Specific Aspects of Turbulent Flow Separation in Nods and Junctions of Pipelines

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Abstract. The paper is devoted to numerical simulation of space effects appearing with flow separation in pipeline junctions. Gas and oil flows through T-bends are considered. Two-parametric turbulence models are analyzed, among them $k$-$\omega$ is chosen. Results of numerical simulation are analyzed and explained, practical recommendations on appropriate t-bend geometry are given.

1. Introduction

Pipeline transportation anywhere in the world demands significant expenditures, both capital in construction / reconstruction and operational for equipment maintenance. The age of pipeline networks grows and risks of environmental hazards grow accordingly. That’s why one can observe increasing interest in technologies that can make possible complete utilization of pipeline network capacities and extend its’ accident-free operation. Under these conditions problems of complex physico-mathematical and numerical simulation of three-dimensional liquid and gaseous viscous flows in pipelines with complex boundaries of current represent broad interest.

Complete and particular enough analysis of flow structure one can obtain in terms of second order statistical models for Reynolds shear stresses (RSS), K-theory of turbulence, including two-parametric dynamic models of turbulence of $k$-$\varepsilon$, $k$-$\tau$, $k$-$\omega$, $k$-$L$ types. This approach makes possible an insight into the momentum transfer process under conditions of low and moderate intensity of velocity pulsations and allows to predict shear flows with adequate success. Understanding of redistribution mechanisms in case of space deformation of viscous flow will develop effective solutions for flow control, decrease of accident rate, effective maintenance of pipeline in many branches of manufacturing – oil –and-gas industry, heat and water supply [1-6].

Investigation of non-linear three-dimensional hydrodynamic processes is commonly carried out in terms of semiempirical theory of turbulence with attraction of Reynolds averaged Navier-Stokes equations (RANS). The method has strong problem of appropriate turbulence model selection. Moreover in calculations of inner low-Reynolds flows it is significant for turbulence model to exert “computational flexibility” and stability against perturbations caused by near-transient regimes of low turbulence [5].
2. Aim of investigation
The aim of the investigation is a detailed mathematical simulation and investigation of separating shear flows appearing in pipeline T-junctions under conditions of low and moderate turbulent vortex intensity in terms of low-Reynolds second order closure schemes. Investigation aims also include prediction of deflected zones in pipelines, estimation of turbulent models’ efficiency in prediction of transient turbulence structure in T-junctions.

3. Statement of problem

Theoretical base
Simulation of flow separation was performed with approximation of stationary turbulent and near-transient flows of incompressible and weakly compressible dropping Newtonian viscous media. Geometry was considered three-dimensional. Heat exchange in system was defined with moderate heat fluxes localized at pipeline wall.

Common mathematical statement of problem includes system of full dynamic Reynolds equations (RANS), equations of state, continuity, energy in Cartesian coordinates [4,6], which is incomplete with respect to Reynolds shear stress tensor $\overline{u_i u_j}$ and specific heat turbulent flows $\overline{u_i u_j}$ [4-6]. The closure of governing equations was performed in terms of Boussinesq hypothesis and two-parametric dynamic turbulence models: standard two-parametric $k$-$\varepsilon$ model of Johns-Launder [4], $k$-ω models of Wilcox and Menter [5] (where $k$ – turbulence kinetic energy, $\varepsilon$ – dissipation rate of $k$, $\omega$ – turbulence frequency, also called pseudovorticity).

Numerical solution was built in terms of control volume approaches (SIMPLE and its’ modifications [7]).

T-bend geometry and oil properties
Computational model was represented by flush joint T-junctions (T-bends) according to GOST 17375-2001 [8]. The “neck” of the T-bend – the place of lateral branch connection into the main line – was expressed by rounding with radius over 5 mm (agreeably to GOST). T-bend models were appended with direct regions of 160 inner diameter length to provide “thin” turbulence parameter stabilization at inlet into T-bend.

Calculations were performed at pipe outer diameters up to 820 mm. Reynolds criterion Re was taken from $3 \cdot 10^3$ up to $10^6$.

Working medium was represented with low- and middle-viscous oils, the Newtonian assumption for which is valid with certain permissible variations excluding low-temperature conditions near the chilling (congelation) or wax deposition temperature.

Figure 1. Flow velocity distribution at symmetry plane for turbulent mode.

Figure 2. Axial velocity distribution along main line axis versus distance to side branch, “+” and “-” correspond to bringing closer and move away from branch.
4. Results and discussion

Results of T-bends’ numerical simulation are represented at figure 1-4. Working medium at given maps flows along OX axis, in T-junction flow separates and a part of it enters lateral branch (OY direction). According to figure 1 zones of maximal motion intensification appear in points of flow separation from the main line at the T-bend’s neck and on inner surface of side branch in place of separated flow strike. At the opposite wall of branch there appear decelerated flow zone. I.e. at the T-bend neck flow sufficiently accelerates, separates from the main line and strikes the lateral branch.

![Figure 3. Radial velocity distribution along main line axis versus distance to side branch (notations according to figure 2).](image1)

Analyzing velocity profile on lines, parallel to OX, one can observe disruption of flow axial symmetry near the flow separation zone, with further reconstruction to axial symmetry at the T-bend outlet (figure 1,2). In flow redistribution area axial symmetry disruption appears in the following way: at fluid flow lines situated under the main line axis one can observe smooth flow rate change (figure 2, solid lines). At the same time at lines close to lateral branch (dashed lines) axial velocity growth is observed, with following sharp decrease to extreme values when crossing the lateral branch axis and further restoration to values corresponding to axisymmetric flow. Radial velocity redistribution in T-bend (figure 3) is also of serious interest: it is sufficiently asymmetric across lateral branch axis (OY) and reaches maximal values in the zone of separated flow strike on branch wall.

![Figure 4. Dimensionless friction factor on T-bend wall at Re=10^4.](image2)

![Figure 5. Turbulence kinetic energy on symmetry plane.](image3)

![Figure 6. Turbulence kinetic energy distribution along main line axis versus distance to side branch (notations according to figure 2).](image4)
Figure 7. Turbulence kinetic energy balance in cross-sections: $x=-1.0D,-0.5D$ correspond to entrance region of T-bend, $x=+0.5D,+1.0D$ – output from T-bend on the main line, $y=+0.5D,+1.0D$ – side branch.

Mentioned above assumption about the separation character of flow in T-bend is approved with shear stress' distribution on T-bend inner surface (figure 4). One can see that zones of potential risk are T-bend’s neck and initial area of lateral branch in which girth weld, connecting pipe to T-bend, is usually located. However with neck rounding growth separated flow intensity decreases that let to reduction of dynamic load on lateral branch.

Analysis of steady flow at the outlets of T-bend shows that flow separation appears significantly not uniform – flow rate in main line after T-bend can hold up to 65% of all flow – thus exceeding flow rate in junction in two times (of course, characteristics of side branch and main line after the T-bend are...
taken to be hydraulically equal). Obtained result can be explained with distribution of turbulence parameters. Thus, according to turbulence kinetic energy figure 5, turbulent vortex occur in lateral branch, creating additional hydraulic resistance to liquid flow into branch.

Turbulence kinetic energy profile analysis on lines, parallel to OX (figure 6), correspond to that of velocity – while along distant from side branch dashed lines $k$ smoothly decreases, near the lateral branch $k$ appears two maximums. This maximums correspond to extreme values of velocity and occur at $x = \pm 0.5 \ R$ – i.e. in the beginning and at the end of lateral branch.

Balance of turbulence kinetic energy is represented at figure 7. In the area before the inlet ($X=-1.0D$), as it takes place for steady flows [9], in near wall region generation of turbulence kinetic energy is balanced with its dissipation. But in the inlet of T-bend ($X=-0.5D$), at T-bend’s neck $Y\approx0.4\div0.5D$ convective mechanisms begin to play governing role, improving flow separation from the wall.

Outlet from the T-bend on the main line ($X=+0.5D$) is also significantly not symmetric. While at the wall opposite the branch balance is quiet to that of steady flow, area of flow attachment characterizes with large scale perturbations of convective and turbulent diffusive components.

In the side branch there observed a very complicated structure of turbulence kinetic energy balance. In both sections ($Y=+0.5D,+1.0D$) convective components play significant role, being balanced with generation and turbulent diffusion at $Y=+0.5D$ and generation and dissipation at $Y=+1.0D$.

Obtained results lead to following practical recommendations: elongation of lateral branch away from recirculation zone and maximization of neck curvature radius. It let not only to increase durability of T-bends but also reduce its hydraulic resistance. Obtained results also illustrate practically important fact of less reliability of welded T-joints [10] in comparison with T-bends. Its explanation partially consists in flow separation (because T-joint has now neck curvature) and intensive dynamic strike in lateral branch wall. In this case preferred utilization of prefabricated T-bends is recommended.

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