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Research Article

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Computational fluid dynamics analysis of the influence of velocity at inlet 2 on heat transfer and fluid flow in the mixing elbow

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Abstract With the use of ANSYS FLUENT software, this work presents a CFD (Computational Fluid Dynamics) analysis of the turbulent flow in the mixing elbow by determining the influence of the variation of the inlet 2 velocity. To describe such flow, which is turbulent the Reynolds averaged Navier-Stokes equations (RANSE), the k-ε closure model and the averaged energy conservation equation were chosen. We used the finite volume method and the coupled scheme for Pressure-velocity coupling. The higher the inlet 2 velocity, the more the effective mixing area increases, the more uniform the temperature at the outlet and the better the mixing. We also note excessively strong shocks (peaks or spikes in speed) with the large inlet 2 velocity values, which can reach velocities of 5m/s and 10m/s respectively for inlet 2 velocities equal to 2.5 and 5 m/s and impact on the material. To have a better mixture, it is necessary to choose high but moderate velocity at inlet 2 while taking into account the properties of the material due to the velocities that these peaks could reach.

Keywords Ansys Fluent, CFD, Finite volume methods, k-ε model.

1. Introduction

Compared to the simple elbow [1]-[13], studies on mixing elbows [14]-[16] are rare. The main difference between an elbow and a mixing elbow is their design and function. An elbow is primarily used to change the direction of flow or flow in a pipeline, while a mixing elbow is specifically designed to promote the even mixing of fluids in a piping system designed with specific internal geometries and configurations that encourage turbulence and efficient mixing of fluids.

The mixing elbow is designed to transfer and mix hot and cold fluids, whether of the same or different types, to promote even distribution of temperatures and properties in a piping system. The pipes that transfer and mix heat have different sections, the quality and precision of the product is directly related to the quality of heat transfer and fluid mixing. Its use has several advantages and interests, mainly in the field of thermal, chemical engineering and industrial processes [14]-[16].

Pavithra, J., et al. [14] presented a model to study the heat transfer and two-dimensional flow behavior of incompressible fluid in the mixing elbow. The k-ε turbulence model is used and the flow modeling was analyzed using the finite volume method-based computational fluid dynamics (CFD) solver, ANSYS Fluent. They found that with increasing speed at a smaller inlet diameter, the mixed temperature distribution in the mixing fluid actually shows a higher heat transfer rate. This gives a good idea of the fluid distribution and flow behavior which can be used for effective elbow design.

In this project, [15] Bhatia, S. S. et al. [15] treated a special case of angled mixing in two different types of fluid flow: laminar flow and turbulent flow (using the k-ε turbulence model), and compared them. For this they used the ANSYS analysis software. At the end of the project, they obtained useful flux (flow) curves for velocity, pressure and temperature inside the mixing tube that can be used as a reference by any designer of the mixing tube.

This work by Das S. et al [16] presents a numerical study of turbulent flow inside a mixing elbow which focuses on the behavior of the fluid flow in this mixing elbow. RANS turbulent models, k-ε model are used for simulation and the variations of axial velocity, wall shear stress and turbulent intensity along the length of the bent pipes are studied. The fluid used for this purpose is water. The simulations are carried out with different Reynolds numbers ranging from 2,500 to 10,000. The turbulent intensities show a decrease at the inlet. The area in which effective mixing takes place depends on physical parameters such as the Reynolds number. The effective mixing area increases with increasing Reynolds number.

Since it becomes very expensive to prepare and study the mixing elbow practically, therefore in this work, we will carry out the CFD (Computer Fluid Dynamics) analysis of the mixing elbow, to determine the influence of the variation of the inlet 2 veloctiy of the mixing elbow on flow, heat transfer and mixing using ANSYS FLUENT software. Today, ANSYS FLUENT becomes a global leader in engineering software, and their solutions are very reliable and more than many others. These results will give a good idea of the transfer, distribution and flow behavior of the fluid, which can be used as a reference for the effective design of a mixing elbow, as it affects its function.

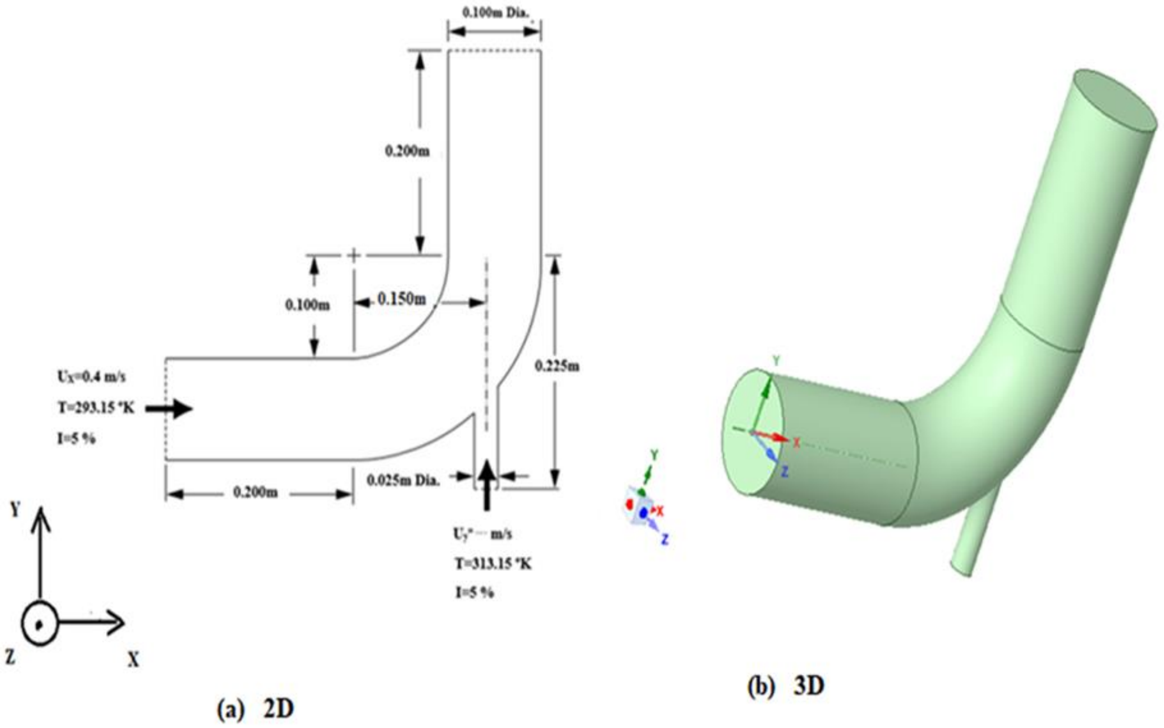
2. Mathematical Formulation

2.1 Description of the physical model or problem

The problem to be considered is a mixing elbow, as shown in Figure 1. The cold fluid (liquid water) having a temperature of 293.15°K enters through inlet 1 (large diameter inlet which is equal to 0.100 m) with a velocity of 0.2 m/s while the hot fluid with a temperature of 313.15°K enters through inlet 2 (small diameter inlet which is equal to 0.025 m) at a velocity varying from 0.4 m/s to 5 m/s and mixes to the turbulent nature of the flow. Elbow dimensions are in meters and fluid properties and boundary conditions are given in SI units.

The physical properties of the fluid considered, liquid water, are:

Density : $\rho = 998.2\ Kg/m^3$
Viscosity: : $\mu = 0.001003$ ou $1.003\times 10^{-3}\ Kg/(m.s)$
Thermal Conductivity: $k = 0.6\ W/(m.K)$
Specific Heat: $C_p = 4182\ J/(Kg.K)$



(a) 2D (b) 3D

Figure 1: Geometry of the mixing elbow (physical model)

2.2 Simplifying assumptions:

In order to study transfers, the following hypotheses were retained:

- The flow generated is turbulent

- The fluid considered is water (in the liquid state) and is incompressible and Newtonian
- The walls of the mixing elbow are adiabatic
- The thermo-physical properties of the fluids and those of the walls are assumed to be constant
- The boundary conditions are solved in stable and incompressible conditions with the Boussinesq approximation, therefore

2.3 Mathematical Modeling: Two-equation turbulence models (Standard k-ε model)

The relation (1) represent the Reynolds averaged Navier-Stokes equations (RANSE (continuity and momentum equations)

$$\begin{cases} \dfrac{\partial \overline{u}_i}{\partial x_i} = 0 \\ \dfrac{\partial}{\partial t}\left(\rho \overline{u}_i\right) + \dfrac{\partial}{\partial x_i}\left(\rho \overline{u}_i \overline{u}_j\right) = \rho f_i - \dfrac{\partial \overline{p}}{\partial x_i} + \dfrac{\partial}{\partial x_j}\left[\overline{\tau}_{ij} - \rho \overline{u_i' u_j'}\right] \end{cases} \quad (1)$$

We note that the averaged momentum balance equation (1) seems identical to that written for the instantaneous flow, with the exception of an added term, having the dimension of a constraint. This term is called the Reynolds tensor. The Reynolds tensor therefore reveals additional terms added to the usual variables. There are therefore more unknowns than equations, and it is then necessary to find a strategy allowing us to "close" this system. We choose the k-ε closure model, which is one of the most used in the industrial world to model flows with a fully turbulent flow. The model works best for single-phase and two-phase flows in elbow mixer pipes. In this model, the turbulence kinetic energy (k) and turbulence dissipation (ε) are solved to determine the turbulent viscosity coefficient (μt).Transport equation for k-ε

For high Reynolds numbers, the Reynolds stress terms are estimated by Launder and Spalding, (1974)

$$-\rho \overline{u_i' u_j'} = 2\mu_t S_{ij} - \frac{2}{3}\rho k \delta_{ij} - \frac{2}{3}\mu_t \delta_{ij} \frac{\partial \overline{u}_k}{\partial x_k} \quad (2)$$

- S_{ij} is the deformation tensor: $S_{ij} = \dfrac{1}{2}\left(\dfrac{\partial \overline{u}_i}{\partial x_j} + \dfrac{\partial \overline{u}_j}{\partial x_i}\right)$
- μ_t is the turbulent viscosity is given by: $\mu_t = \rho C_\mu \dfrac{\kappa^2}{\varepsilon}$
- In which $k = \dfrac{1}{2}\overline{u_i' u_j'}$ and $\varepsilon = \nu \left(\overline{\dfrac{\partial u_i'}{\partial x_j} \dfrac{\partial u_j'}{\partial x_i}}\right)$ Are respectively the turbulent kinetic energy and its dissipation rate. This satisfies the transport equations cited below at any point in the flow domain..

The standard k-ε closure model is estimated by their transport equation. Respectively:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \rho\varepsilon \quad (3)$$

In equations (3) and (4), Pk characterizes the generation of turbulent kinetic energy resulting from the average velocity gradient, and the effects of gravity (buoyancy). $C_{1\varepsilon}$, $C_{2\varepsilon}$ are constants. σ_k et σ_ε and are called Prandtl number, respectively for k and (These two numbers characterize the pressure-velocity correlation, and remain very difficult to model). The constants involved in this model were determined in the following:

$$C_\mu = 0.09 \quad C_{1\varepsilon} = 1.44 \quad C_{2\varepsilon} = 1.92 \quad \sigma_k = 1.0 \quad \sigma_\varepsilon = 1.3$$

The energy conservation equation can be expressed as follows:

$$\frac{\partial \overline{T}}{\partial t}+\frac{\partial}{\partial x_j}\left(\overline{T}\overline{u}_j\right)=\frac{\partial}{\partial x_j}\left(\lambda_{eff}\frac{\partial \overline{T}}{\partial x_j}\right) \qquad (5)$$

In the equation. (5):

- $\overline{T}$ represents the average temperature,
- λeff is an effective coefficient that includes the contribution of turbulent mixing in addition to molecular conduction and can be expressed as: $\lambda_{eff}=\lambda+\frac{\mu_t Cp}{\Pr_t}$, where k and Cp are the thermal conductivity and specific heat at constant fluid pressure and µt is the turbulent viscosity.
- Prt is a turbulent Prandtl number, we will take: Prt= 0.85.

3. Numerical modeling

Our problem, described by the equations above (non-linear and coupled together), only admits analytical solutions for very simplified cases. It is therefore almost impossible to obtain an exact analytical solution of the equations. A numerical resolution is required. To solve this problem, we used the finite volume method [17]… More efficient than classical methods based on finite differences in the treatment of complex geometry problems, the finite volume method is more economical in terms of volume and calculation time while guaranteeing great stability with regard to calculations.

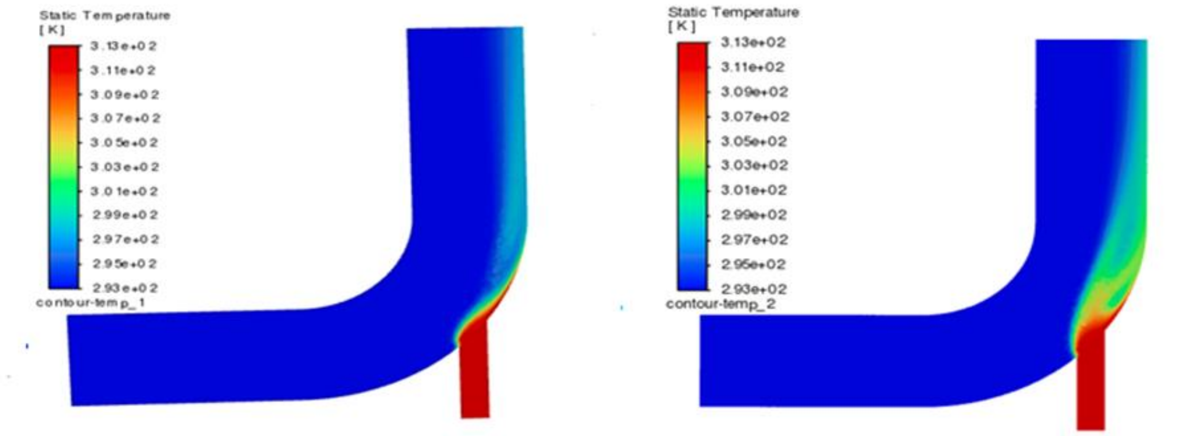
To minimize numerical diffusion effects, the QUICK scheme [17] is used to discretize the convective terms. It is known for its accuracy in representing gradients and is particularly effective for turbulent flows and high gradients. For Pressure-velocity coupling, we used the coupled scheme.

All numerical tests are performed with convergence threshold residuals for the momentum, k-epsilon, continuity and energy equations equal to 10^{-6} to meet both the speed, precision and better convergence of calculations.

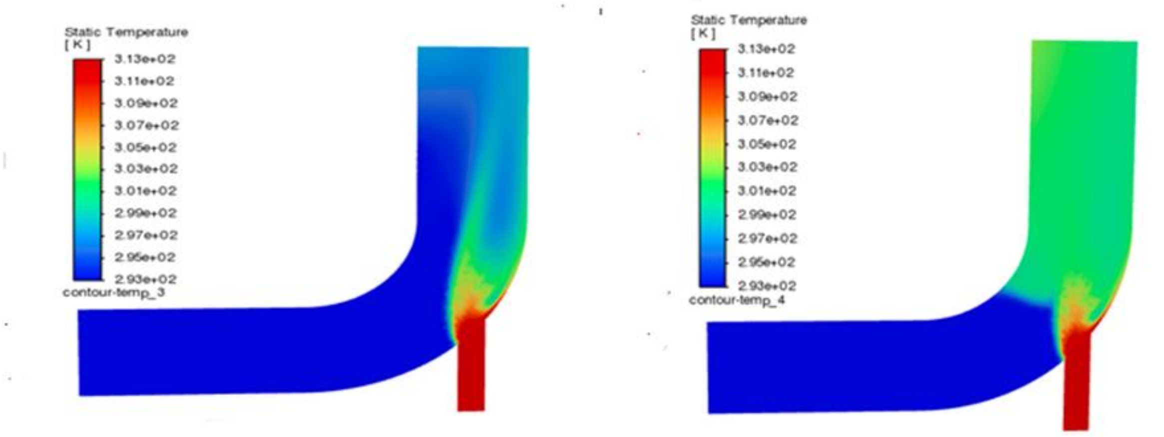
4. Results & Discussion

In this study, we will carry out the CFD (Computational Fluid Dynamics) analysis of the mixing elbow, to determine the influence of the variation at inlet 2 velocity, using the ANSYS FLUENT software.

The results presented in this article are the temperature profile and the velocity profile and have been validated against the available literature [14]-[16].



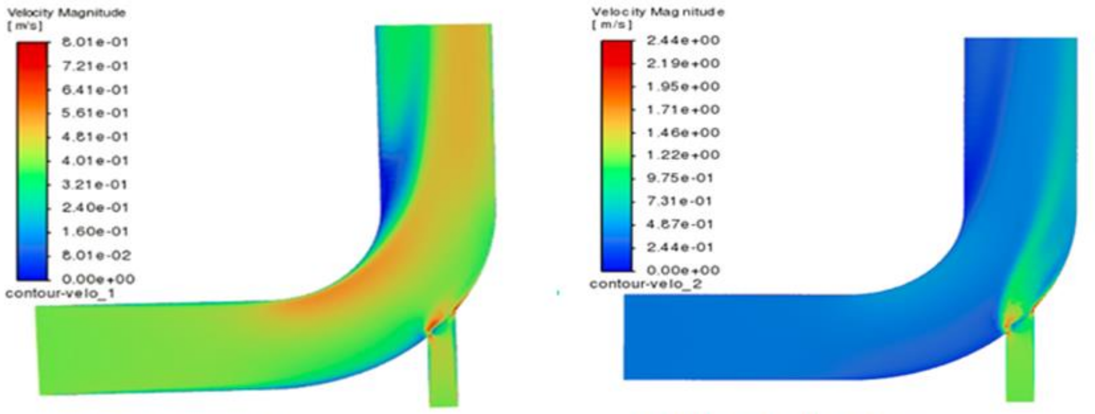
(a) Inlet 2 velocity : 0.4 m/s (b) Inlet 2 velocity : 1.2 m/s



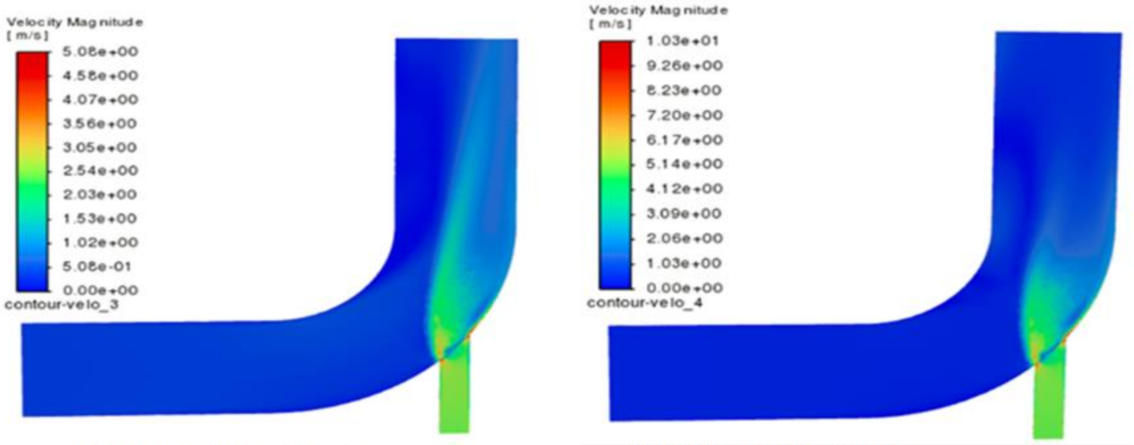
(c) Inlet 2 velocity : 2.5 m/s (d) Inlet 2 velocity : 5.0 m/s

*Figure 1**:** Temperature profile in the Mixing elbow at different of inlet 2 velocity values*

The temperature and velocity profiles in the plane (x,y,z=0) and the temperature in the plane of the section at the outlet of the mixing elbow according to the of inlet 1 velocity to 0.4 m/s and with four different of inlet 2 velocities (Inlet 2 velocities: 0.4 m/s; 1.2 m/s; 2.5 m/s and 5.0 m/s) are presented in Figure 2, Figure 3 and Figure 4 according to contours. The cold fluid with a temperature of 293.15°K enters through the large diameter inlet (inlet 1) with a velocity of 0.4 m/s while the hot fluid with a temperature of 313.15°K enters through the small diameter inlet (entry 2) and mixes with the turbulent nature of the flow. The temperature distribution undulates the surface of the fluid despite the viscosity of the fluid and the properties of the mixing elbow (effect of convection). The temperature contour of the (x,y,z=0) plane of the mixing elbow is shown in Figure 2.



(a) Inlet 2 velocity : 0.4 m/s (b) Inlet 2 velocity : 1.2 m/s



(c) Inlet 2 velocity : 2.5 m/s (d) Inlet 2 velocity : 5.0 m/s

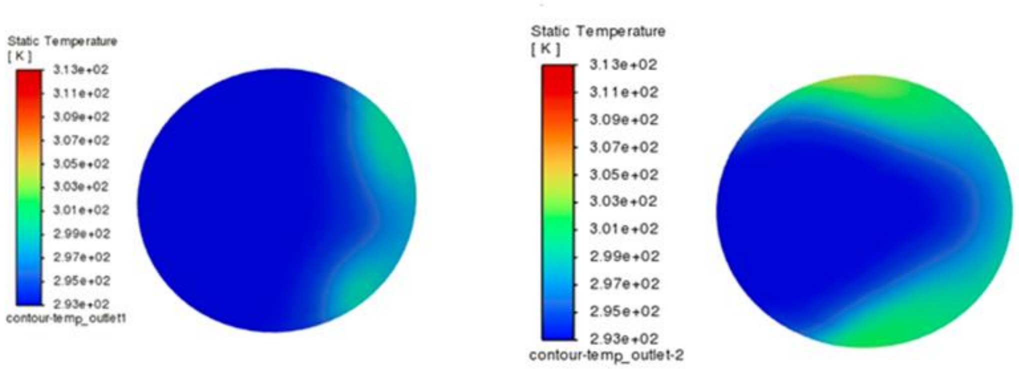
Figure 3: Velocity profile in the mixing elbow at different values of inlet 2 veloctiy

Figure 3 shows the velocity profiles at different inlet 2 velocities. When the fluid enters the elbow through inlet 1 with a uniform velocity of 0.4 m/s, near the wall, the velocity is essentially zero due of the shear stress without slip conditions and increases slightly further from the walls.

We notice that the mixing occurs at the elbow, before the outlet. The area in which effective mixing takes place varies with inlet 2 velocity. These areas, areas of effective mixing for temperature (Figure 2) and for velocity (Figure 3) increase with increasing inlet 2 velocity.

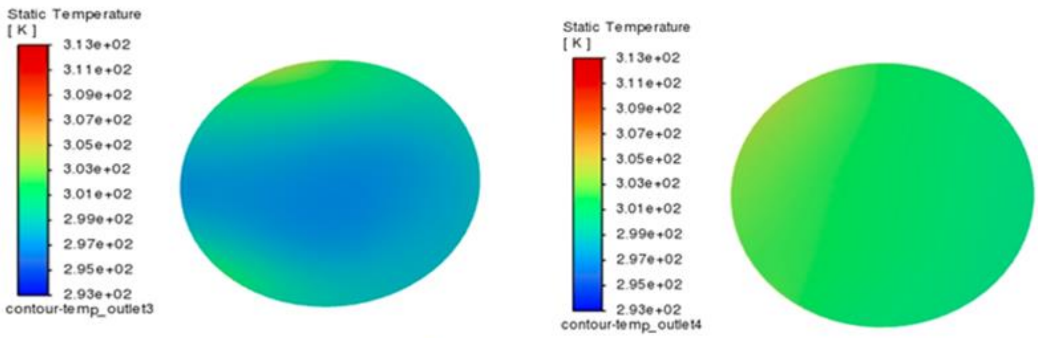
We also see that the higher the inlet 2 velocity, the more uniform the temperature at the outlet, the more efficient and better the mixing is (Figure 4).

With its increase (inlet 2 velocity), we notice excessively strong shocks (peaks or spikes in velocity) of the flow at the meeting of the two flows (of the two inlets) due to turbulence. For example, for values of inlet 2 velocity equal to 2.5 and 5 m/s, the shocks reached respective velocities of 5m/s and 10m/s. These very high velocities can have consequences (or effect) on the resistance of the elbow material.



(a) Inlet 2 velocity : 0.4 m/s

(b) Inlet 2 velocity : 1.2 m/s



(c) Inlet 2 velocity : 2.5 m/s

(d) Inlet 2 velocity : 5.0 m/s

Figure 4: Temperature profile at the outlet section of the mixing elbow at different inlet 2 velocity values

5 Conclusion

In this study, we carried out the CFD (Computational Fluid Dynamics) analysis of the mixing elbow by determining the influence of the variation in of inlet 2 velocity with the use of the ANSYS FLUENT software. To describe such a flow, which is turbulent, the Reynolds averaged Navier-Stokes equations (RANSE) and the k-ε closure model and for the temperature field, the conservation equation of the averaged energy were chosen. For the numerical resolution of this problem, we used the finite volume method and for Pressure-velocity coupling, we used the coupled scheme. After validating our model, the influence of the input speed 2 was studied.

The following conclusions were drawn:

- The greater the of inlet 2 velocity, the more the effective mixing zones increase, the more uniform the temperature at the outlet and the better the mixing,
- We also note excessively strong shocks (velocity peaks or spikes) with the high values of inlet 2 velocity, shocks which can impact the material.

To have a better mixture, we must choose high but moderate of inlet 2 velocity while taking into account the properties of the material because of the velocities that these peaks could have.

Nomenclature

Latin letters

Cp: Specific Heat, J/(Kg.K)
D : Main pipe diameter, m
g : Acceleration of gravity, $m.s^{-2}$
K: kinetic energy of turbulence, $m^2.s^{-2}$
P: Pressure, Pa

S_{ij} :Strain rate tensor
t : Time, s
$\overline{T}$: Filtered temperature, K^{-1}
u, v, w : Velocity components, m.s^{-1}
u', v', w': Fluctuating velocity components, m.s^{-1}
$\overline{u}_i$: Filtered velocity component in x_i direction, m.s^{-1}
u_τ : Parietal Friction Velocity
x, y, z: Cartesian coordinates, m
Pr: Laminar Prandtl number
Pr_t : Turbulent Prandtl number

Greek letters

α : Thermal diffusivity, m^2.s^{-1}
β : Coefficient of thermal expansion, K^{-1}
λ : Thermal conductivity, W.m^{-1}.K^{-1}
υ : Kinematic viscosity, m^2.s^{-1}
ρ' : Density, kg.m^{-3}
μ : Dynamic viscosity, kg.m^{-1}.s^{-1}
α : Thermal diffusivity, m^2.s^{-1}
λ : Thermal conductivity, W.m^{-1}.K^{-1}
ν : Kinematic viscosity, m^2.s^{-1}
ρ : Density, kg.m^{-3}
σ_{ij}: Laminar stress tensor, Pa
τ_{ij}: Subgrid scale stress tensor, Pa
μ: Molecular dynamic viscosity, kg.m^{-1}.s^{-1}
μ_t: Turbulent dynamic viscosity, kg.m^{-1}.s^{-1}
ν: Molecular kinematic viscosity, m^2.s^{-1}
ν_t: Turbulent kinematic viscosity, m^2.s^{-1}
ε: Turbulence kinetic energy dissipation rate, m^2

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