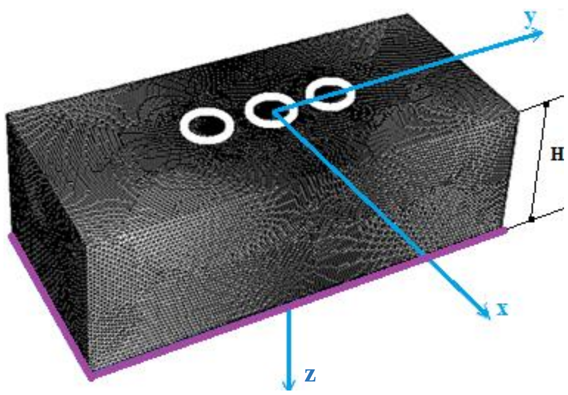


Figure 4. Domain calculation and mesh geometry for three diffusers with height of impact 4*D*.

Nusselt number Nu

The heat transfer from the impinging jets is characterized by the Nusselt number. 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, /10/,

$$\text{Nu} = \frac{hL}{\lambda}, \tag{17}$$

where: h local convective heat transfer coefficient [W/m^{2}K]; λ thermal conductivity of air, taken at reference temperature [W/mK]; L length of plate [m]. It is calculated by an empirical formula:

$$\mathrm{Nu} = 0.037\,\mathrm{Re}^{0.8}(\mathrm{Pr})^{0.33}, \tag{18}$$

where: Re is the Reynolds number, defined by:

$$\mathrm{Re} = \frac{\rho U D}{\mu}, \tag{19}$$

where: ρ is density of air [kg/m^3]; U is average velocity [m/s]; D is hydraulic diameter [m]. The Prandtl number, Pr, is a dimensionless number, It represents the ratio of momentum diffusivity and thermal diffusivity,

$$\mathrm{Pr} = \frac{\mu C_p}{\lambda}, \tag{20}$$

where: μ is dynamic viscosity [Ns/m^2]; C_p is specific heat [J/kgK]; λ is air thermal conductivity [W/mK].

NUMERICAL RESULTS

Reduced temperature and velocity profiles

Figures 5 and 6 show superimpositions of the profiles of reduced temperature T_r and the experimental dimensionless mean radial velocity U_r in the (y, z) plane, with an impact height H = 4D, for an input configuration of respective temperatures and velocities, (T, T, T) (U, U, U).

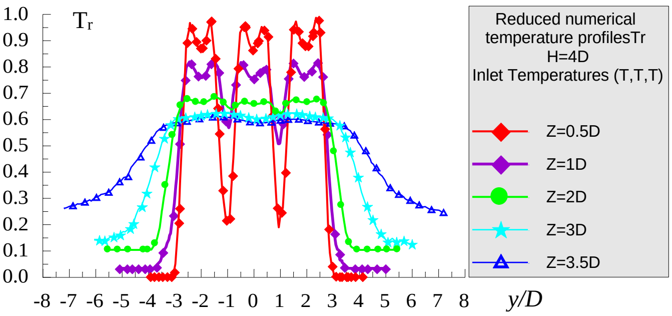


Figure 5 . Reduced temperature profiles for a triple jet with 4D impact height and inlet temperature configuration (T, T, T) in plane (y, z).

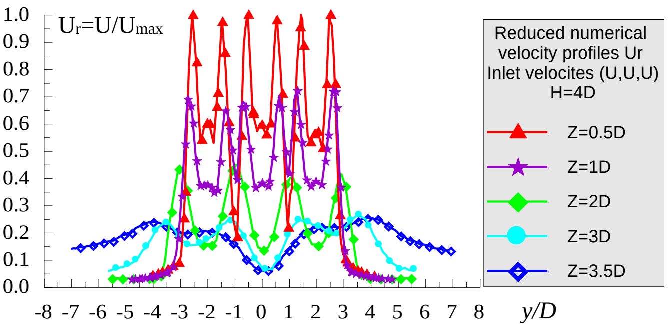


Figure 6. Reduced velocity profiles for a triple jet with impact height 4D, and a configuration of input velocities (U, U, U) in plane (y, z).

For all the cases presented above, in the first stations, the profiles of reduced temperatures and velocities show maximal (amplitudes) at each air diffusion orifice. In the free-jet region, these amplitudes decrease as you move downstream of the jet. As you approach the impact region, the temperature amplifies to become almost uniform across the surface of the plate. Then it decreases in the region of the boundary layer to reach room temperature. The velocity curve becomes almost parallel to the impact wall. This results in a slight spread of the overall jet system.

Nusselt number profiles

Figure 7 shows the superposition of Nusselt number profiles, whose impact height is H = 4D, for an inlet velocity in the diffusers (U, U, U) and inlet temperature (T, T, T). Initially, the Nusselt profiles indicate peaks at the blast port and disturbances. These disturbances are due to the support of the fins. Amplitudes and disturbances decrease progressively as we move downstream of the jet. At station Z = 3.5D, the Nu number is moderate at the level of impact surface, ensuring homogenization of heat transfer plate.

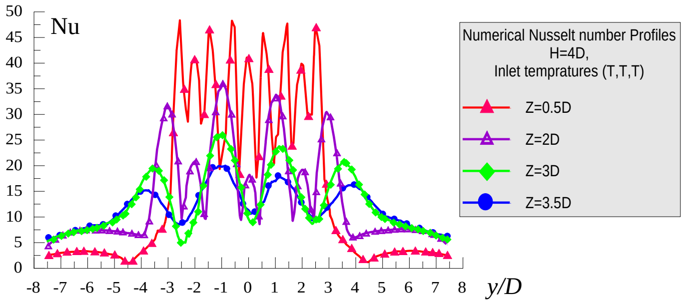


Figure 7. Nu number profiles with impact height H = 4D and inlet temperatures (T, T, T).

Temperature field and velocity vector field

Figure 8 shows the temperature field (a), and the velocity vector field (b), for impact height H = 4D, with inlet temperatures (T, T, T), and input speeds (U, U, U). We notice that the multi-jet system appears at the beginning as a free jet: it is the region of established flow going from the injection orifice to the end of the potential cone, then its axial velocity and its expansion weakens. Then the jet is deflected from its initial axial direction - this is the deflection region. Finally, the velocity becomes mainly radial, and boundary layer thickness increases radially, this is the region of the parietal jet.

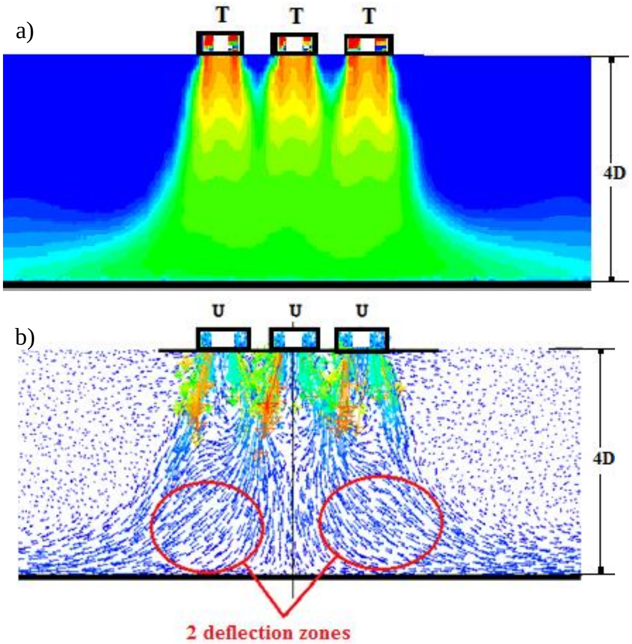


Figure 8. (a) Temperature field; (b) velocity vector field with impact height 4D, inlet temperatures (T, T, T) and velocities (U, U, U).

Validation of results

The comparison quality is presented for profiles of reduced temperature T_r, profiles of reduced velocity U_r and Nusselt number Nu, respectively shown in Figs. 9, 10, and 11 by the two turbulence models and experimental results. A benefit is obtained with the use of a high level model such as the Reynolds stresses turbulence model (RSTM), but this does not justify the significant contribution of the complexity introduced with this model with the addition of six equations of Reynolds transport.

Indeed the RSTM model highlights the presence of anisotropy in normal stresses and the stabilizing effect of swirling which results in a decline of the shear stress field and, therefore, even in an almost non-viscous flow opposite the model (k-ε). The latter is unable to account for the curvature, as it gives a rapid erosion of momentum of the central jet. This is due to an excessive level of diffusive transport calculated by the model (k-ε).

In conclusion, all calculated numerical results allow a fairly good prediction of the turbulent swirling jets with the RSTM model, and a relatively acceptable prediction with the (k-ε) model.

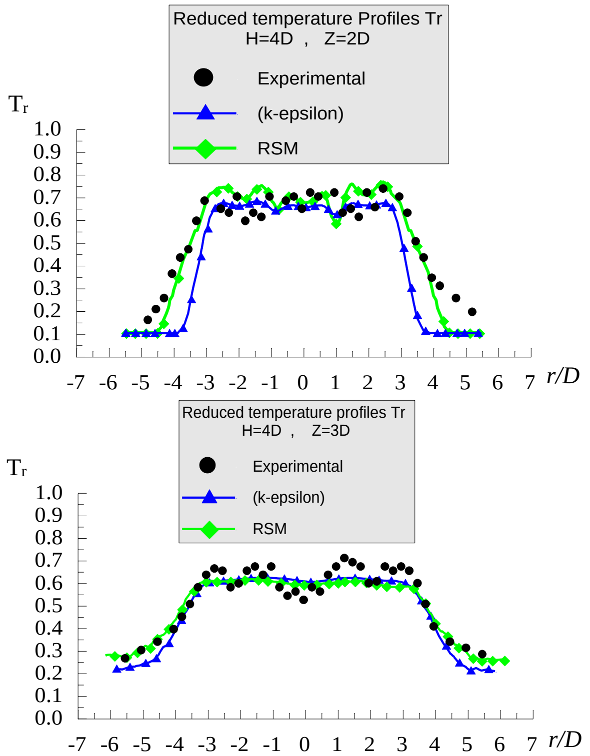
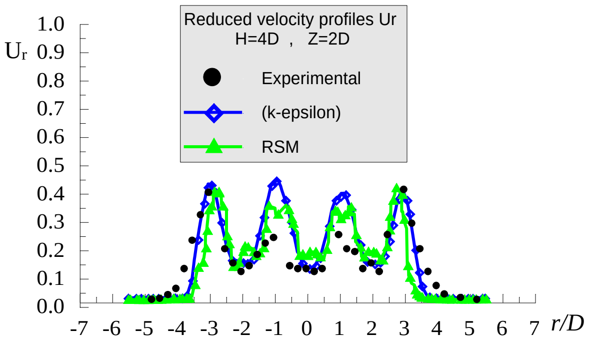


Figure 9. Compared experimental profiles of reduced temperature T_r.



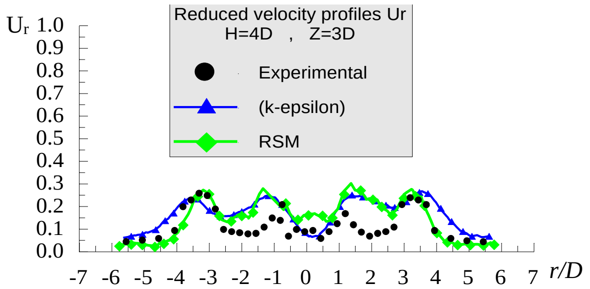


Figure 10. Compared experimental profiles of reduced velocity U_r.

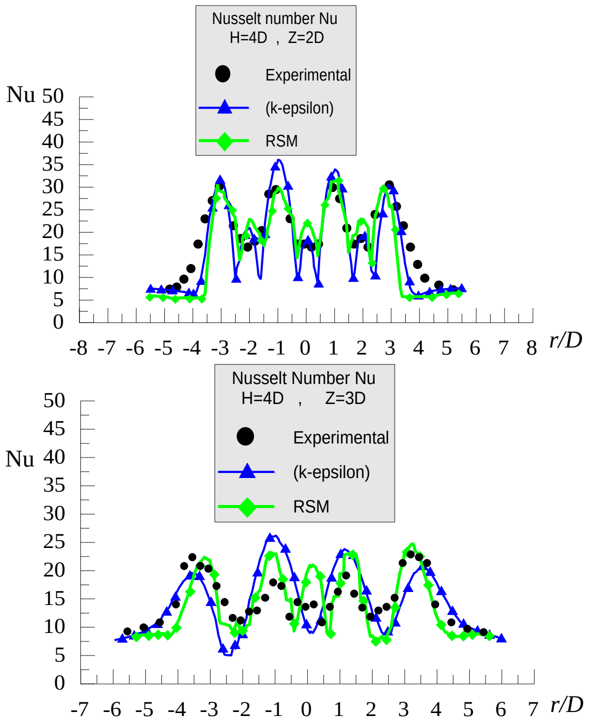


Figure 11. Compared experimental profiles of Nusselt number.

CONCLUSION

The presented study deals with a numerical prediction of thermal and dynamic behaviour of a system of jets impacting a flat plate by numerical model RSTM. The results clearly show that at the beginning, the jet has the same characteristics as a free jet. Very close to the obstacle it undergoes a considerable deflection characterised by the weakening of the speeds and the expansion of the jet (the temperature amplitudes decrease), on contact with the plate, the curves are almost parallel to the plate, the speeds change direction and develop radially. The swirling ensures thermal homogenization with a large spread.

The presence of the plate reduces temperature amplitudes as well as the recirculation zone, the plate temperature decreases as it moves away from the diffuser and becomes negligible beyond ten diameters of the blowing orifice.

After optimisation studies of the best configuration of multiple jets systems in impact of the plate, the one that has a diffuser with a temperature distribution (T, T, T) and a balanced flow rate at the inlet of the diffuser with vortex and an impact height $H = 4D$.

For stations close to the wall of the plate, the temperature and speed are almost uniform along the plate, and better promote the flow of the jet.

The comparison between numerical and experimental results presented indicates that the RSTM model produces satisfactory and comparatively acceptable results. The latter presents a good numerical prediction of the jets impacting in the zones of fluctuations than that with two transport equations (k-ε). We say that the RSTM model substantially surpasses the (k-ε) model. In fact, the RSTM model highlights the presence of anisotropy in normal stresses and the stabilizing effect of swirling which results in a decline in the shear stress field and, therefore, even in an almost non-viscous flow in contrast to the model (k-ε). The RSTM model remains a relatively more powerful simulation tool than the (k-ε) model for the case of shear flows imposed by swirling.

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Nomenclature

D	diameter of diffuser [m]
d	diameter of valve diffuser support [m]
H	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 diffuser [m]
r, X	dimensional cylindrical coordinates [m]
R_h	radius of 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 considered point [°C]
T_r	reduced temperature [-]
$T_{\max}$	maximal temperature at diffuser outlet [°C]
U	dimensionless velocity in axial direction [m/s]
$U_{\max}$	maximal velocity at the exit of diffuser [m/s]
U_r	reduced dimensionless axial velocity [-]
U_i	jet velocity at considered point [m/s]
V	dimensionless velocity in radial direction [m/s]
W	dimensionless velocity in tangential direction [m/s]
α	inclination angle of the vanes [°]
u'	fluctuating velocity [m/s]
$\rho \overline{u'_i u'_j}$	Reynolds stresses [kg/m^{2}s^2]