Effect of Local Turbulent Structures on the Hot Jet in Transitional Flow

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Abstract. Turbulent parts localized in flow direction may arise in a pipe with transitional regime of the stable laminar Poiseuille flow. A key condition for occurrence of such structures is a pipe with rather long length relative to its diameter. Our paper presents numerical modelling of the hot air jet flowing from the long pipe into the cold open volume at Re=2426. The modelling was performed in OpenFOAM software on the basis of the large eddy simulation (LES) method. The WALE (Wall-adapting local eddy-viscosity) model was used for closure of Navier-Stokes equations on subgrid scales. We demonstrated that local turbulent structures have a weak effect on the hot jet at flowing into the cold open volume.

1. Introduction
Turbulent parts localized in flow direction may arise in a pipe with transitional regime of the stable laminar Poiseuille flow [1]. A key condition for occurrence of such structures is a rather long pipe length relative to its diameter. In most experimental works devoted to the so-called turbulent puff-structures an outer action generates the eddy package that allows obtaining well-determined structures suitable for diagnostics. Puffs are generally about 20 pipe diameters long and travel at a velocity that is approximately $0.9U$ [2], where $U$ is the mean velocity of the flow. The lowest Reynolds number of finding the puff-structures varies in different investigations in the range Re=1750-2150. There are well-known methods that allow a significant delay in the start of the transition to turbulence in a pipe, e.g. a curvature of channel. Vester et al. [3] demonstrated experimentally that the secondary eddies arise in the laminar flow at Dean number $D_n = \text{Re} \sqrt{(d/R)} > 1$. Under such conditions the start of the transition in curved pipe delays up to Re~3500. The arising of puff-structures has a random character. A probability of the structure formation increases with an increase in the Reynolds number. Such structures may decay inside the pipe. A reverse process may take place, when adjacent structures increase in size and merge with each other during the pipe flow. These events lead to the local decrease in velocity and, consequently, arising of pressure pulsations. Pulsating flows are often placed at the edge of the transition to turbulence. The mostly expressed example is a cardiovascular flow, where the Reynolds numbers of the flow in large blood vessels belong to the transitional regime. Xu et al. [4] state that there is a linear dependence between critical Reynolds number and Womersley number: $\sqrt{Wo} = \text{Re} \sqrt{2\pi f/v}$.

Puff is a set of eddies, which have the inner structure with time and spatial anisotropy [1, 4]. Unlike the pipe stream, the sets of eddies in a free jet flow into a free space acting on a mixing layer. Lemanov et al. [5] demonstrated that disturbance of the mixing layer may have a delay in time after...
full flow laminarization at the axis of the jet. In thermally stratified flows scenarios of puff effect on the mixing layer apparently has to depend significantly on the density gradient in radial direction. The goal of the present paper is investigation of the hot air jet with puff-structures flowing into the cold free volume.

2. Flow configuration and modelling approach
We considered the flow of the air hot jet with the inlet temperature of $900\, K$ from the adiabatic long pipe with a diameter of $8\, mm$ and a length of $0.8\, m$ into the free space with air temperature $T_{\text{out}} = 300\, K$. Such conditions give $Re=2426$. The modelling volume of the free space was limited by the cylinder with a height of $80\, mm$ and a diameter of $80\, mm$. We set the following conditions at the pipe inlet: fixed velocity field with $U_{\text{in}} = 35\, m/s$, isotropic turbulence $T_u = 2\%$ and the respective kinetic energy of turbulence $k_u = 0.735\, m^2/s^2$.

![Diagram of the flow considered.](image)

**Figure 1.** Diagram of the flow considered.

2.1. Equations and boundary conditions
The modelling was performed in OpenFOAM software on the basis of the large eddy simulation (LES) method. The interaction between velocity and pressure was established by the PIMPLE algorithm. We used solver «rhoPimpleFoam» that consists of the conservation laws of mass, momentum and enthalpy:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0,$$

$$\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_j u_i)}{\partial x_i} = -\frac{\partial P}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i,$$

$$\frac{\partial (\rho)h}{\partial t} + \frac{\partial (\rho u_i h)}{\partial x_i} = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\lambda_{\text{eff}} \frac{\partial (\rho h)}{\partial x_i}\right],$$

where $\tau_{ij}$ is the viscous and turbulent stress tensor given by $\tau_{ij} = \mu_{\text{eff}}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu_{\text{eff}}\frac{\partial u_k}{\partial x_k}\delta_{ij}$.

Here, $K$ is the kinetic energy of the flow, $\lambda_{\text{eff}}$ and $\mu_{\text{eff}}$ are sums of eddy and molecular heat conductivity and viscosity, respectively. The WALE (Wall-adapting local eddy-viscosity) model [6] was used to calculate turbulent parts of these parameters.

The following conditions were applied at borders of the modelling volume:

$x = 0: \ U = U_{\text{in}}, \ dP/\,dn = 0, \ T = T_{\text{in}}$ at the pipe inlet,

$y^2 + z^2 = \left(4\times10^{-3}\right)^2$ at $0 \leq x \leq 0.8: \ U = 0, \ dP/\,dn = 0, \ \partial T/\,\partial n = 0$ on the inner pipe surface,
$y^2 + z^2 = \left(40 \times 10^{-3}\right)^2$ at $0.8 \leq x \leq 0.88$ and $x = 0.88$: on free borders of the modelling volume.

At the initial time ($t = 0$), the modeling volume had the following parameters: $U = (0.1; 0; 0)$, $P = 10^5\, Pa$, $T = 300K$.

2.2. Mesh

To perform the simulation we created a hexagonal mesh with a number of cells of $1\, 203\, 200$ (Fig.2). The time step did not exceed $\Delta t = 10^{-6}\, s$. The imaginary continuation of the pipe in the free volume has the same size and distribution of cells as ones inside the pipe. The cell size increases with an increase in the distance from the central axes. The mesh has the following characteristics: maximal aspect ratio of 12.66, minimal cell volume of $1.66 \times 10^{-11}\, m^3$, maximal cell volume of $1.48 \times 10^{-8}\, m^3$, maximal non-orthogonality of 32.3, average non-orthogonality of 5.937, and maximal skewness of 1.15.

Figure 2. Mesh.
3. Results

Figure 3a shows variation of the instantaneous axes streamwise velocity at \(0.6m\) far from the pipe inlet. The turbulent structure goes through the pointed position at \(0.08s \leq t \leq 0.09s\). The structure is characterized by the decrease in the average velocity and by the increase in velocity fluctuation amplitudes. Figure 3a presents the behavior of the instantaneous axes streamwise velocity at the outlet of the pipe (\(x=0.8m\)). Here, we could not identify clearly the turbulent flow part similar to puff-structure since the flow has strong turbulization at the final part of the pipe (\(0.7m \leq x \leq 0.8m\)), and the velocity has a sinusoidal character of changing over time. Nevertheless, we tracked down the movement of the turbulent structure from \(x=0.6m\) to \(x=0.8m\) (pipe outlet) using visual analysis of the flow. It turns out that the centre of the structure leaves the pipe at \(t=0.091s\). Also, we know that the turbulent structure lies between two peaks of the average velocity. Then we may conclude that time limits of the structure at the pipe outlet correspond to \(t \approx 0.089s\) and \(t \approx 0.093s\), respectively.

![Figure 3a](image1)

**Figure 3.** Instantaneous streamwise axes velocity inside the pipe at \(x=0.6m\) (a) and at the pipe outlet \(x=0.8m\) (b).

![Figure 4](image2)

**Figure 4.** Instantaneous streamwise axes velocity in the vicinity of position \(x=0.6m\) during the movement of front border \((t=0.08s)\), centre \((t=0.085s)\) and the end \((t=0.09s)\) of the turbulent structure.
Figure 5. Instantaneous streamwise axes velocity in the vicinity of position $x = 0.8m$ (pipe outlet) during the movement of front border ($t = 0.089s$), centre ($t = 0.091s$) and the end ($t = 0.093s$) of the turbulent structure.

On the basis of instantaneous streamwise velocity fields, Fig. 4 illustrates the movement of the turbulent structure through the middle part of the pipe. At $t = 0.08s$, the start of the structure is situated in the vicinity of position $x = 0.6m$. Downstream the flow has a laminar regime. The
conventional centre of the structure, characterized by the low average velocity, moves through the pointed position at $t = 0.085s$. The end of the turbulent structure is well-distinguished from the next following laminar part ($t = 0.09s$). One may note that the turbulent structure generates some large scale eddies within the subsequent laminar flow, which are absent within the preceding laminar part.

Figure 5 presents the fields of instantaneous streamwise velocity in the vicinity of the pipe outlet into the free volume. The jet behavior at the start ($t = 0.089s$), the centre ($t = 0.091s$) and the end ($t = 0.093s$) of the turbulent structure exit has no noticeable differences. It is worth noting that large scale eddies occur within the final part of the pipe flow ($0.7m \leq x \leq 0.8m$) regardless of the flow regime. The reason for these eddies is the significant density drop between the hot air in the pipe and the cold air in the free volume. Thus, the local turbulent structures have a weak effect on the hot air jet blowing into the free cold volume.

4. Conclusions

Large eddy simulation of the hot jet flowing from the long pipe under the conditions of the transitional regime demonstrated the following results:

- The localized turbulent structures may arise inside the pipe with the non-isothermal jet and $Re_J = 2428$.
- The localized turbulent structure takes place only within the limited part of the pipe flow. While the structure moves to the pipe exit, it is "compressed" and collapsed due to the noticeable difference of the air density inside the pipe and in the outer volume.
- The localized turbulent structures have no effect on the hot jet flowing into the cold outer volume.

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