Brazilian Journal of Chemical Engineering

Assessment of the use of static mixers for the dilution of heavy oils with the use of a computational fluid dynamics model

Journal:	*Brazilian Journal of Chemical Engineering*
Manuscript ID	BJCE-2018-0228
Manuscript Type:	Original Article
Date Submitted by the Author:	29-May-2018
Complete List of Authors:	Lozada Garcia, Nayla; Universidade Estadual de Campinas, Engenharia Quimica Gonzalez Silva, German; Universidad Industrial de Santander, Ingeniería de Petróleos Alvarez Castro, Helver; Unidades Tecnologicas de Santander, AC Ingenieria Virtual Nunhez, José; Universidade Estadual de Campinas, Engenharia Quimica
Keyword:	Static mixers, Montionless mixers, Heavy oil transport, Heavy oil dilution

Assessment of the use of static mixers for the dilution of heavy oils with the use of a computational fluid dynamics model

Abstract

Static mixers have a wide range of applications in different industrial fields. They normally consume less energy and have a lower operation cost when compared to other blending systems. This study analyses the behavior of the blending of two miscible liquids in a heavy oil dilution process. The fluids are hydrocarbons mixed either with alcohol or with a hydrocarbon derivate. The goal is to optimize the transport process of petroleum in a lower pressure drop with the use of a static mixer. The homogenization performance was analyzed using CFD. The 3D model considers multicomponent flow inside the static mixer. The results so far have shown to be consistent with those found in the literature data. The number of mixing elements in the static mixer is a very important parameter in the design of this type of device because it not only determines the final coefficient of variation, but also establishes the cost of the equipment. In addition, results show that the use of alcohol for heavy oil dilution is an excellent alternative, not only because it improves mixing, but it also represents a significant reduction in the price of the solvents that are normally used in the petroleum industry.

Key Words: Static mixers, montionless mixers, heavy oil dilution, heavy oil transport.

1. Introduction

Static mixers have become extensively used in industrial processes and new designs have been implemented in different areas. There are more than 30 types of commercial static mixers available and about two thousand patents around the world. Their wide range of use relates to their low energy consumption and maintenance cost due to the non-presence of mobile parts. Another reason for their being widely used is the high degree of homogenization achieved in a fluid mixture (Thakur R.K. et al. 2003). Besides the above mentioned advantages, motionless mixers, as they are also called, become attractive when parameters of cost-effectiveness of the process are being considered. The installation of equipment should also be taken into account, and in this aspect static mixers are ideal since they only replace a piece of tube where they are installed. The residence time of the fluid is low (Akram G. et al. 2014). The design of this equipment uses fixed solid elements inside pipes. Those solid elements have the objective of diverting the fluid in the radial direction in order to obtain a better fluid homogenization. The number of elements inside the static mixer and the way they are distributed are paramount to achieve an optimal mixture of the fluid (Theron F & Le S.N. 2011). In general, the degree of efficiency in mixing operations of highly viscous liquids in static mixers depends on two different important factors. The first one is the energy consumption, which is measured by the pressure drop, and the second one is its compactness, which is measured by the length of the equipment (Meijer E.H. et, al 2011). Mixing operations in static mixers usually depend on three main mechanisms. The first one is the fluid movement generated by the action of the mixing elements inside the system, which is the main mechanism that defines the degree of homogenization. Mixing by diffusion is the second mechanism that occurs in static mixers. Diffusion occurs by contact between the different fluids. The third mechanism is shear, which takes place due to a high velocity gradient (Mayer C.L. et.al. 2014).

The dilution of the petrol can help in lowering the viscosity of the crude oil and reduce the energy consumption to transport the oil (Gateau P. et.al., 2004). Nafta is the solvent normally used for the dilution of the heavy oil. However, others fluids such as alcohols (ethanol and penthanol), also provide decrease in the viscosity of the crude oil (Saniare A. et.al. 2007; Shadi W. et.al. 2010).

2. Model Parameters for the static mixer development.

The performance of static mixers is normally investigated using two parameters: mixing efficiency (estimated via a coefficient of variation) and pressure drop.

Mixing efficiency is one of the fundamental criteria used when selecting a static mixer (Akram G. et al. 2014). It depends on the flow regime (laminar or turbulent), fluids properties and the percentage of fluids being mixed. In a turbulent flow the mixing efficiency is expected to be higher than in a laminar flow, due to the formation of vortices increasing the mixing process (Funakoshi M. 2008).

Mixing efficiency in static mixers is normally described by a coefficient of variation (CV), which is defined as the ratio of the variance of the mass fraction (σ) in relation to the average of the concentration of the sample $\bar{C}$ in the outlet profile of the static mixer as shown in Eq. (1) (Heywood N.J. 1984).

$$CV = \frac{\sigma}{\bar{C}} \tag{1}$$

The estimate of the standard deviation (σ) considers the concentration of the product at the exit, the average of the concentration at the exit ($\bar{C}$), and the number of points (n) where concentration is determined at the outlet, as shown in Eq. (2) (Heywood N.J. 1984).

$$\sigma^2 = \sum \frac{(C - \bar{C})^2}{n - 1} \tag{2}$$

The acceptable value of CV that indicates a good quality of mixing in chemical industrial applications of static mixers is 0.05 (Etchells III et. al. 2004). The CV is directly affected by parameters such as the geometry of the static mixer, viscosity and relative proportion of the fluids being mixed and flow regime. The mixing of fluids with considerable differences in viscosity presents an unusual homogenization pattern, especially if the most viscous fluid in present in a relative small amount, resulting in low efficiency of the device if the geometry is not suitable (Montante G. et al., 2016)

The pressure drop is another relevant parameter for the selection of static mixers (Vial C. et al 2000). It is taken into account to evaluate the energy consumption for that device. The pressure drop is analyzed in terms of the Z factor that is ratio of the pressure generated by the static mixer (ΔP_{mixer}) in relation to the pressure drop generated by the empty pipe (ΔP_{tube}) at the same flow conditions and length of the static mixer, as shown in Eq. (3) (Rauline D. et al., 1998).

$$Z = \Delta P_{mixer}/\Delta P_{tube} \tag{3}$$

The pressure drop increases depending on the number of fixed elements inside the pipe and the nature of the fluids (Etchells III et. al. 2004).

3. Mathematical model and simulation conditions.

The static mixer simulated in this work is a similar design to Low Pressure Drop (LPD) propose in Jovanović A. et al, (2014). In the first stage, the LPD was simulated with the same dimensions of Jovanović A. et al, (2014), and was analyzed the velocity to validated the model. In the second stage was varies the dimensions of the static mixer. The design and angles of the mixer elements are the same. Variation in dimensions was made considering the diameter of oil pipelines to transport heavy oil. The geometric configuration of LPD is usually used in laminar and turbulent flow. Its characteristics are appropriate for high viscosity flow. The geometry for the second stage is shown in Figure 1. The length of the static mixer has a diameter of 0.2286 metros (D = 0.2286 m) and a length of 12D.

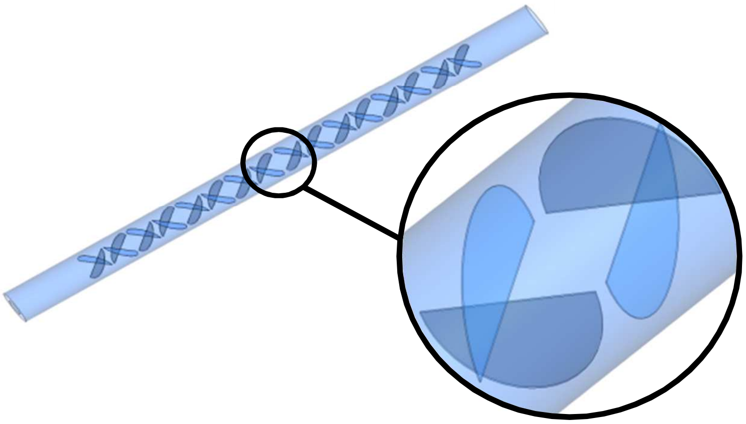

Figure 1 – LPD static mixer geometry

The simulation for this work considered a static mixer with two concentric surfaces for the inlet fluid, which covered the full inlet cross-section. The fluids were fed at the inlet and atmospheric pressure were considered at the outlet of the static mixer. The hydrocarbon fluids used were completely miscible, and the gravitational force did not have an effect on the flow. The value of the fluid diffusivity was $10^{-10}\ m^2/s$ the molecular diffusion which was insignificant.

The numerical solution for this model was performed with the finite volumes method, with the use of the CFD software CFX, from ANSYS. The proposed mathematical model in this work uses the Continuity Equation (Eq. 4), the momentum equations also known as Navier Stokes Equations and it considers turbulent flow (Eq. 7 and 8). Turbulence is included in the methods for solution of Navier Stokes Equations. In cases that is include the turbulence, the velocity (the transported quantity) is the sum of an equilibrium and a fluctuating components U and u'. Consequently, the solution is based on the Reynolds average Navier Stokes (RANS) equations (Eq. 5 and 6). Therefore, the velocity u is dispersed into mean velocity U and fluctuating part *u'* (Mirella C. et.al., 2012):

$$\nabla \cdot (\rho \mathrm{U}) = 0 \tag{4}$$

$$\nabla \cdot (\rho \mathbf{U}\mathbf{U}) = -\nabla p + \mu \nabla^2 U - \nabla \cdot (\rho \overline{u'u'}) \tag{5}$$

Where **U** is the main velocity vector, ρ is the averaged density of the fluid, μ is the viscosity of the fluid, $\rho\overline{u'u'}$ is the Reynolds stress tensor. Mixing of Fluid 2, Fluid 3 and Fluid 4 into the Fluid 1, is evaluated coupling with the Navier-Stokes equations with the Reynolds convection-diffusion equation for the component:

$$\nabla(\rho U\Phi) = \nabla\cdot\left(\rho D_m \nabla\Phi + \frac{\mu_t}{\sigma_t}\nabla\Phi\right) \tag{6}$$

Where Φ is the component volumetric fraction, D_m is the molecular diffusivity, μ_t is turbulent viscosity and σ_t is the turbulent Schmidt number. The molecular diffusivity was considered a value of 10^{-10} m/s. A tetrahedral mesh (non-structured) was used for the domain discretization. Non – structured meshes allow for easier refinement of specific areas, such as the boundary layer and the walls. Five layers of prims were placed at the wall for a correct prediction of the velocity and concentration at the walls. A growth rate of 1.3 was considered. The geometry used about 600.000 elements. The converged solution considered that the residue in all equations were less than 10^{-5}.

Turbulence significantly influences the solution of the mass and momentum equations. In addition, turbulence equations bring a closure to the conservation equations (Peyret 2004). The Shear Stress Transport Model (SST) is the model of turbulence used in the development of this project. The SST model uses the κ-ω model at the walls of the static elements and the pipe and the κ-ε model for the bulk flow. The Turbulence equations are given in Eq. (7) and Eq. (8) (Menter F.R. 1994).

$$\rho\left(\frac{\partial k}{\partial t}+\frac{\partial k}{\partial x_i}\right) = P_k - \beta^*\rho k\Omega + \left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] \tag{7}$$

$$\rho\left(\frac{\partial\Omega}{\partial t}+\vec{U}\frac{\partial\Omega}{\partial x_i}\right) = \alpha\rho S^2 + \beta\rho\Omega + \frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\omega}\right)\frac{\partial\Omega}{\partial x_i}\right] + 2(1-F_1)\rho\sigma_{\omega 2} + \frac{1}{\Omega}\frac{\partial k}{\partial x_i}\frac{\partial\Omega}{\partial x_i} \tag{8}$$

Where k is the kinetic energy of turbulence, $\vec{U}$ is the velocity vector in the *i* direction, P_k is the production of turbulence energy, β^* and β are constants equal to 0.09 and 0.075

respectively, Ω is frequency of the turbulence, μ_t stands for the turbulent viscosity, α is the contant of the SST model, S represents the shear stress, σ_k , σ_ω and $\sigma_{\omega 2}$ are the constants equals to 1, 0.5 and 0.856 respectively, and F_1 is a blend function.

4. Fluid conditions

Two hydrocarbons with a great difference in viscosity and density were considered. Table 1 describes the characteristics of each fluid. Fluid 1 is heavy oil (low API) and Fluid 2 is light oil (high API), while Fluid 3 and Fluid 4 are ethanol and penthanol, respectively. This blend of the heavy oil with any of the other fluids aims to lower the density and viscosity of the heavy oil in order to decrease the power consumption of the transport of oil through the pipeline.

Table 1 – Simulation conditions and property fluids

Characteristic	Fluid 1	Fluid 2	Fluid 3	Fluid 4
Viscosity (cP)	390,577	1.129	1.074	3.936
Density (kg/m^3)	1,003.940	717.500	789	814
API	7.8	58	-	-
Heat Capacity (J/Kg°k)	153.240	1,036.650	2,439.760	2,353.370
Thermal Conductivity (Wm^{-1}k^{-1})	0.133	0.112	0.179	0.145
Inflow (m^3/s)	0.037	0.005	0.005	0.005
Velocity (m/s)	1.180	0.530	0.530	0.530

Field velocity at the inlet is shown in Figure 2. It is possible to observe that fluids enter at the static mixer in two concentric entrance, with different and constant velocities. Fluid 1, which is in a high concentration (red profile), enter at 1.18 m / s, and Fluid 2, 3 and 4 enter at 0.53 m / s (green profile).

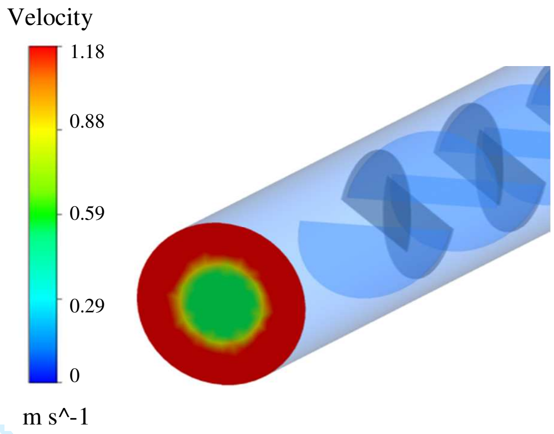

Figure 2 - Field Velocity in the inlet

Results

Mixing efficiency (CV)

Figure 3 presents the cross section mass fraction profiles for Fluid 2 at the length distances of L/D=0, L/D=4, L/D=6, L/D=12. It can be noticed that there is a clear mixing of the liquids throughout the static mixer from the inlet to the outlet. It was also observed at the profile L/D=4 that the mass fraction variation is high, between 0.05 and 0.2 (CV = 0.473), compared with the profile L/D=12, where the mass fraction varies between 0.15 and 0.2 (CV = 0.029).

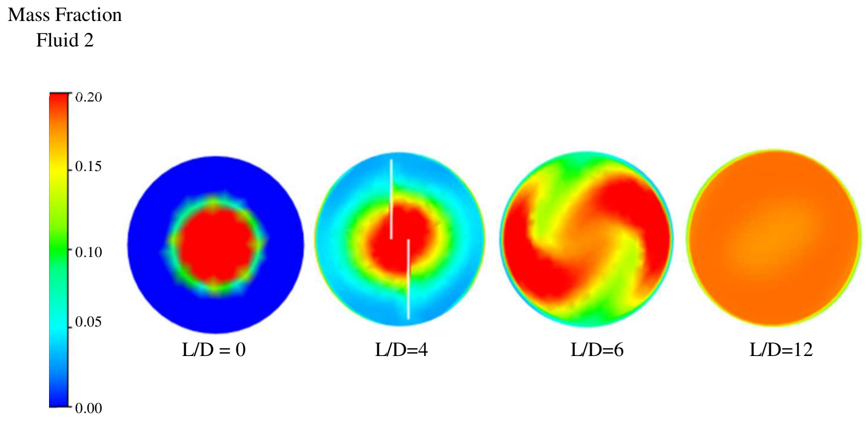

Figure 3 – Transverse profile of mass fraction for Fluid 2

The values of the coefficient of variation decrease from the inlet to the outlet, as expected, reaching the condition of being mixed at the outlet (CV = 0.0286 at L/D=12).

Figure 4 shows the mass fraction profiles for Fluid 2, Fluid 3 and Fluid 4. These profiles show that mixing is improved for Fluid 3 and Fluid 4, with the concentration varying between 0.17 and 0.20 at L/D = 12, while Fluid 2 varies between 0.15 and 0.20. The value of CV for Fluid 3 and Fluid 4 at L/D = 12 are 0.100 and 0.120, respectively. The value of CV clearly shows that the mixture was better homogenised using Fluid 3 and Fluid 4.

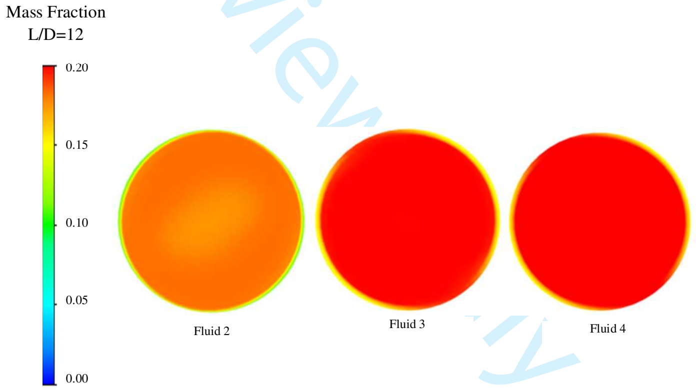

Figure 4 – Profiles of mass fraction for Fluid 2, Fluid 3 and Fluid 4

Table 2 shows the coefficient of variation (CV) through the static mixer for Fluids 2, 3 and 4. Fluids 3 and 4 present similar variations of the mass fraction throughout the mixer. The values of CV at L/D = 12 for Fluid 3 and Fluid 4 are 0.012 and 0.010 respectively, showing that the fluids are mixed.

Table 2 – Coefficient of Variation for Fluid 2, Fluid 3 and Fluid 4 at L/D = 4, 6 and 12.

Coefficient of Variation (CV)	L/D =4	L/D =6	L/D =8	L/D = 12
Fluid 2	1.077	0.183	0.045	0.028
Fluid 3	0.473	0.139	0.040	0.012
Fluid 4	0.397	0.125	0.038	0.010

The degree of homogenization of Fluid 2 at L/D = 12 is higher (CV=0.03) when compared with Fluid 3 and Fluid 4. Even considering the worst case of mixing (Fluid 2), the results show that if the number of elements in the static mixer decreases from L/D=12 to L/D=8, the concentration at the outlet continues to be mixed, since the Coefficient of Variation achieved is CV=0,045. Obtaining acceptable mixing efficiencies with a lower static mixer length is important, since it decreases both the pressure drop and the cost for manufacturing the equipment. Figure 5 present the cross section profiles for Fluid 2 at L/D=8 and L/D=12.

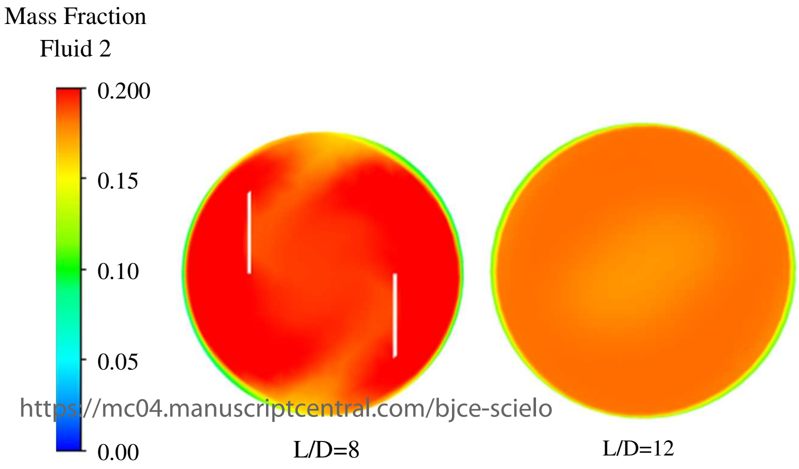

Figure 5 – Transverse profiles of mass fraction for Fluid 2 in L/D=8 and L/D=12.

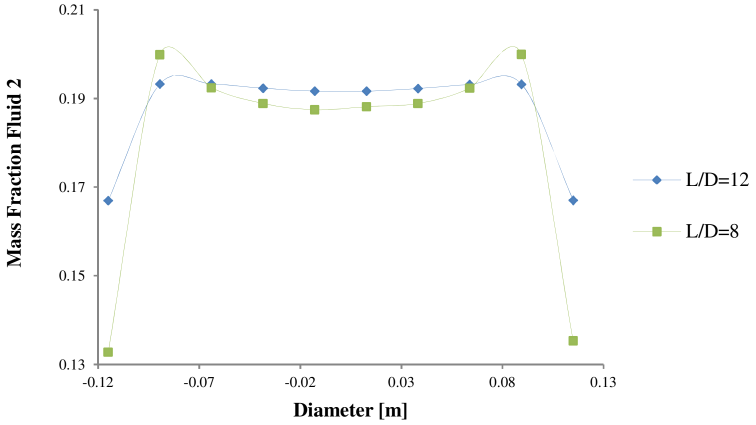

Figure 6 – Distribution of concentration for Fluid 2 in L/D=12 and L/D=8

4.2 Pressure drop

The pressure drop is an important criterion of selection and design of static mixers. The energy needed to inject the fluids depends on the pressure drop and this must be sufficient for the mixture to occur. This energy determines the cost operation of the equipment. Figure 7 presents the pressure drop (ΔP) in the static mixer similar to the LPD used in this work. It can be observe that the pressure drop is higher compared to the literature data of Sulzer and Kenics static mixers (Joaquim Jr., 2008). This comparison was made for turbulent flow and relation L/D=12. The high ΔP in the static mixer for this work is due to the high viscosity of the heavy oil. The high pressure drop makes it necessary to increase the pump energy of the fluids injection or the diameter of the static mixer.

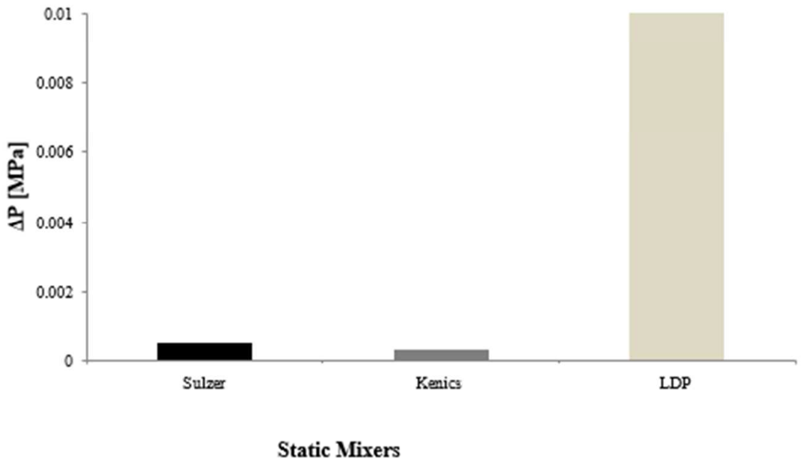

Figure 7 – Compared of pressure drop between Sulzer, Kenics and LPD statics mixer.

4.3 Velocity

Figure 8 represents the velocity profile throughout the static mixer Low Pressure Drop. As discussed earlier, in the first stage of this study, was simulated the static mixer with the same dimensions of Jovanović A. et al (2014) to validate the proposed model. The velocity profile taken from the literature data for LPD static mixer by Jovanović A. et al (2014), can be observe in Figure 8a. Figure 8b shows the velocity of the fluids obtained from the model simulation being studied, which made use of the data provided by the literature for LPD static mixer. When both profiles are compared, it is evident that the results show a high level concordance between the literature and the simulation data.

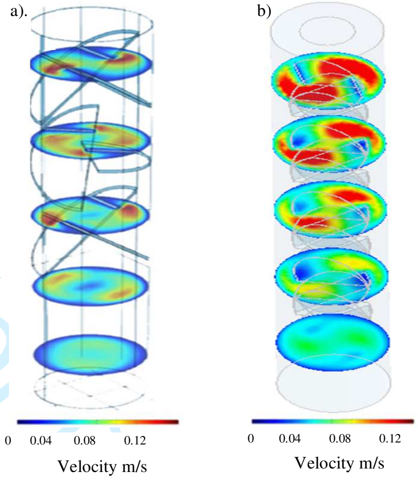

Figure 8 – Velocity profile model simulation compared to data from Jovanović A. et al (2014).

The velocity behavior through the static mixer obtained in this project is shown in Figure 9. This velocity profile was obtained with different dimensions to those used in the static mixer Jovanović A. et al (2014). These different dimensions are common in pipelines to transport of heavy oil. The velocity profiles of both fluids differ at the inlet of the static mixer, as shown in Figure 9a, becoming unified as soon as the mixing process is completely satisfactorily. The velocities distribution for the profiles L/D=0, L/D=6 and L/D=12 presented in Figure 9b. It can be seen that the velocity of the mixture varies significantly along the mixer becoming lower after the fluids blending. Near the outlet, the velocity becomes uniform showing values between 1.4 and 1.6 m/s in most part of the profile. This behavior is similar to the profile velocity of the literature Jovanović A. et al (2014).

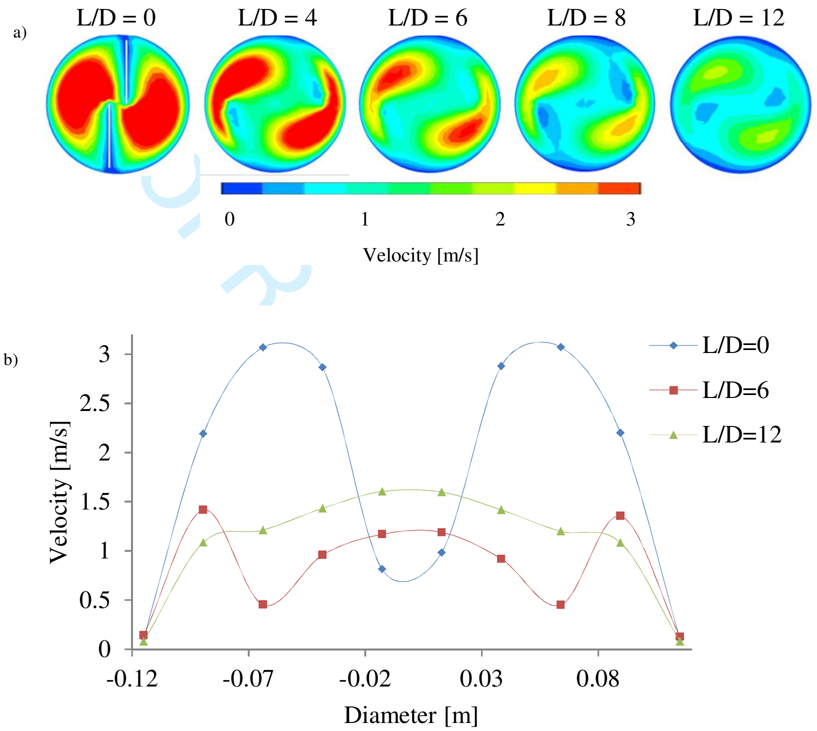

Figure 9 – Velocity behaviour throughout static mixer. a. Velocity profile planes. b. velocity distribution in the outlet profile.

5. Conclusions

The proposed simulation model for the performance of the static mixer LPD (Low Pressure Drop) reveled good prediction in all variables (velocity, mass fraction, coefficient of variation and pressure) when compared with the data from Jovanović A. et al (2014) and Joaquim Jr. et al (2011).

According to the coefficient of variation CV=3% obtained for the Fluid 2, it is evident that the static mixer LPD provides an excellent quality of the mixture. The results presenting uniform mass fraction profiles in the outlet of the device.

The suggested simulation model for alcohols, corresponding to Fluids 3 and 4, showed good prediction and presented better CV values compared with the CV value found for Fluid 2. Consequently, it is possible state that the use of Fluids 3 and 4 represent a lower cost, for the process.

NOMENCLATURE

SST	Shear Stress Tensor	
LPD	Low pressure drop static mixer	
CV	Coefficient of Variation	
σ	Standard Deviation	
$\bar{C}$	Average of the concentration	
Z	Ratio pressure drop in the static mixer and pressure drop in the empty pipe	
ΔP_{mixer}	Pressure drop generated by static mixer	Pa
ΔP_{tube}	Pressure drop generated by empty pipe	Pa
L	Length	m
D	Diameter	m
L/D	Ratio length and diameter	
API	American Petroleum Institute	
ΔP	Pressure drop	
k	kinetic energy of turbulence	
P_k	Production of turbulence energy	
$\vec{U}$	Velocity vector	
μ_t	Turbulent viscosity	

References

Akram G., Lemenand T., Valle D.D., Peerhossaini H. Static mixer: Mechanisms, applications, and characterization methods – A review. Chemical Engeneering Research and Design 92, 205-228 (2014).

Mirella Coroneo, Giuseppina Montante, and Alessandro Paglianti Computational fluid dynamics modeling of corrugated static mixers for turbulent applications. Industrial & Engineering Chemistry Research 51, 15986-15996 (2012).

Etchells III, A.W., Meyer, C.F. Mixing in pipelines. Handbook of Industrial Mixing – Science and Practice, 391–478 (2004).

Funakoshi M. Chaotic mixing and mixing efficiency in a short time. Fluid Dynamics Research 40, 1–33 (2008).

Gateau P., Hénaut I., Barré L., Argullier J. F. Heavy oil dilution. Oil & gas science and technology 91, 110-116 (2004).

Hasan S.H., Ghannam M.T., Esmail N. Heavy crude oil viscosity reduction and rheology for pipeline transportation. Fuel 89, 1095-1100 (2010).

Heywood, N. J., Viney, L. J. E Stewart, I. W. Institution of Chemical Engineers Symposium 89, (1984).

Joaquim Jr. C.F., Reynol A., Cekinski E., Seckler M.M., Nunhez J.R. Development of static mixers for miscible fluids in laminar flow with the use of computational fluid dynamics (CFD). The Canadian Journal of Chemical Engineering 89, 734-744 (2011).

Joaquim Jr. C.F.. Desenvolvimento e otimização de misturador estático com o uso da fluidodinâmica computacional (CFD). Tese de doutorado. Campinas SP, Brasil (2008).

Jovanović A., Pezo M., Pezo L., Lević L., "DEM/CFD analysis of granular flow in static mixers," Powder Technology 266, 240-248 (2014).

Mayer C.L, Gatumel C, Beerthiaux H. Mixing dynamics for easy flowing in a lab scale Turbula mixer. Chemical Engineering Research and Design 95, 248-261 (2014).

Meijer E.H., Singh K.M., Anderson D.P. On the performance of static mixers: A quantitative comparison. Progress in Polymer Science 37, 1333-1349 (2011).

Menter F.R. Two-equation Eddy-viscosity turbulence models for engineering applications. AIAA Journal 32, 8 (1994).

Peyret, Roger. Hanbook of computational fluid dynamics. Université de Nice. (2004).

Montante, G., Coroneo, M., & Paglianti, A. Blending of miscible liquids with different densities and viscosities in static mixers. Chemical Engineering Science 141, 250–260 (2016).

Rauline D., Tanguy Philippe A., Le Blévec J.M., Bousquet J. Numerical Investigation of the Performance of Several Static Mixers. The Canadian Journal of Chemical Engineering 76, (1998)

Saniare A., Henaut I., Argillier J.F. Pipeline transportation of heavy oils, a strategic, economic and technological challenge. Oil and Gas Science and Technology 59, 345-360 (2004).

Shadi W. Hasan, Mamdouh T. G., Nabil E. Heavy crude oil viscosity reduction and rheology for pipeline transportation. Fuel 89, 1095-1100 (2010).

Thakur R.K., Vial Ch., Nigam K.D.P., Nauman E.B., Djelveh G. Static mixers in the process industries – A review. Institution of Chemical Engineers 81, 205-228 (2003).

Theron F., Le S. N. Comparison between three static mixers for emulsification in turbulent flow. International Journal of Multiphase Flow 37, 488-500 (2011).

Vial, C., Camarasa, E., Poncin, S., Wild, G., Midoux, N. and Bouillard, J. Study of hydrodynamic behavior in bubble columns and external loops airlift reactors through analysis of pressure fluctuations. Chemical Engineering Science 55, 2957-2973 (2000).